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CONCURRENT RELIABILITY AND STABILITY ANALYSIS FOR RISK ASSESSMENT OF MICROGRIDS AND POWER SYSTEMS

**BY
ALI AZIZI**

PhD Thesis 2024



AALBORG UNIVERSITY
DENMARK

Concurrent Reliability and Stability Analysis for Risk Assessment of Micro- Grids and Power Systems

PhD Thesis 2024

Ali Azizi



AALBORG UNIVERSITY
DENMARK

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Biography



Ali Azizi

Ali received his B.Sc. in Electrical Power Engineering from Tabriz University in 2011. He then received his M.Sc. in Electrical Power Engineering from Sharif University of Technology, completing it in 2013. After gaining seven years of valuable work experiences as an electrical engineer in the industry, he started a new academic journey by joining Aalborg University as a PhD student in 2021, where he continued his studies until 2024. During his PhD program in the Department of Energy, he focused on the risk assessment and design of microgrids, with an emphasis on integrating reliability and stability simultaneously. His research was conducted under the supervision of Prof. Frede Blaabjerg and Associate Prof. Saeed Peyghami. During his PhD studies, he was involved as a research assistant in two projects: risk assessment of large-scale PV power plant for TotalEnergies and Developing the RelyPES reliability assessment software. In addition, he gained valuable practical experience during his study abroad program at Blue Power Partners (BPP), working on the risk assessment of a large-scale offshore wind power plant. His major research interests include risk assessment of power systems, system-level reliability modeling of power plants, and analysis of stability in power systems.

Abstract

Microgrids which are combining various renewable energy sources with conventional power generation and storage systems, play a pivotal role in the pursuit of a sustainable and secure energy supply. However, their reliable and stable operation poses significant challenges due to the inherent complexity and variability of renewable energy sources. Additionally, the prevalence of power electronics in microgrid components intensifies these challenges, as they inherently exhibit higher failure rates compared to conventional power system components. Furthermore, the small size, lower inertia, and strong coupling between variables in microgrids mean that even minor disturbances can disrupt stable operation and affect dynamic performance. Recognizing the critical importance of addressing dynamic failures initiated from stability challenges in the design and operation of microgrids, this thesis aims to develop a comprehensive solution for doing concurrent engineering design. It is noted that conventional design guidelines often focus solely on component failures or static failures, neglecting the impact of dynamic failures and their constraints. However, these dynamic failures can have a significant impact on both short-term and long-term operation of microgrids, ultimately deteriorating the overall risk of the system. Therefore, the need to address these dynamic failures in microgrid design and operation is paramount for ensuring their reliable and stable performance.

To address these concerns, the first step is to introduce a new design guideline that provides a specific roadmap for integrating stability issues into conventional risk assessment models and methods. This framework enables simultaneous evaluation of both static and dynamic failures in microgrids, considering different time resolutions. If the overall risk is deemed unacceptable, the microgrid will undergo redesigning, starting from the component level up to the system level. The redesign strategies may involve reconfigurations within the microgrid, adjustments to the quantity and size of specific components, and the selection of appropriate renewable energy sources.

To address the diverse impacts of stability issues on system risk, the proposed model introduces a comprehensive guideline for addressing all stability challenges in microgrids. This involves conducting root cause analyses and time domain simulations to identify instability causes, followed by determining the feasibility of incorporating specific stability challenges as constraints or limitations in the reliability modeling. Some stability challenges may be excluded from the analysis due to their duration or low significance in the overall system risk. This approach allows for the analysis of various short-term and long-term challenges and mitigates their impacts on system risk through appropriate system redesign measures.

This multi-domain design framework offers practical solutions to do risk assessment and mitigate stability issues during both the planning and operation phases of microgrids. Case studies and comparative analyses further validate the efficacy of the proposed framework, demonstrating its ability to understand and analyze the reliability and stability of microgrid systems and reduce the system risk.

Dansk Resume

Elektriske mikronet, som ofte kombinerer forskellige typer af vedvarende energikilder med konventionel elproduktion og lagrings-systemer, spiller en afgørende rolle i bestræbelserne på udviklingen af en fremtidig bæredygtig og sikker energiforsyning. Dog udgør deres drift betydelige udfordringer for pålideligheden på grund af den iboende kompleksitet og variabilitet. Samtidig øges dette af udbredelsen af effektelektronik-systemer i mikronettene, da de ofte har højere fejlrate sammenlignet med konventionelle komponenter el-systemet. Ydermere betyder størrelserne af enhederne en lavere inertie og der er en stærkere kobling imellem enhederne, hvorfor selv mindre forstyrrelser kan give ustabil drift og påvirke den dynamiske ydeevne af mikronettet. I anerkendelsen af dette i forbindelse med design og drift af Mikronet, har denne afhandling til formål at udvikle et nyt design paradigme, der både tager højde for komponenternes pålidelighed og hele systemets stabilitet for at kunne bestemme mikro-nettets samlede performance. Konventionelle design retningslinjer fokuserer ofte kun på komponentfejl eller statiske fejl, og overser virkningen af de dynamiske fejl og de begrænsninger det giver.

De dynamiske fejl kan have en betydelig indvirkning på både kort- og langtidsdrift af mikronettene, hvilket i sidste ende forværrer systemets samlede risiko for at kunne fejle. Derfor er behovet for at adressere disse dynamiske fejl i design af mikronettet, samt i deres drift afgørende for at sikre en pålidelig og stabil elforsyning. For at løse disse udfordringer er det første skridt at introducere en ny metode for design af Mikronet, der integrerer af stabilitetsproblemer ind i de konventionelle risikovurderingsmodeller. En sådan metode vil samtidig muliggøre en evaluering af både de statiske og de dynamiske fejl i mikronettet, idet der tages højde for forskellige tidshorisonter i analysen. Hvis den samlede risiko for nedbrud af mikronettet så vurderes som uacceptabel, vil mikronettet gennemgå et redesign, der starter fra komponentniveau og ender på systemniveau i forbindelse med analysen.

Strategierne for redesign kan blandt andet involvere om-konfigurationer i selve mikronettet, justeringer af antallet og størrelsen af de specifikke komponenter samt valg af passende vedvarende energikilder. For at kunne adressere de forskelligartede virkninger på stabiliteten introduceres nye retningslinjer og analyse-metoder, der kan adressere alle stabilitetsudfordringer i mikronettet samtidigt. Dette indebærer udførelse af årsagsanalyser for ustabiliteten, system-simuleringer, efterfulgt af muligheden for at inkludere dette som begrænsninger i den eksisterende pålidelighedsmodel. Ofte kan nogle af stabilitetsudfordringerne udelukkes fra analysen på grund af deres begrænsede varighed eller de har mindre betydning for den samlede systemrisiko. Denne analyse tilgang muliggør identifikation af forskellige kort- og langtidsudfordringer, samt muligheden for at afbøde deres indvirkninger på systemrisikoen via passende re-designs. Resultatet er en ny design metode, der kan give praktiske løsninger til at udføre en mere komplet risikovurdering og afbøde stabilitetsproblemer både i forbindelse med planlægningen og under driften af mikronet. Afhandlingen fremviser eksempler og sammenlignelige analyser, der

demonstrerer effektiviteten af de foreslåede design-metoder og resultaterne bidrager til en bedre forståelse til sikring af mere pålidelig el-forsyning.

Thesis Details

Thesis title: Concurrent Reliability and Stability Analysis for Risk Assessment of Micro-Grids and Power Systems
Ph.D. student: Ali Azizi
Supervisors: Prof. Frede Blaabjerg, Aalborg University
Associate Prof. Saeed Peyghami, Aalborg University

The main part of the dissertation is based on the following publications:

Publication in refereed journals:

- [J1] **A. Azizi**, F. Blaabjerg, and S. Peyghami. "A new risk assessment approach for design of hybrid microgrids considering stability issues." IET Generation, Transmission & Distribution 18.2 (2024): 314-325, doi:10.1049/gtd2.13040.
- [J2] **A. Azizi**, S. Peyghami, and F. Blaabjerg. " A New Multi-Domain Design Method for Hybrid Microgrids Integrating Reliability and Stability Simultaneously." Submitted in Renewable and Sustainable Energy Review (2024). (Revision)

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- [C1] **A. Azizi** , S. Peyghami, S. F. Zarei, and F. Blaabjerg, "The Impact of Sun Tracking on the Reliability of Solar Inverters," in 2022 International Power Electronics Conference (IPEC-Himeji 2022-ECCE Asia), 2022, pp. 1553–1559, , doi: 10.23919/IPEC-Himeji2022-ECCE53331.2022.9807153.
- [C2] **A. Azizi**, S. Peyghami, H. Wang and F. Blaabjerg, "Risk Evaluation of Hybrid Microgrids Considering DC-Link Voltage Stability," 2022 IEEE 13th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Kiel, Germany, 2022, pp. 1-6, doi: 10.1109/PEDG54999.2022.9923273.
- [C3] **A. Azizi**, S. Peyghami and F. Blaabjerg, "A Perspective on Power Converters Design: Stability and Reliability Aspects," 2023 11th International Conference on Power Electronics and ECCE Asia (ICPE 2023 - ECCE Asia), Jeju Island, Korea, Republic of, 2023, pp. 180-185, doi: 10.23919/ICPE2023-ECCEAsia54778.2023.10213671.

This dissertation has been submitted for assessment in partial fulfillment of the Ph.D. degree. Based on the publications shown above, the thesis integrates the research findings, providing a comprehensive overview of the primary outcome of the Ph.D. project. Parts of the results are used directly or indirectly in the extended summary of the thesis. The co-author statements have been made available to the assessment committee and they are also available at the Energy Department, Aalborg University.

Preface

This dissertation presents the outcomes of the Ph.D. project titled "Integrated Design of Microgrids Considering Reliability and Stability," conducted at the Department of Energy, Aalborg University, Denmark.

I extend my heartfelt gratitude to Professor Frede Blaabjerg, whose excellent support and guidance have been indispensable throughout my Ph.D. journey. His passion and enthusiasm will always be a source of motivation. I am equally grateful to Associate Professor Saeed Peyghami for his invaluable support and the fruitful discussions we shared. His brilliance and enthusiasm have left an indelible mark on my academic pursuits.

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To my colleagues at the Department of Energy, Aalborg University, I extend my sincere appreciation for their constant support and technical discussions. My friends in Aalborg have been a constant source of encouragement and support, sharing both the joys and challenges of life with me.

Last but certainly not least, I express profound gratitude to my wife for her unwavering support, understanding, and encouragement. Her presence has been my basis of strength throughout this journey.

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Part I

Report

Chapter 1. Introduction

1.1. Background

Over the past decades, there has been an increasing global recognition regarding critical environmental issues such as climate change, global warming, and fossil fuel depletion. Consequently, there has been a strong shift in governmental policies towards the pursuit of a decarbonized and oil-independent power systems [1]. These notable advancements have been adopted by developed countries, leading to a shift in their energy policies from traditional fossil fuel-based utilities to sustainable energy sources and innovative technologies like wind farms and solar power plants [2]. This change demonstrates a global trend toward more sustainable and environmentally friendly energy sources. Figure 1-1 illustrates the growth of renewable energy sources over 23 years from 2000, reaching almost 4000 GW in 2023 [3]. It also shows notable increase in wind and solar energy capacities compared to other energy sources, which are now essential parts of the developed energy infrastructure.

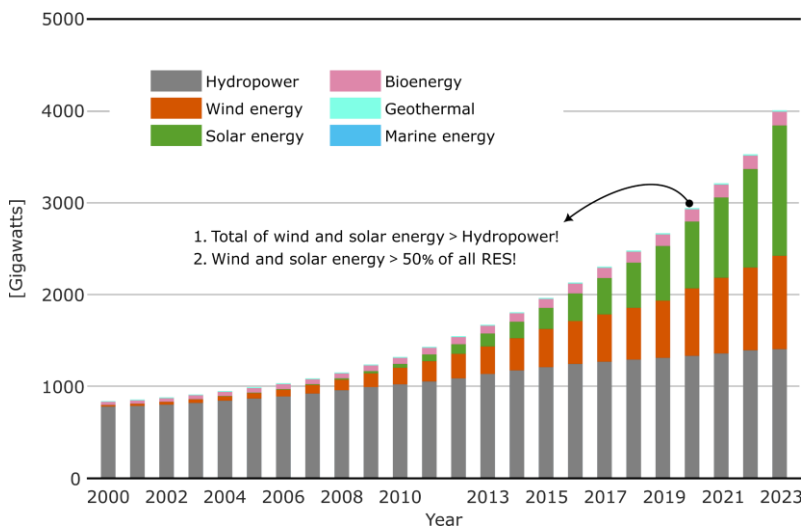


Figure 1-1: Global renewable energy annual installed capacity in Gigawatt [3]

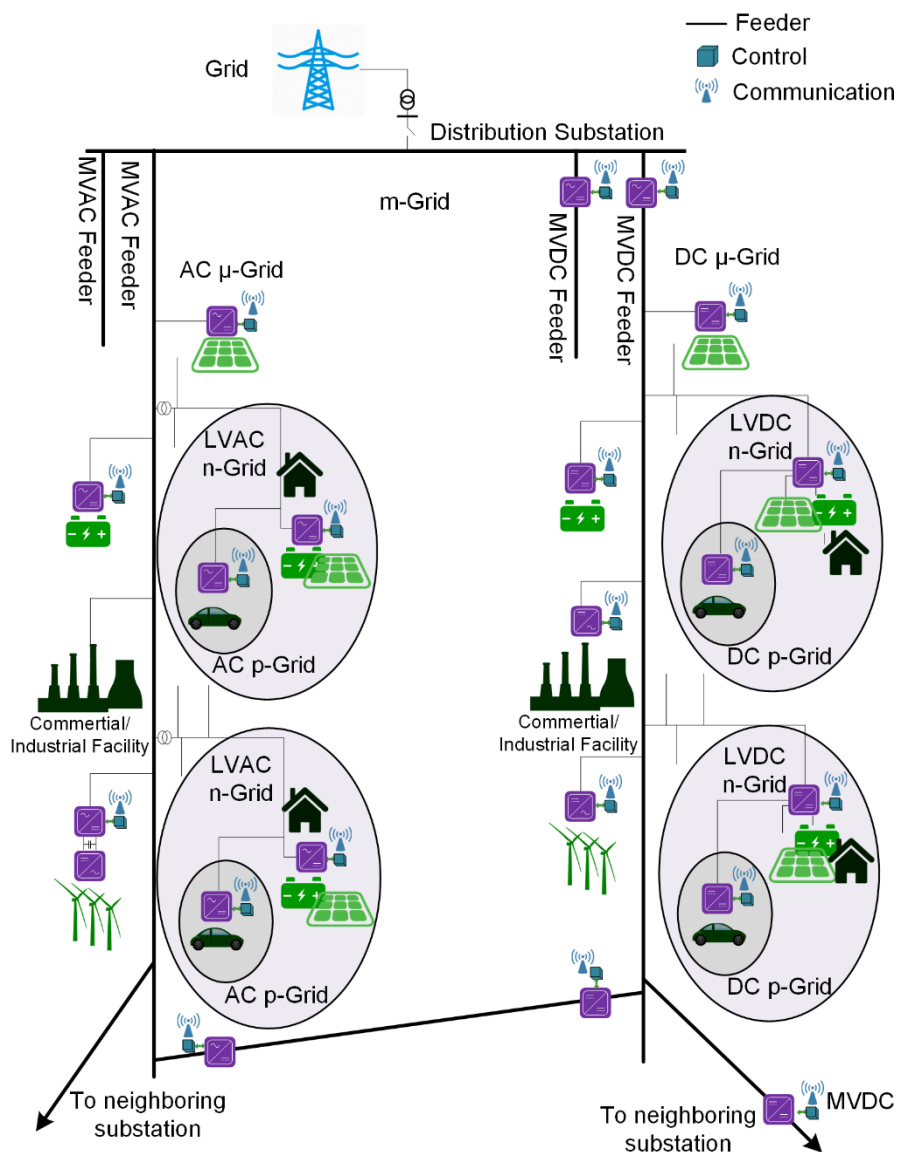
Due to the increasing worldwide shift towards sustainable energy sources, microgrids have become a key component of today's energy paradigm [4], [5]. These independent power systems not only offer adaptability, efficiency, and resilience but also act as a reflection of the innovative advancements made in the transition to green energy alternatives. Microgrids provide a more flexible and scalable electrical infrastructure that is more economical and operationally efficient than large conventional power systems. Microgrid projects are becoming more and more significant in the power systems as evidenced by the annual growth trend in the number of recently established

microgrid projects. Recent statistics indicate that, in 2023, the US saw the installation of 692 new microgrid systems with a total capacity of 4.4 GW [6], [7]. This indicates a significant increase in comparison to the preceding decade, with an approximate five times rise in the number of new projects. Moreover, microgrids have already established their dependability in delivering electricity during emergency situations, as illustrated by their contribution to the Texas blackout of January 2021 [8].

However, the significant penetration of microgrids has resulted in notable changes for the power systems structures. Power electronics have been the foundation for modern power systems since they enable the energy conversion in microgrids [9], [10]. In the past, power systems heavily leaned on centralized generation and distribution, relying on large-scale power plants and extensive transmission networks. But with the emergence of microgrids, this traditional approach has undergone a major shift. The focus is now on localized and decentralized generation and distribution, making power electronics essential for an efficient energy conversion. Power electronics components, including energy storage systems, inverters, converters, and their controllers, are essential for controlling the electricity flow in microgrids and facilitating the smooth integration of diverse loads, renewable energy sources, and energy storage systems. The move towards decentralized energy systems highlights the crucial role of power electronics in upgrading and optimizing power systems for improved efficiency and reliability. Figure 1-2 illustrates the projected structure of a future energy system, highlighting power electronic devices as central components driving the energy transition.

By incorporating power electronics into microgrid systems, the management and regulation of electricity flow becomes more flexible and potentially more efficient. Because of this, microgrids can operate separately or in combination with the main grid. Essential operations of microgrids heavily rely on power electronic devices, which include maintaining stable voltage, controlling frequency, and maybe improving power quality [11]. Microgrids can quickly cope with changing demand patterns and generation conditions due to power electronics advanced control algorithms and real-time monitoring features. Additionally, power electronics may make it easier to switch between grid-connected and off-grid modes, guaranteeing a steady supply of essential loads even in the event of main grid interruptions or outages. Thus, the development of power electronics technology has transformed the architecture, functionality, and integration of microgrids into current power systems, opening the door to a more efficient, sustainable, and resilient energy future.

However, microgrids face a wide range of design and operational challenges as well as constraints, which are initiated from their unique characteristics such as small size, low inertia, lower reactance-to-resistance (X/R) ratio and strong coupling between variables [12]. Integration of power electronics and uncertain energy sources intensifies these challenges, necessitating a comprehensive approach in the design and planning phases for microgrids.



LVDC: Low Voltage Direct Current
 MVDC: Medium Voltage Direct Current
 LVAC: Low Voltage Alternating Current
 MVAC: Medium Voltage Alternating Current

Figure 1-2: Illustration of upcoming power systems incorporating power electronics and renewable energy sources using different grid structures [13].

The low inertia problem in microgrids presents a major challenge because it affects the microgrid's ability to maintain stable frequency regulation and respond quickly to load changes. Additionally, the strong coupling between variables within microgrids complicates control dynamics and leads to potential stability issues and reliability concerns. Researchers in [14] have presented a summary of grid integration technologies, energy management approaches, and ancillary services for microgrids. It discusses different control schemes for interfacing converters, including centralized and decentralized strategies. Microgrids control challenges including Battery Energy Storage System (BESS) is discussed in [15], [16] to ensure proper operation of renewable energy sources, optimizing power transfer, seamless disconnection and reconnection processes, and managing sensitive loads. Findings show that the capacity, control, and energy management of the BESS has a crucial impact on stable operation of microgrid, and suitable control strategies need to be designed to properly respond to the rapid changes. Control solutions must optimize system operation to meet these challenges. It has been noted, though, that managing the shifts from islanded to grid-connected modes of operation, as well as controlling a multitude of uncertain sources with different characteristics, is expected to present major challenges. In order to overcome these obstacles, appropriate control strategies and cutting-edge communication systems are crucial in order to be successful.

Microgrids must also address issues related to reliability, harmonic distortion, and protection, each of which can be categorized as a risk in power systems. In power systems, risk refers to the probability and impact of undesirable events that could affect the reliability, safety, and economic performance of the electrical grid. It involves assessing potential threats to the system, such as equipment failures, natural disasters, cyber-attacks, operational errors, or market fluctuations, and understanding their consequences on the power supply, stability, and overall system integrity. Therefore, these difficulties and challenges highlight the complexity of microgrid operation, as provides the vulnerability of control systems to unstable and intermittent energy sources. Investigations have been conducted into a number of power system protection-related topics, such as communication protocols, protective relays, dc distribution systems, fault detection and protection in dc microgrids, their difficulties, and solutions [17], [18]. Microgrid protection challenges include bidirectional fault currents, fault current variations under various operating conditions, cybersecurity issues, automation system standards, appropriate grounding system design, quick fault detection/location techniques, and DC microgrid efficiency requirements for circuit breakers. Additionally, topology changes and renewable energies impacts, such as the impact of distance to fault, grid configuration, and control mode, also pose challenges for protection systems [19].

Among these challenges, reliability and stability emerge as two of the most important issues. Microgrid performance and risk are seriously threatened by higher power electronics failure rates and control system vulnerability to energy generation uncertainties. It is important to address these challenges, since a more reliable and stable microgrid design may mitigate other associated issues like control dynamics, harmonic distortion, and protection concerns. Hence, there is an imperative need for

adequate microgrid design and planning procedures that prioritize reliability and stability. By strengthening the robustness of microgrid systems in the face of operational challenges, such as low inertia and uncertain energy sources, we can realize a more reliable and efficient energy infrastructure in the future.

Moreover, microgrids operational risk is a significant concern despite of their potential to transform the energy system. The dynamic characteristics of microgrids, when combined with complicated control systems and intermittent energy sources, create inherent vulnerabilities that could negatively impact stability and reliability. Consequently, comprehensive risk assessment becomes crucial to guarantee the robustness of microgrid design and operation [20]. The process of risk assessment in microgrids includes the identification of potential failures, analysis of their probability and potential impact, and implementation of mitigation strategies to minimize adverse effects [21]. Operational risks may affect microgrid performance, leading to disruptions in power delivery and compromising system stability. Examples of these risks include equipment failures and inconsistencies in energy supply [22]. The effectiveness of risk management methods has a direct impact on the two key aspects of microgrid operation: reliability and stability. Inadequate risk management can lead to more downtime, lower system performance, and even cascading failures that take down the entire microgrid network [23]. Thus, in order to maintain the integrity and resilience of microgrid systems, proactive risk assessment and mitigation measures are crucial. Furthermore, the interdependency of microgrids in larger power systems emphasizes the need to address systemic risks. The potential impact of operational failures can be increased by the spreading disruptions from one area of the microgrid network to other interconnected systems.

In the conventional power systems, stability and reliability have been considered as independent concepts, each analyzed and optimized during system design and operation. However, in power electronics-based systems like microgrids, where converter-based power sources are prevalent, the interaction between stability and reliability becomes most important. For example, the aging of power converter components may result in potential interactions with converter control systems, change the characteristics of the ac filters [24], and cause stability issues. Therefore, it is crucial to take stability and reliability into account throughout the entire lifetime modeling process, from design to operation, in power electronics-based power systems like microgrids.

The main issue arises from the inherent independency of stability and reliability, and their interactions have not been adequately modeled so far. Therefore, the fundamental goal of this PhD program is to develop a multi-domain framework for bridging stability and reliability concepts in power electronic-based power systems as microgrids. This requires implementing a modeling approach that comprehensively addresses system risk, taking into consideration both stability and reliability concerns. Specifically, power grid risk can be measured by evaluating system performance in the context of uncertainties, such as device outages, mission profiles, operating conditions, and environmental conditions. By introducing a novel framework that integrates stability and reliability through appropriate risk measures, it becomes

possible to achieve optimal design of power electronics microgrids while ensuring acceptable risk levels.

This thesis will first propose a new multi-domain analysis framework that links stability and reliability and enables system risk modeling and analysis. Subsequently, it will introduce guidelines for the optimal design of microgrids to maintain acceptable risk levels considering both stability and reliability issues and thereby having a concurrent design method. Notably, the proposed approach will provide a general guideline applicable to a wide range of stability challenges without losing generality. Furthermore, the proposed methodology will be validated using a hybrid microgrid as a representative example of a power electronics-dominated power system. The resulting framework can be applied to various power electronic-based systems facing different stability challenges. By implementing this comprehensive methodology, which encompasses all essential criteria from system formation to operational planning, reliable and robust microgrids are aimed to be designed for various operating conditions.

1.1.1.1. Navigating Uncertainty: The Risk Classification in Modern Power Systems

Before diving into the detailed design and planning of microgrids and performing risk assessments considering reliability and stability, reviewing current frameworks is essential for evaluating power electronic-based power systems' performance and risk over the short and long terms. The ability of a system to meet demand has traditionally been measured using reliability indices like security and adequacy. However, the conventional risk assessment models are centered around centralized structures, where a single entity controls the entire system, which may not fully represent the complexities of decentralized microgrid systems, where control is distributed among multiple smaller units. The Cigre 1.27 working group has proposed new reliability definitions that take into consideration the use of battery energy storage systems and renewable energy sources as a result of this limitation. According to Cigre 1.27, in addition to supplying loads, modern power systems must also be reliable for suppliers, including private generating units [25]. It is crucial to understand how the integration of microgrids will affect the security and sufficiency of power systems as well as how to modify current frameworks to account for the impact of modern technologies on system reliability.

Decentralized generation and power electronics become important in this situation. To precisely evaluate the stability and reliability of microgrids, which increasingly use decentralized generation sources and power electronics for control and management, traditional reliability assessment methods must change. Thus, to guarantee the successful integration of microgrids into modern power systems analysis, it is crucial to investigate the relationship between decentralized generation, power electronics, and overall system reliability. The risk classification of conventional power systems, as depicted in Figure 1-3, comprises two primary sub-categories: planning and operation. The planning phase is associated with Adequacy, while the power systems operation is covered by the term "Security". The concept of

security refers to the power system's ability to withstand sudden contingencies and outages, ensuring uninterrupted operation, while adequacy reflects the system's ability to consistently meet demand requirements [25], [26]. Therefore, the long-term performance of a system can be assessed using adequacy measure, while security metric represents its short-term performance.

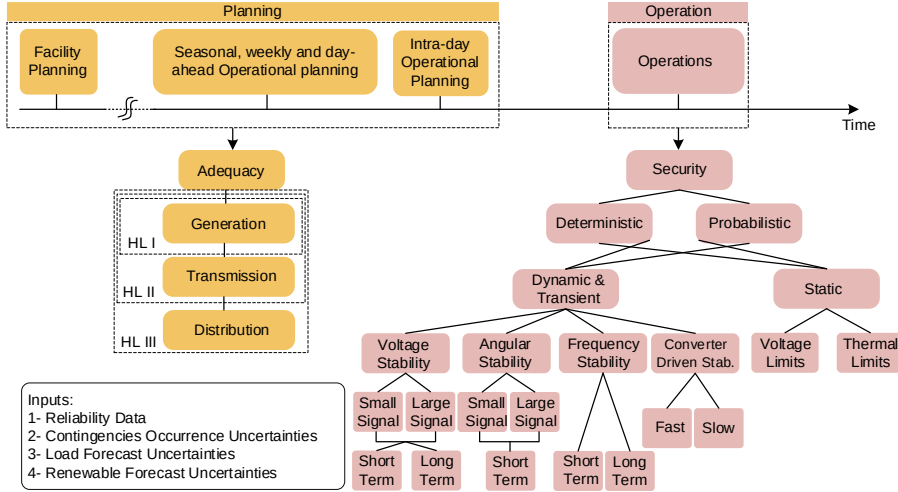


Figure 1-3: Risk classification from planning and operation perspective in conventional power systems [27]

According to Figure 1-3, the adequacy typically involves three hierarchical levels: Generation, Transmission, and Distribution. Generation level focuses on the adequacy of generation capacity to meet the demand. It involves assessing the availability and reliability of power plants and their ability to supply electricity under normal and contingency conditions. In the transmission level, the focus is on the transmission network's ability to deliver power from generation sites to distribution networks. It includes evaluating the transmission system's capacity, stability, and resiliency to faults or disruptions. The distribution networks that provide end users with electricity are the focus of the distribution level. The evaluation involves investigating the distribution system's transformer and line reliability as well as their fault tolerance and capacity to withstand variations in load.

Furthermore, security comprises two main domains: Dynamic security, and Static security, which together guarantee the system's stable operation in the short term. Static security assesses whether the power system can withstand sudden disruptions without losing stability. Steady-state analysis is used to make sure the system can function within acceptable limits following a disturbance. Dynamic security involves evaluating the response of power system to time-varying disturbances, like fluctuations in demand or supply. It includes also the assessment of system stability over time and the ability to recover from transient events. Finally, cybersecurity has become a crucial domain due to the increasing integration of information and

communication technologies (ICTs) in power systems. It involves protecting the power system's cyber infrastructure from attacks or failures that might have an impact on the physical system's reliability and stability. Thus, by integrating the summarized emerging challenges in modern power electronic-based power systems, as depicted in Figure 1-4, modifications have been implemented to the conventional risk assessment framework. The adequacy assessment has been updated in accordance with Figure 1-5, which includes reliability evaluations for cyber-physical power systems, taking into account the integration of microgrids [27]–[29].

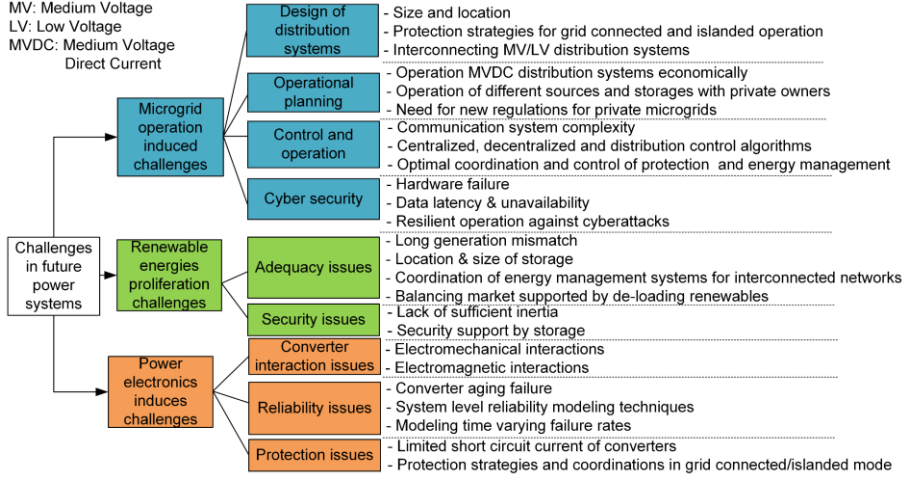


Figure 1-4: Challenges in future power systems relying on power electronics [27]

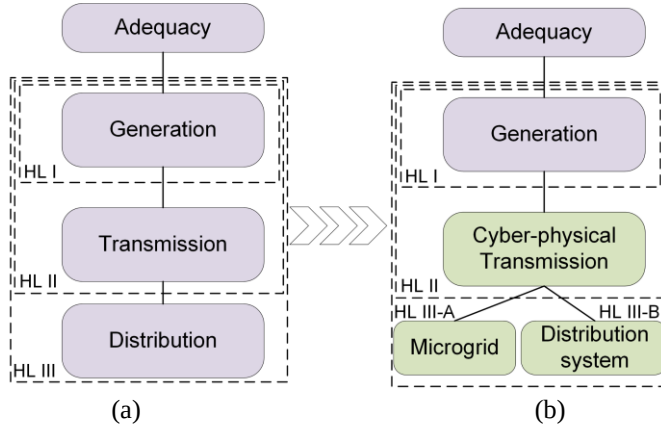


Figure 1-5: Power systems adequacy assessment. (a) Conventional method, (b) Modern method. HL x: Hierarchical Level x [27].

In addition, there are three primary ways to look into the security of modern power systems.: cyber security, static security, and dynamic security, as illustrated in Figure

1-6. In contrast to the conventional assessment approaches, there is a focus on analyzing the thermal limits of power electronics. Further discussions have followed in [27]. Microgrids can be designed and operated more precisely and reliably by incorporating the identified risk factors using the improved risk assessment approach, which makes it easier to incorporate different microgrid issues for both short- and long-term operational conditions. Most of the previous research on microgrid designs has focused on various configurations [30], [31], control methodologies [32], management techniques [33], [34], and alternative approaches to enhance efficiency.

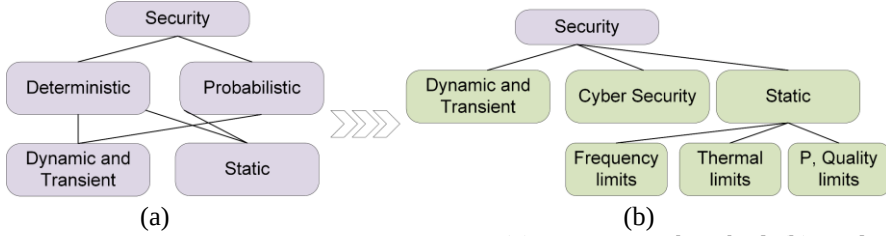


Figure 1-6: Power system Security assessment. (a) Conventional method, (b) Modern method [27].

Particularly, researchers in [35] have highlighted relevant standards, like those specified by IEEE and Cigre, in microgrid design. However, because of the increasing risks associated with power electronic-based control frameworks resulting from the growing number of control hardware and the intermittent nature of renewable sources, in recent years, risk assessment has gained importance and become a critical focus [35].

The first attempts at risk assessment predicted reliability from component to system levels using historical data from MIL-HDBK-217 [36] and IEC TR 62380 [37]. A brief overview of reliability analysis has been covered in [22], [38], with a special emphasis on microgrids and the implications for design. Researchers in [39] provided a comprehensive overview of existing research on microgrid reliability and offered various perspectives for design and operation of microgrids. However, it did not clearly outline comprehensive concurrent design methods. In [40], the optimal placement of renewable energy sources in microgrid design was investigated, using specific load-point reliability indices integrated into the objective function. The findings demonstrated an improvement in the reliability and robustness of the microgrid. Additionally, various studies have concentrated on enhancing the reliability of microgrids by considering both component-level and converter-level perspectives [41]–[43]. At the component level, efforts are focused on estimating the lifetime of sensitive and most fragile components of converters, such as power switches and capacitors, to ensure their continuous operation until their designated lifetime. To identify the most reliable and strong components for power converters, these methodologies involve thoroughly analyzing components under specific operational conditions and a wide variety of mission profiles [44]–[47]. These strategies aim to increase power converter life expectancy, which in turn increases the

reliability of power electronic-based power systems (PEPS). Power converters are only one component of a much larger power system, and this must be recognized. None of these methods provided one comprehensive set of design guidelines that apply to the whole system.

Furthermore, with reliability as the main objective function, researchers have investigated a variety of short- and long-term planning strategies for microgrid design. Investigations into the optimal placement and sizing of renewable energy sources have been conducted [48]–[50], with the goal of ensuring that the required level of reliability is reached during long-term operations. Introducing innovative energy and power management strategies in microgrid design is another approach to guarantee reliable operation under diverse operating conditions and also keep a long term reliability level [51]–[54]. By incorporating reliability metrics into the objective function and utilizing probabilistic optimization algorithms, these methodologies reduce the likelihood of load loss in the event of source and component failures.

The most recent and comprehensive model-based design guideline for microgrids has been proposed in [13]. Illustrated in Figure 1-7, this model initially identifies suitable components for power converters at the component level, ensuring a high level of reliability under specific load and generation mission profiles. Reliability indices are then evaluated at the system level. When these indices exceed acceptable risk limits, failure mode analysis and other techniques are used to identify weak points, after which the weakest converter is redesigned.

However, the proposed methodology demonstrates notable limitations that can impact the overall risk of the system:

- a) Strong coupling between system variables are seen in microgrids, which are distinguished by their small size and relatively low inertia when compared to conventional power systems. Therefore, a single outage or small disturbance in a generating unit has the potential to impact the dynamic performance of the entire microgrid. The simultaneous interactions between different components must therefore be considered in the design model. These interactions may lead to additional failures that may not be implemented when modeling them separately.
- b) Stability, one of the most critical challenges in microgrid design, can cause a variety of problems in short-term operation and introduce restrictions in long-term operation. These factors influence the dynamic performance of microgrids and could lead to more systemic failures. Therefore, in order to guarantee a reliable and robust design for microgrids, it is crucial to address and balance the impact of both dynamic failures and static failures resulting from component failures.

These shortcomings, which are highlighted in red in Figure 1-7, demonstrate the necessity of including the effects of dynamic failures in the risk assessment framework in order to redesign microgrids and make them more dependable and resilient. Because microgrids are smaller than traditional power systems and have

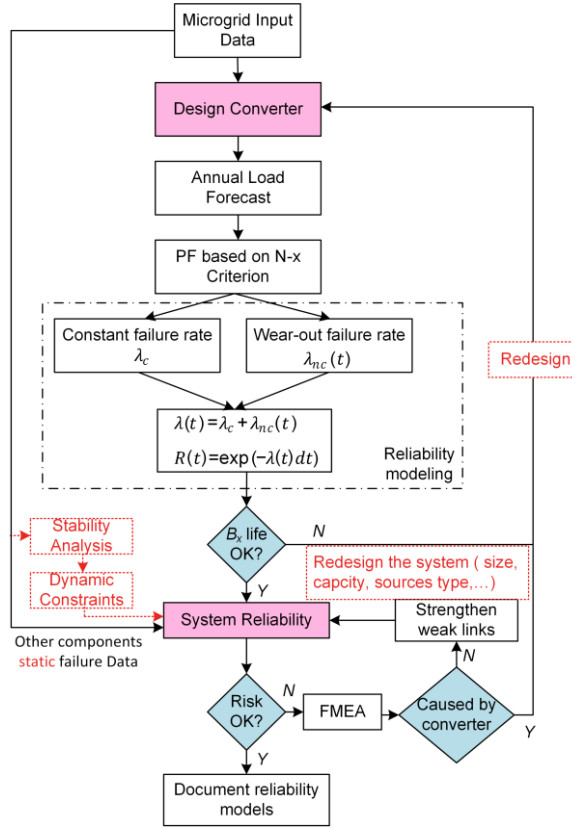


Figure 1-7: System-level design for reliability in microgrids, as outlined in [13], highlighting present shortcomings in red boxes.

different energy generation paradigms, their stability challenges compared to those of traditional power systems, they are distinct. Thus, the following criteria can be used to categorize microgrid stability [12]:

- Magnitude of disturbance
- Duration of instability
- Methodology for predicting instability and conducting stability analysis
- Physical source of instability

It is interesting to note that any instability in microgrids usually causes fluctuations in all system variables due to the strong coupling among them. The two main categories of microgrid stability challenges are identified in IEEE PES Technical Report 66: (i) control system stability, as well as (ii) power supply and balancing stability [12].

The stability of the control systems used in microgrids is the main focus of the control system stability, as seen in Figure 1-8. It includes evaluating and analyzing the different methods and systems utilized to regulate the microgrid's voltage, frequency, and power distribution. This category includes problems with control system design,

tuning, and coordination. Furthermore, power supply and balancing stability relate to ensuring the overall stability and balance of power within the microgrid. It discusses factors that have an impact on power generation, distribution, and utilization of electrical power within the microgrid. Balance between load and demand, integration of renewable energy, islanding operations, and stability of grid interactions are important issues.

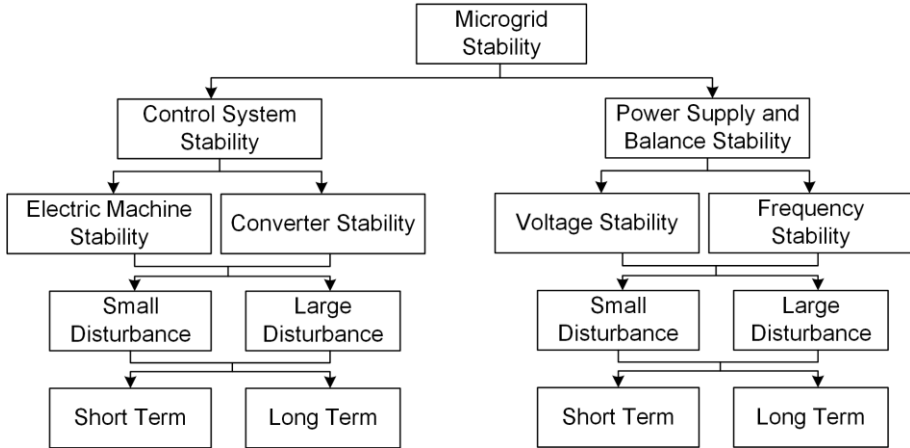


Figure 1-8: Classification of microgrid stability issues [12].

Transient disturbances can lead to instability in a microgrid during short-term operation like abrupt changes in load or the loss of a single distributed generation (DG) unit, as per the classification described in IEEE PES TR 66 [12]. The microgrids complicated balance between power generation and demand can be upset by these transient events, which can cause voltage and frequency fluctuations that affect the system stability. Additionally, certain stability problems could arise during the microgrid's long-term operation, affecting its overall resiliency and reliability. These stability challenges, whether experienced in the short or long term, make running microgrids more risky. It is crucial to note that these risks may occur even without component failures, emphasizing the importance of proactive stability management and risk mitigation strategies in ensuring the resilience of microgrid systems.

Many studies have been conducted to improve the stability of microgrids during both the planning and operating phases [55]–[60]. From a control point of view, researchers in [61] have summarized various control strategies for both current and voltage control loops. These strategies are designed to improve overall reliability, maintain power quality, maximize performance, and stabilize the system. DC-link voltage stability in bidirectional interlinking converters (ICs) operating in rectifying mode has been investigated in [62], [63].

The present analysis reveals particular circumstances which impose limitations on the operational capacity of the IC to maintain stable operation of the hybrid microgrids. Furthermore, various techniques have been applied for transient stability analysis in

microgrids to model their behavior and dynamic response under diverse operating conditions, such as the loss of generating units [64], significant load changes [65], and faults [66]. Time-domain simulation methods are extensively employed in microgrid design to assess the functionality and optimal arrangement of the proposed system [67]. These methods address challenges like synchronization [68], transient stability of voltage and frequency [69], voltage angle deviations [70], and frequency oscillations [71]. Power and energy function techniques, such as Lyapunov [72], [73] and Equal Area Criteria (EAC) [74], [75], offer alternative approaches to explore stability issues in microgrids. These techniques, however, are unable to measure the effect of dynamic performance on microgrid risk directly, indicating the necessity for improvements and changes in component quantity, size, control, and structure. Basically, they do not specify which topology during the operational and planning stages ensures a higher degree of stability and reliability.

Recently, the authors in [76] have introduced a reliability assessment framework constrained by stability for microgrid converters. The emphasis lies in analyzing the impact of adjusting droop gains, which serve as control parameters for converters, on dynamic performance and, consequently, their effect on converter lifespan. The objective is to identify suitable droop gains that ensure both reliable and stable converter operation. It also includes the use of a power system stabilizer (PSS) to enhance system stability, especially when instability can arise due to increased droop gains aimed at reliability enhancement.

Moreover, the authors in [77] explored the effects of reducing the feedforward gain within the current control loop on voltage stability. The model assesses the lifetime of converter switches and capacitors under these circumstances, along with changes in droop gains, to determine converter reliability. The overall risk is a combination of the independent evaluations of stability and reliability provided by the proposed model. A comparable methodology was utilized in [78], considering the degradation of AC filter capacitance. Results indicate that degradation of capacitance increases the probability of instability and, as a result, the unreliability of the converter.

However, the main focus of these frameworks is on lifetime modeling and modifying converter control parameters. It is crucial to take into account a number of factors when performing a stability-oriented risk assessment for microgrids. These include energy source types and characteristics, power management techniques, short- and long-term stability issues, a thorough model that can be used to analyze different aspects of reliability and stability, and more. This PhD project will introduce a comprehensive multi-domain design guideline specifically for microgrids, considering all of these recognized limitations and shortcomings. This guideline will carefully address both short-term and long-term stability challenges and their impact on risk, in addition to traditional reliability assessment techniques.

1.2. Thesis Motivation and Research Tasks

As discussed above, maintaining the reliability and stability of microgrids is severely constrained by the inherent complexity of these systems as well as the uncertainty and fluctuation of renewable energy sources. Although most traditional risk assessment

techniques focus on static failures caused by component failures, it is equally important to consider the critical impact of dynamic failures caused by stability problems. These difficulties become more severe by the limits and restrictions resulting from both short- and long-term operations, which raises the total risk associated with microgrid operation. Managing microgrid risks effectively requires an understanding of the interaction between static and dynamic failures and how they influence each other.

Overcoming these challenges necessitates bridging the gap between stability and reliability concerns in microgrid operation and design. Highlighting the effects of dynamic failures demonstrates how crucial it is to take proactive steps in both phases to improve the system resilience and successfully reduce risks. Consequently, the development of a multi-domain design guideline becomes imperative. This guideline should describe the impact of dynamic failures on the microgrid's overall risk profile, in addition to identifying their causes. Using this design guideline, the model will provide different redesign strategies to optimize the microgrid configuration, ultimately aiming for a stable and dependable system, if the risk level deviates from standard thresholds. This proactive strategy guarantees that, even in the case of changing operational and environmental conditions, microgrid systems are able to adjust to new challenges while maintaining operational integrity. Below are the key motivations detailed for this PhD project:

Reliability and Stability Concerns: The research reveals that while microgrids offer numerous advantages, they also pose several stability and reliability challenges that require attention. The incorporation of renewable energy sources can result in fluctuations in power supply, which, if not managed properly, can cause stability issues. These instability concerns, in turn, may give rise to dynamic failures that undermine the overall reliability of the microgrid.

Dynamic Failures: It also emphasizes the need to consider dynamic failures in the design and operation of microgrids. Dynamic failures triggered by stability issues can significantly affect the overall system risk. The motivation here is to develop a design guideline that not only addresses static risks but also mitigates dynamic risks to ensure a more reliable microgrid.

Comprehensive Design Guideline: The project proposes a comprehensive multi-domain design guideline that integrates both reliability and stability considerations. The motivation is to bridge the gap between these two critical aspects of microgrid design, which have often been treated separately. The vision is to improve both static and dynamic performance by providing a more comprehensive approach to microgrid design.

Risk Assessment Model: The project aims to introduce a new model for risk assessment in microgrids that includes stability challenges in the assessment framework. The motivation is to develop a methodology that can manage stability

issues arising from short term and long-term periods, which are critical for maintaining the continuous operation of the microgrid.

Microgrid Redesign and Configuration: The study investigates the need for system redesign to mitigate overall risk and minimize dynamic failures. The motivation here is to provide solutions that can be implemented in existing microgrids to improve their reliability and stability. This includes sensitivity analysis to identify critical components, reconfiguration strategies, and optimization of renewable energy sources. Accordingly, the tasks and research activities completed for this PhD project are summed up in Figure 1-9.

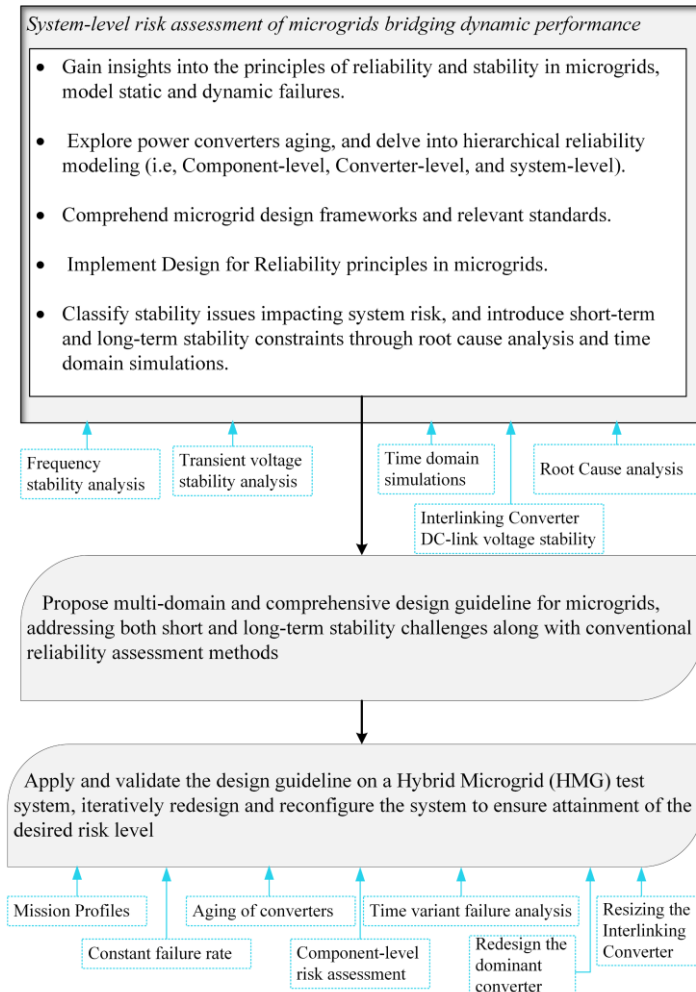


Figure 1-9: Tasks and activities outlined in this PhD thesis research.

1.2.1. Research Questions and Objectives

The primary aim of this PhD project is to develop a comprehensive design guideline for microgrids, addressing both reliability and stability concerns simultaneously. This framework initially focuses on quantifying dynamic and static risks within microgrids, followed by proposing design solutions to ensure operation within desired and standard risk levels. The proposed solutions and redesign guidelines are applicable in both the planning and operation phases of microgrids. This introduces several scientific challenges, which are summarized in the following research questions:

- 1) *How can the stability connected to the operational phase be combined with the reliability related to the planning horizon?*

The combination of stability related to the operational phase and reliability related to the planning horizon requires a comprehensive plan that takes into account both the short- and long-term aspects of system performance. Adequacy and security are the two primary measurement metrics used in traditional reliability assessment techniques, as was previously discussed. Problems with stability may arise that impact both metrics. Stability limitations may restrict a component's maximum allowable power transfer during long-term operation, which may further affect the load supply associated with the concept of adequacy. These limitations could result from intrinsic component characteristics or control strategies. Additionally, some significant disruptions, like sudden changes in load or the loss of a single generating unit, can result in transient instability problems which the microgrid is unable to handle. These unforeseen events are linked to the idea of security. It becomes clear that operational stability issues have a direct impact on the overall risk of the microgrid. These dynamic failures can be addressed using overall risk assessment models by integrating time-variant failure analysis with various time resolutions. By the integration of stability and reliability considerations throughout the planning and operation phases, this unified strategy ensures a robust and reliable microgrid system.

- 2) *How can stability issues of microgrids be mitigated during the design and planning phase?*

Microgrid stability problems can be reduced in the planning and design phases by employing an integrated approach that incorporates the following strategies:

Optimal selection of energy sources: A more sustainable and stable grid structure can be achieved by mindfully selecting and sizing the energy sources within the AC and DC subgrids. Throughout the design and operation phases of the system, this selection process should take into account the dynamic performance of various energy sources and their impact on the stability of the system.

Strengthening the dominant components: It is crucial to recognize and strengthen the dominant component, as it has the greatest influence on both dynamic and static performance. By concentrating on strengthening this critical component at the component level, the microgrid's overall stability can be enhanced.

Reconfiguration of components: Reconfiguring certain components in terms of quantity and size can also contribute to stability enhancement. Adjusting the

configuration of components based on their criticality and expected operational conditions may help optimize the microgrid's stability and performance.

Advanced control strategies: In addition to the aforementioned strategies, implementing advanced control strategies for current and voltage control loops can further improve the system stability. These advanced control techniques are specifically appropriated to enhance performance, ensure optimal power quality, and boost overall system reliability, all of which are critical for effectively mitigating stability issues in microgrids. However, the utilization of different control concepts is not the primary focus of this PhD project for two main reasons.

Firstly, the main aim is to introduce a multi-domain design guideline wherein multiple control strategies can be analyzed comprehensively, and their impact on overall risk can be measured to determine the optimum control strategy. Secondly, it is crucial to note that many of the significant instability issues in microgrids are independent of control strategies. While control strategies play a vital role in enhancing stability, addressing more expansive design considerations and system-level factors are essential for ensuring reliable and stable microgrid operation. Consequently, in order to efficiently achieve these objectives, the project gives priority to a general approach that includes a variety of aspects outside of control strategies. By implementing these strategies in the design and planning phase, microgrid developers can proactively address stability issues and guarantee the system's resiliency to possible fluctuations and disruptions.

3) *How to design the microgrid reliably concerning stability issues.*

To address this question, it is crucial to start with a comprehensive risk assessment that includes both static and dynamic stability concerns. This assessment should precisely evaluate how stability constraints might affect various system components and operations. By analyzing measured reliability indices, various scenarios can be outlined: If the overall system risk remains within acceptable thresholds, redesign efforts may not be necessary. Alternatively, reinforcing critical equipment with more strength components, particularly those with most impact on overall risk, should be considered. Another scenario involves redesigning components that directly influence dynamic failures by adjusting their size and quantity to effectively mitigate the overall risk. Optimizing system redesign entails conducting sensitivity analyses to identify dominant components, exploring reconfiguration strategies, and assessing changes in energy source types during the design phase. Each of these methodologies contributes significantly to system optimization and risk reduction.

Considering the aforementioned research questions and the unique characteristics of microgrids, the main objectives of the PhD project are outlined as follows:

- Develop a comprehensive risk assessment model for power-electronic based power systems that incorporates stability issues into the reliability framework. This involves identifying and classifying the main stability issues of microgrids and devising solutions that can be implemented during the design or planning phase.

- Integrate the reliability of power converters into stability considerations to enhance the overall system reliability. By addressing stability issues at the component level, the project aims to improve the resilience of microgrid systems.
- Formulate a design guideline for modern power electronic-based microgrids that takes into account both stability and reliability challenges. This guideline will provide a structured approach for designing microgrids that are robust, reliable, and capable of withstanding dynamic operating conditions.

To achieve these objectives, the thesis is structured into two main phases:

Phase 1: New risk assessment methodology proposal

The first phase of the thesis involves the development of a novel risk assessment methodology for microgrids. This methodology will address various stability issues encountered in microgrid systems and classify them based on their root causes. The main causes of instability challenges will be discovered through detailed studies, enabling better understanding of the underlying mechanisms. Then, a decision will be made about whether these stability problems can be effectively addressed in the design phase. If feasible, strategies for incorporating stability considerations into the overall system performance will be developed. This integration will be assessed using recognized risk metrics like Loss of Load Expectation (LOLE), Loss of Load Frequency (LOLF), as well as two additional indices: Expected Interruption Duration (EID) and Expected Interruption Frequency (EIF), which will be elaborated in subsequent chapters. In this phase, a reliability model will be developed to evaluate the impact of system stability on overall system reliability. Monte Carlo simulations will be employed to assess the reliability of the microgrid system under various operating conditions and uncertainties, including component outages, failures, aging, and fluctuations in renewable energy sources and loads. The main results of this phase will be comprehensive evaluation of the system risk, taking into account stability issues arising from the uncertainties inherent in microgrid operation. Figure 1-10 illustrates the workflow of the first phase of the PhD program, highlighting the systematic approach taken to address stability-related challenges in microgrid systems.

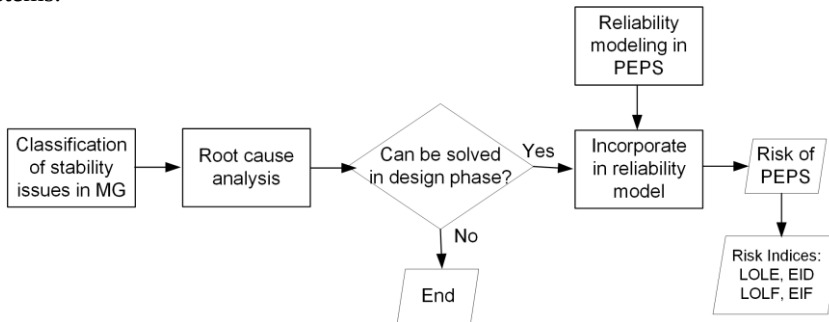


Figure 1-10: Workflow of the first phase in risk assessment of this PhD program.

Phase 2: Integrated Design for Reliability and Stability

During the second phase, a guideline for the integrated design of microgrids, focusing on stability and reliability indices, will be developed. Following the process outlined in Figure 1-11, the power system will undergo analysis, considering factors such as grid topology, converter structures, and mission profiles. Subsequently, the system risk will be assessed, taking into account various sources of uncertainty such as component outages and mission profiles, which may lead to stability issues. The system risk will then be evaluated using appropriate indices to determine acceptability. A redesign will be implemented if the system risk is found to be unacceptable. At this stage, a suitable strategy will be chosen in accordance with the identified instability cause. For example, strength converter components will be designed to mitigate stability issues under system uncertainties if risk results from converter aging.

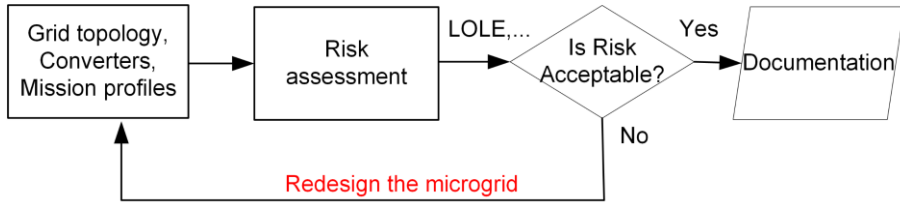


Figure 1-11: Workflow of the first phase 2 – Design for Reliability and Stability

1.2.2. Thesis Limitations

Within the scope of this PhD project, assumptions and simplifications are necessary for the development and implementation of the proposed multi-domain design guideline for microgrids. Some of these are summarized as follows:

- In the component-level reliability assessment and lifetime modeling, only the IGBTs have been considered, given their status as the most fragile component in converters. Redesigns of converters have been conducted with a focus on different IGBT models. Therefore, the impact of other components such as capacitors, PCBs, connectors, and sensors has not been investigated extensively, as precise component-level reliability modeling is not the primary focus of this PhD project.
- Understanding the different time scales at which stability challenges appear (from microseconds to several minutes) is crucial when addressing them. However, due to limitations in computational resources and feasibility constraints, this PhD project has focused on stability challenges occurring at longer time scales, specifically in the minutes to hour range. This decision is practical, as utilizing smaller time scales for risk assessment, while potentially more accurate, can be computationally intensive and sometimes infeasible. Consequently, the risk assessment model employed in this project, based on Monte Carlo simulations, has been assumed to accommodate stability issues occurring within these longer time frames. This

methodology guarantees an accurate and effective evaluation of system risk, in balance with the objectives and limitations of the project.

- As this PhD project aims to establish a new framework, certain simplifications are necessary, including limiting the microgrid size to the kilowatt scale and restricting the number of generating sources. The complexity of managing power and energy in the microgrid, particularly in terms of dynamic performance and stability constraints might necessitate sophisticated strategies. However, as the primary focus is not on introducing new power and energy management techniques, the project imposes constraints on the number of generating units and the overall microgrid topology.
- A few of the assumptions are related to the modeling of component behavior, system dynamics, and operating conditions in microgrid environments. It is acknowledged that although these models are useful for analysis and forecasting, they might not fully capture the complex variability and complexity which is presented in real microgrid systems. Consequently, differences between simulation results and real-world observed phenomena may naturally occur.
- In addition, the research may have missed additional factors that could have an impact on microgrid performance because it concentrates on a particular set of stability and reliability issues. As a result, even though the suggested framework tries to cover significant aspects of microgrid design and operation, the assumptions and simplifications in the modeling approach may limit its applicability.

1.3. Thesis Outline

Based on the analyses carried out and the papers published throughout the study, the results of this PhD thesis are outlined in Figure 1-12 and illustrates the structure of the thesis, highlighting the relationship of each chapter to the publications. The thesis consists of seven chapters, where the necessity of integrating risk assessment into microgrid design and operation has been highlighted in Chapter 1, along with research gaps and the imperative need to align dynamic failures resulting from stability issues with conventional reliability assessment models. This chapter also outlined the research questions, addressed identified shortcomings, and clarified the main objectives.

The planning and design of power electronic-based power systems are covered in detail in Chapter 2, with a focus on microgrids and considerations for both short- and long-term planning. In the domain of design, there is a focus on Design for Reliability (DfR), including a range of model-based system engineering methodologies. These methods, which are critical to ensure stability and reliability of microgrid designs, include device-level reliability assessment, converter-level reliability assessment, and system-level reliability assessment. Chapter 3 explores the power system dynamic failures, with a particular focus on stability issues encountered in microgrids. The chapter explores the classification of stability challenges in microgrids, assessing their

impact on Hybrid Microgrid (HMG) risk. It conducts a detailed examination of interlinking converter (IC) DC-link voltage stability, transient angle stability (TAS), and frequency stability, utilizing mathematical modeling and time domain simulations. Chapter 4 introduces a multi-domain design framework appropriate for HMGs, seamlessly integrating reliability and stability considerations. This chapter begins with an exploration of conventional risk assessment methodologies, including device-level and system-level approaches. Then, the proposed stability-oriented risk assessment methodology is presented, offering a comprehensive perspective on risk evaluation and design in HMGs. In Chapter 5, the integration of dynamic stability in the risk analysis for HMGs is examined through a comparative analysis of case studies. Chapter 6 suggests potential solutions for HMG redesign to enhance the overall performance. Finally, Chapter 7 represents the conclusion of the thesis, summarizing the key findings and contributions made throughout the research.

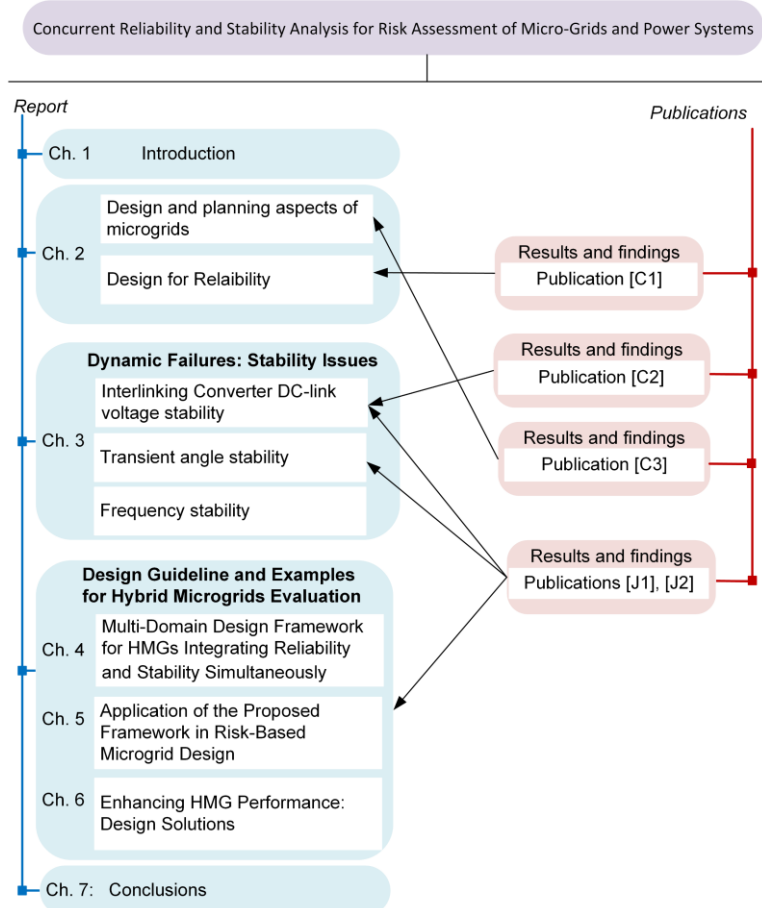


Figure 1-12: PhD thesis outline and related publications for each part.

1.4. List of Publications

The list of papers linked to this thesis demonstrates the sharing of research results and contributions to the technical community. These publications, which include conferences and journals, all indicate significant developments in our knowledge of microgrid stability, reliability, and design. The full list of published papers is given here:

Journal Papers:

- [J1] **A. Azizi**, F. Blaabjerg, and S. Peyghami. "A new risk assessment approach for design of hybrid microgrids considering stability issues." IET Generation, Transmission & Distribution 18.2 (2024): 314-325, doi:10.1049/gtd2.13040.

- [J2] **A. Azizi**, S. Peyghami, and F. Blaabjerg. " A New Multi-Domain Design Method for Hybrid Microgrids Integrating Reliability and Stability Simultaneously." Submitted in Renewable and Sustainable Energy Review (2024) (Revision).

Conference Papers:

- [C1] **A. Azizi** , S. Peyghami, S. F. Zarei, and F. Blaabjerg, "The Impact of Sun Tracking on the Reliability of Solar Inverters," in 2022 International Power Electronics Conference (IPEC-Himeji 2022-ECCE Asia), 2022, pp. 1553–1559, , doi: 10.23919/IPEC-Himeji2022-ECCE53331.2022.9807153.

- [C2] **A. Azizi**, S. Peyghami, H. Wang and F. Blaabjerg, "Risk Evaluation of Hybrid Microgrids Considering DC-Link Voltage Stability," 2022 IEEE 13th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Kiel, Germany, 2022, pp. 1-6, doi: 10.1109/PEDG54999.2022.9923273.

- [C3] **A. Azizi**, S. Peyghami and F. Blaabjerg, "A Perspective on Power Converters Design: Stability and Reliability Aspects," 2023 11th International Conference on Power Electronics and ECCE Asia (ICPE 2023 - ECCE Asia), Jeju Island, Korea, Republic of, 2023, pp. 180-185, doi: 10.23919/ICPE2023-ECCEAsia54778.2023.10213671.

Chapter 2. Planning and Design of Power Electronic-Based Power Systems

2.1. Introduction

As renewable energy sources are implemented more quickly and power electronic technologies advance, microgrids are becoming more and more integrated into power systems, which emphasizes how important it is to design microgrids properly. Design of microgrids is mainly focused on their various structures, optimization methods, and control strategies. Microgrid design, however, involves also other aspects, such as stability, reliability, protection, and power quality, therefore thorough planning and studies are required. This chapter will explore the standards and framework that determine the microgrid design, with a particular emphasis on the planning aspects. Since the goal of this PhD project is to propose a risk-based design guideline for microgrids, it is necessary to examine conventional design frameworks and standards. Understanding these basic principles is essential for developing a microgrid architecture that is more reliable and stable. In addition, the durability and operational efficiency of microgrid components are critical to ensure the system's continues functionality. This idea is contained in the Design for Reliability (DfR) framework, which includes reliability assessment approaches that range from system-level evaluation to component-level analysis. The longevity and stability of microgrids will be guaranteed by closely analyzing the power electronics, from individual components to the overall system.

2.2. Microgrid Design Framework and Related Standards

Specific technical criteria need to be satisfied to ensure optimal design of microgrids. To attain this goal, research and development (R&D) efforts are undertaken, and the effectiveness of the design process is confirmed through implementation in practical scenarios. One comprehensive design framework applicable across various contexts is depicted in Figure 2-1 [79]. This design procedure involves three main steps in the R&D phase: defining microgrid characteristics, conducting system studies, and developing case studies. Selecting the proper microgrid benchmark and modeling the component, control, and communication elements are part of the microgrid characteristics and modeling process. In this phase, the system is ready to undergo testing for the proposed design features [80]. The selection of the benchmark test system is based on its features and the suitability for evaluating the suggested design, taking into account variables such as integration of renewable energy and also reliability data. The microgrid element models are then defined, accounting for variables like model complexity, timescale, and required variables.

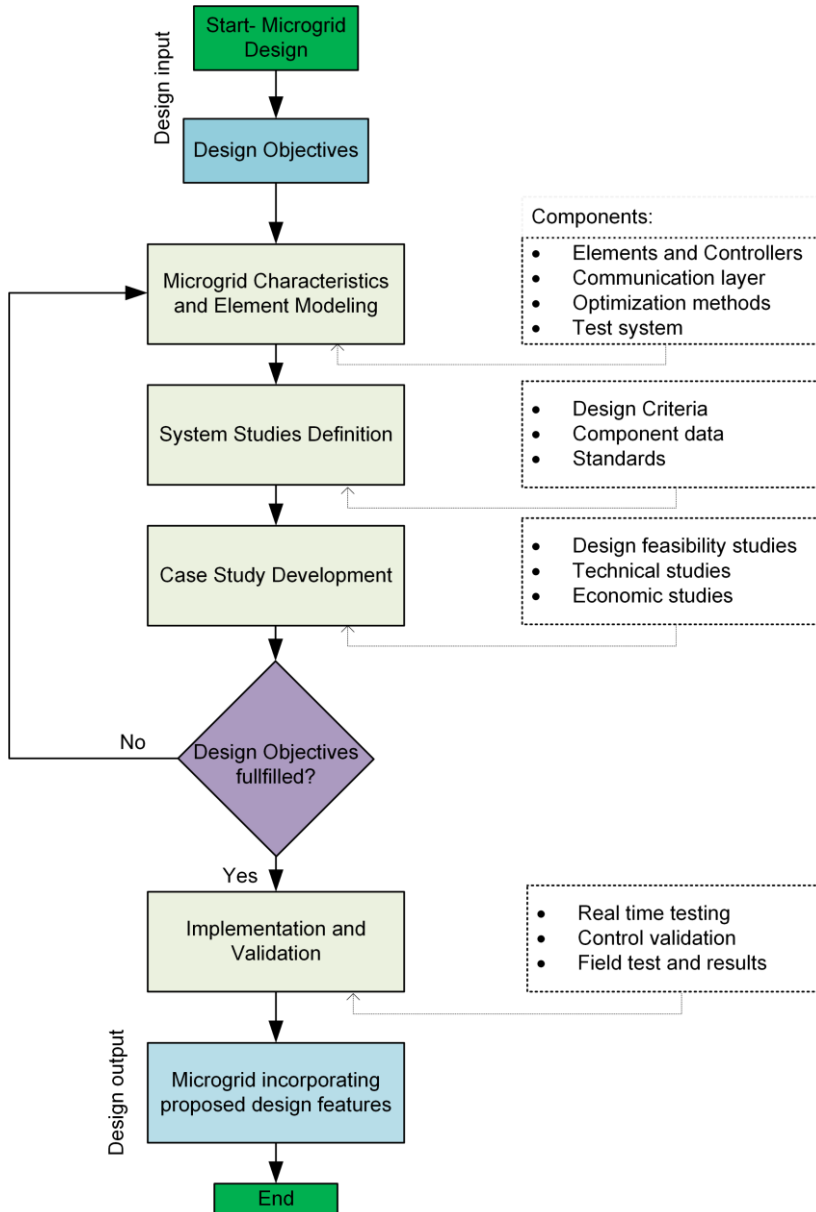


Figure 2-1. Design and planning process of MicroGrids [79].

By defining the design criteria and gathering the necessary information required for the study's execution, the system studies definition is achieved. It also involves looking into various standards that are relevant to microgrid design and adding them to the definition of the study. The design criteria can generally be categorized into three main aspects: Reliability, Economics, and Environmental considerations. Each

category encompasses specific design objectives. For instance, under the reliability aspect, the design objectives include:

- Enhanced reliability of power supply to rural regions [81]
- Improved resilience of systems serving critical loads [52]
- Enhanced distribution network reliability [82]

On the other hand, case study development, entails developing and implementing case studies to investigate various microgrid aspects and determine whether the recommended design features meet the design criteria. These case studies can be divided into four groups: technical, economic, standard and regulation applicability, and design feasibility.

According to Figure 2-1, control of microgrids during the design phase is a crucial aspect of microgrid characteristics. The primary control issues in the design of microgrids are outlined in [32] and also presented in Table 2-1.

Table 2-1. Main challenges in the control of microgrids during the design and planning phase [32]

Challenge	Description
Integration of diverse energy sources	Microgrids often incorporate various renewable and non-renewable energy sources, requiring complex control strategies for optimal integration.
Dynamic load variations	Microgrids experience dynamic changes in load demand, requiring adaptive control algorithms to maintain system stability and reliability.
Islanding detection and synchronization	Effective detection and synchronization mechanisms for islanding are necessary to guarantee a smooth transition between connected and isolated modes.
Voltage and frequency regulation	Microgrids must maintain stable voltage and frequency levels, necessitating precise control mechanisms to respond to fluctuations in generation and demand.
Energy management and storage integration	Effective energy management and integration of energy storage systems pose challenges in optimizing energy dispatch and storage utilization.
Cybersecurity and communication infrastructure	Robust cybersecurity measures and reliable communication infrastructure are crucial for secure and efficient operation of microgrid control systems.

In addition, numerous approaches and optimization strategies frequently employed in microgrid energy management design. The primary contributions, and their limitations are summarized in Table 2-2.

Table 2-2. Main contributions and constraints of different control strategies and optimization techniques in microgrid design [83].

Method/Optimization Technique	Main Contributions	Limitations
Rule-based Control	Simple implementation	Limited adaptability to changing conditions
Centralized Control	Efficient coordination of resources	Vulnerable to single points of failure
Decentralized Control	Enhanced scalability and robustness	Complexity increases with system size
Distributed Control	Improved fault tolerance and reliability	Increased communication overhead
Model Predictive Control	Provides optimal control strategy based on predictive models	Computational complexity may limit real-time implementation
Optimization Algorithms	Finds optimal solutions based on defined objective functions	May struggle with large-scale, nonlinear systems

The standards related to microgrid design include IEEE Std 2030.9-2019, IEEE Std 1547.3-2007, IEEE Std 2030.3-2016, IEEE Std 2030.5-2013, IEEE Std 2030.6-2016, IEEE Std 2030.7-2017, Technical Brochure 311, and technical Brochure 450. These standards provide guidelines and specifications for monitoring, information exchange, control of distributed resources, electric energy storage equipment, smart energy profile application protocol, microgrid controllers, operating dispersed generation with ICT, and grid integration of wind generation, respectively. The IEEE Std 2030.9-2019 provides technical guidelines and specifications for microgrid design, aiming to enhance the previously non-standardized design procedures. It includes six main phases for microgrid design and planning, covering aspects such as electrical design, safety protocols, power quality management, electric energy measurement, system configuration, and evaluation procedures, as depicted in Figure 2-2.

According to this guideline, initially, objectives are set comprising economic, reliability, and environmental factors. Subsequently, system configuration is determined, followed by electrical system design, including safety evaluation. The fourth phase involves automating systems, addressing protection, communication, control, and energy management. Finally, different microgrid schemes are investigated based on technical and economic criteria to identify the most suitable design solution. The evaluation process includes thorough assessment from both technical and economic standpoints. Technical evaluation focuses on aspects such as power supply reliability, grid loss, and power quality. Meanwhile, economic evaluation considers factors like life-cycle cost, payback time, and net present value. Environmental factors are also taken into consideration, such as the amount of renewable energy generated, the amount of fossil fuels used, the reduction of energy

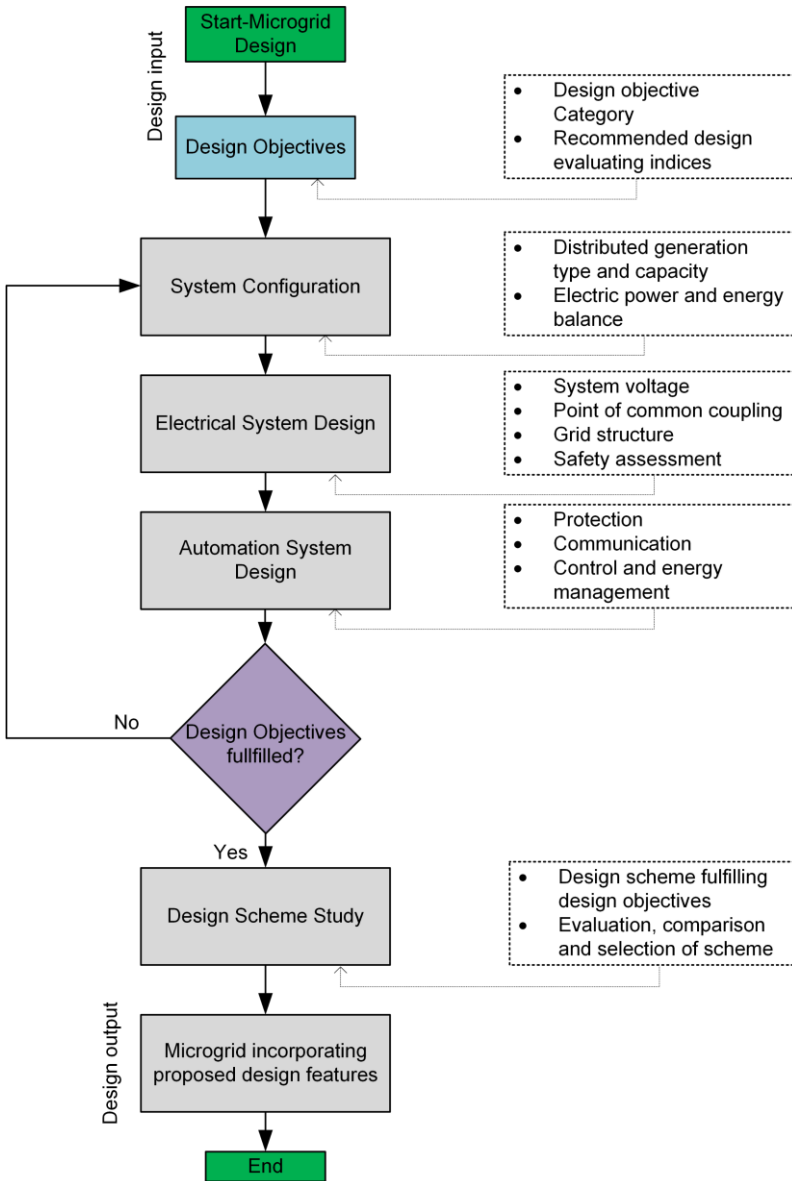


Figure 2-2. Design and planning process of MicroGrids as outlined in IEEE 2030 [84].

emissions, and the emissions of gaseous pollutants. Ultimately, the design solution with the highest overall score across these criteria is selected as the optimal choice. Considering the three main stages in the design and planning of microgrids in Figure 2-1 an applicable standard for each stage can be categorized as shown in Figure 2-3.

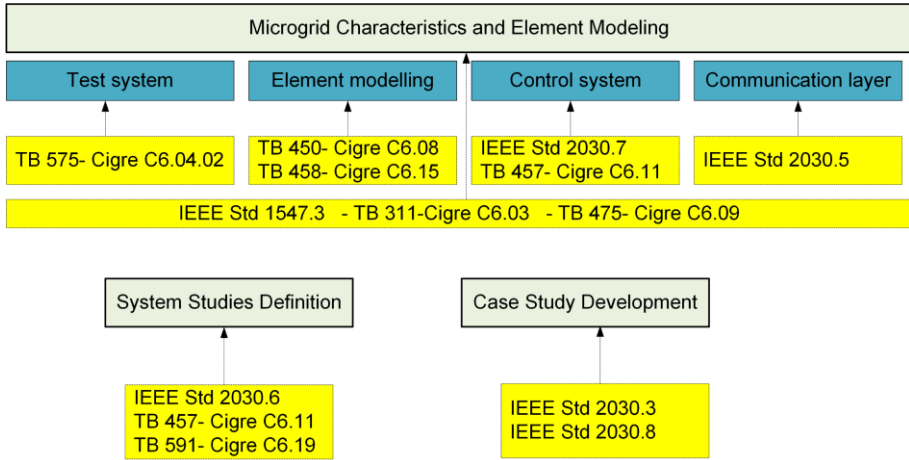


Figure 2-3. Application of IEEE Standards (Std) and Cigre Technical Brochures (TB) across three stages of microgrid design procedure.

Standards related to microgrid design are primarily concerned with defining standards and guidelines for different aspects of microgrid planning and design. These standards act as benchmarks, providing guidelines for managing distributed resources, exchanging information, validating tests, ICT, power, communication, and system design. Their goal is to guarantee that designs for microgrids meet certain requirements concerning operational efficiency, safety, and reliability. The main scope of each standard is summarized in Table 2-3.

Table 2-3. Key Focus Areas of IEEE Standards and Cigre Technical Brochures in MicroGrid design and planning.

Std/ TB	Scope
IEEE Std 1547.3 [85]	Give specific technical specifications for distributed energy resources' smooth integration and interoperability with electric power systems.
IEEE Std 2030.3 [86]	Assessment, design, and integration of energy storage systems (ESS) within microgrids, focusing on optimizing system performance, reliability, and efficiency while ensuring compatibility with existing standards and regulations.
IEEE Std 2030.5 [87]	Planning, design, and operation of microgrid systems, emphasizing the integration of distributed energy resources (DERs), renewable energy sources, energy storage, and advanced control systems to enhance grid resilience, reliability, and sustainability.
IEEE Std 2030.6 [88]	Specifying the architecture, functions, and interfaces of microgrid control systems to ensure effective integration and coordination of distributed energy resources (DERs),

	energy storage systems, and other grid assets within the microgrid environment.
IEEE Std 2030.7 [89]	Specifying microgrid controller requirements, focusing on communication protocols and operational modes for seamless integration and efficient microgrid operation.
IEEE Std 2030.8 [90]	Outlines guidelines for the cybersecurity of microgrids, emphasizing measures to safeguard against cyber threats and ensure the secure operation of microgrid systems.
Cigre TB 311 [91]	Assessment and management of power system reliability, including methodologies for analyzing and improving system reliability, as well as strategies for mitigating risks and enhancing resilience.
Cigre TB 450 [92]	Integration of renewable energy sources into power systems, including technical considerations, grid integration challenges, and solutions to facilitate an effective and reliable integration of renewable energy.
Cigre TB 457 [93]	Planning, design, and operation of microgrids, focusing on technical aspects such as protection, control, and communication systems.
Cigre TB 458 [94]	Design, operation, and control of hybrid AC/DC microgrids, including technical considerations, system configurations, control strategies, and interoperability aspects to ensure the efficient and reliable operation of such systems.
Cigre TB 475 [95]	Planning, design, and operation of multi-energy systems, including integration of various energy sources such as electricity, heat, and gas, to optimize system efficiency, reliability, and sustainability while considering technical, economic, and environmental aspects.
Cigre TB 575 [96]	Design, operation, and control of hybrid AC/DC microgrids, aiming to ensure system stability, reliability, and efficiency while integrating diverse energy resources and accommodating various loads.
Cigre TB 591 [97]	Hybrid renewable energy system (HRES) planning, design, and operation with an emphasis on combining various renewable energy sources and energy storage technologies to maximize system efficiency, dependability, and financial sustainability.

2.3. Planning Aspects of Microgrids

In traditional power systems, planning typically involves analysis from both perspectives on short-term operations and long-term development [80]. The same principles and methodologies used for planning in traditional power systems can

generally be applied to microgrids, although with some adaptations and considerations specific to microgrid characteristics.

To guarantee reliable, economical, and efficient functioning, careful planning is necessary for both conventional power systems and microgrids. However, because of their decentralized design, ability to integrate renewable energy sources, and variety of load profiles, microgrids offer special opportunities as well as challenges. In planning for microgrids, factors such as distributed energy resources (DERs), energy storage systems (ESS), grid interconnection options, control strategies, and cybersecurity must be taken into account. Additionally, considerations for islanding operation, resilience, and local energy management play significant roles in microgrid planning. While the fundamental principles of power system planning apply to microgrids, specialized approaches customized to their specific characteristics are necessary for successful implementation and operation.

2.3.1. Long-Term Planning

The primary objective of long-term planning in microgrids is to optimize and economically develop microgrid systems, typically analyzed over a span of years. During this timeframe, load changes are forecasted, and the optimal timing for integrating new generating units to meet the demand is identified [98]. Furthermore, long-term planning includes determining the optimal sizing and type of generating units, as well as system reconfiguration, to ensure efficient operation and reliability over an extended period. Reliability is a critical factor in long-term planning because it guarantees the continuous operation of microgrids for long periods of time. Evaluating the effect of wear-out failures on power electronics components—which are essential to the functioning of microgrids—is one crucial component. If these issues are not sufficiently resolved, the system may eventually malfunction and perform improperly. Thus, it becomes essential to incorporate strategies to mitigate wear-out effects, such as putting in place accurate maintenance schedules, using robust component designs, and adding redundancy where needed.

Microgrid operators can improve system resilience, reduce downtime, and maximize operational efficiency by proactively addressing wear-out failures and other reliability concerns during the long-term planning phase. This will ensure a reliable and sustainable power supply in the case of changing demands and challenges. Some key long-term planning targets for microgrids are summarized in the Table 2-4.

Table 2-4. Some key long-term planning targets for MicroGrids.

Targets	Description
System expansion	Plan for the addition of new generating units and infrastructure to accommodate growing load requirements.
Load forecasting	Predict changes in load patterns over extended periods to anticipate future demand trends.

Component sizing	Determine the optimal size and type of generating units and system components to meet forecasted loads while maximizing efficiency.
Reliability enhancement	Implement measures to enhance system reliability and resilience, including addressing wear-out failures and mitigating potential risks.
Cost optimization	Minimize lifecycle costs by optimizing investment decisions and operational strategies to achieve long-term economic viability.
Environmental sustainability	Incorporate renewable energy sources and implement eco-friendly practices to promote sustainability and reduce environmental impact.
Maintenance scheduling	Develop schedules for regular maintenance activities to ensure the ongoing reliability and performance of microgrid components over time.

2.3.2. Short-Term Planning

Short-term planning, aims to optimize the economic utilization of existing system resources to meet load demand efficiently [80]. Short-term planning in microgrids comprises various essential activities, including microgrid adequacy studies [99], unit commitment [53], maintenance scheduling [100], and scheduling under uncertainty [101]. These tasks are crucial for ensuring the effective and reliable operation of the microgrid, optimizing resource allocation, and managing uncertainties in the system. By conducting adequacy studies, microgrid operators can assess the sufficiency of available resources to meet demand requirements.

Unit and generation commitment involve determining which generation units to operate based on factors like cost, availability, and reliability. Reliable and maintenance scheduling ensures that necessary maintenance activities are carried out without compromising system reliability, while scheduling under uncertainty involves developing strategies to address unpredictability in factors such as renewable energy generation and demand fluctuations. Overall, short-term planning plays a vital role in optimizing microgrid performance and resilience in dynamic operating conditions.

In addition, stability is crucial in short-term microgrid planning to guarantee the safe and reliable operation of the system. In order to keep voltage and frequency within allowable bounds after disturbances, a microgrid must be able to maintain equilibrium. There are serious risks to the integrity of the microgrid and the connected loads from instability, which may cause voltage sags, frequency variations, and even system-wide blackouts.

Thus, evaluating and improving stability via techniques like voltage stability analysis, transient stability analysis, and contingency analysis are part of short-term planning activities. By identifying crucial situations that could result in instability, contingency analysis assesses how well the system reacts to possible disruptions. Some key long-term planning targets for microgrids are summarized in the Table 2-5.

Table 2-5. Some key short-term planning targets for microgrids

Targets	Description
Microgrid adequacy study	Assessing the capability of the microgrid to meet current and forecasted demand, ensuring that sufficient resources are available to supply electricity reliably.
Unit Commitment	Determining the optimal operation schedule for generating units, including starting, stopping, and ramping up or down, to meet demand while minimizing operating costs and maximizing efficiency.
Reliable and maintenance scheduling	Planning and scheduling maintenance activities for equipment and infrastructure to maintain reliability and prevent unplanned outages, ensuring the continuous operation of the microgrid.
Scheduling under uncertainty	Creating reliable scheduling techniques that take demand, fuel prices, renewable energy generation, and other uncertainties into consideration to maintain system reliability and minimize costs despite variability and unpredictability.

This section has provided an exploration of the design framework and planning aspects crucial for the development of robust microgrids. The multi-stage process has been outlined covering both long-term and short-term planning considerations. However, it is imperative to underscore the necessity of addressing inherent risks, uncertainties, and constraints during the design phase. Failure to account for these factors can trigger reliability and stability issues, impacting both long-term operation and short-term responsiveness. Microgrids can be designed to withstand dynamic operating conditions by taking stability and reliability issues into account early on in the design process. This reduces the probability of load loss frequency and duration. With this proactive approach, microgrids are guaranteed to meet future challenges with resilience and to meet current demands as well, which will ultimately contribute to the development of a more reliable and sustainable energy infrastructure.

2.4. Design for Reliability (DfR) of Microgrids

Design for Reliability (DfR) is a methodology that focuses on incorporating reliability considerations into the design phase of a system or product to ensure its long-term performance and durability [102]. It involves predicting the lifetime and failure modes of components, stress analysis, and reliability mapping to enhance the overall reliability of the system. By addressing reliability early in the design process, DfR aims to reduce costs, shorten development cycles, and improve the overall reliability of the system. In this context, it is crucial to explore fundamental principles and methodologies for designing for reliability in power electronic based power systems. This includes understanding the failure mechanisms, thorough component selection, effective thermal management strategies, environmental consideration, and validation [103].

Understanding potential failure mechanisms that systems and components may experience is the basis of designing for reliability. These mechanisms can include

temperature fluctuations and humidity, as well as environmental elements like material degradation, thermal stress, and electrical overstress [104], [105]. Through a thorough analysis of failure modes and their root causes, designers can put specific strategies into place to mitigate these risks. On the other hand, improving system reliability depends extensively on the careful selection of components. Selecting reliable, high-quality components with defined reliability indices may significantly reduce the chance of failures. Furthermore, adding redundancy to crucial parts or subsystems can provide protection against unexpected failures and guarantee continuous functioning even in the case of component failure.

In addition, a common cause of many electronic reliability problems is heat [106]. To effectively eliminate heat and prevent component overheating, effective thermal management techniques are necessary. These techniques include heat sinking, thermal vias, and proper air circulation design. Moreover, extending component lifetime and improving overall system reliability can be achieved by minimizing mechanical stress through careful mechanical design and guaranteeing sufficient margins in electrical stress. Beside this, the reliability of power systems and electronics is seriously compromised by environmental factors. Considering the operating environment and putting protective measures in place appropriately are part of designing for reliability. This could include ruggedized enclosures [107] for challenging environments, conformal coating [108] to protect against moisture and contaminants, and sufficient insulation to withstand temperature swings. Finally, verifying the reliability of designed systems requires rigorous testing and validation. Techniques employed to assess system robustness and identify potential failure points encompass accelerated life testing, environmental stress screening, and fault injection testing. Designers can iteratively improve their designs to meet exact reliability requirements by putting them through simulated real-world conditions.

Designing microgrids becomes challenging with the extensive integration of power electronics if conventional power system methods are employed without adequate emphasis on reliability concerns within microgrids. Frequent failures in power converters must be evaluated and incorporated into long-term planning to minimize unsupplied energy in the system. While this may increase microgrid costs due to the need for additional energy sources, it mitigates unpredictable outages, enhancing overall reliability. Moreover, when choosing the best scheduling strategy, short-term planning should take power electronics reliability into consideration. This will put a significant amount of stress on the power electronics, accelerating the accumulation of damage and reducing component lifetimes over time. Hence, the design for reliability method aims to thoroughly determine which power converter components—such as switches and capacitors—are the most susceptible to prevent early aging before reaching their planned lifetimes. A comprehensive reliability assessment for power electronic-based power systems is illustrated in Figure 2-4, which includes three main hierarchical levels: Device-level, Component-level, and System-level (sub system and power system) [109].

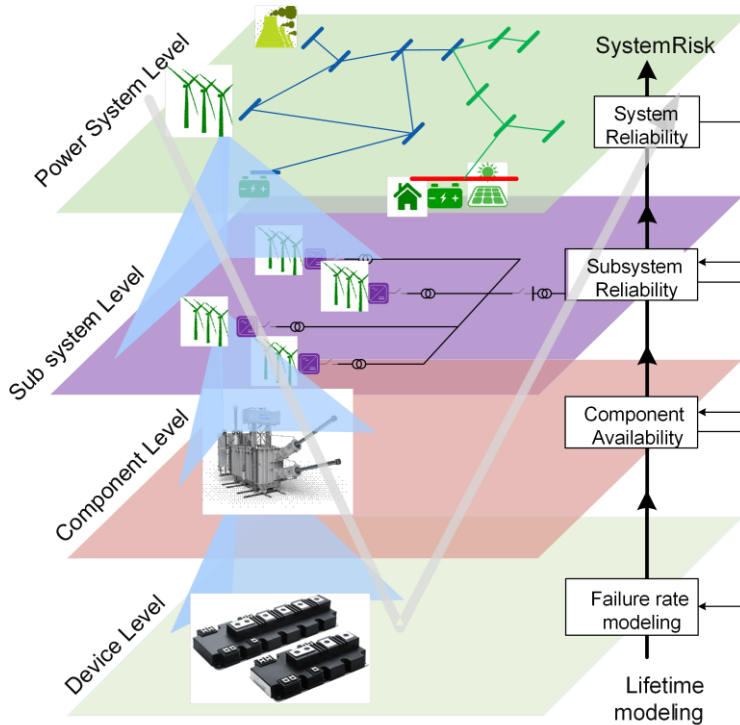


Figure 2-4. Hierarchical level for reliability assessment of power electronic based power systems (e.g., MicroGrids) [109].

The first hierarchical level assesses the failure rates and lifetime of components in power converters, such as capacitors and power semiconductors. This procedure is the same for other components in the system. The second level evaluates the reliability of key components like power converters and power transformers. Finally, at the subsystem and system level, the reliability of the entire power plant and power system is evaluated. In this stage, the availability and probability of failure of each power plant, such as PV or wind farms, are determined, providing overall power system reliability indices at the Point of Interconnection (PoI). Each level will be further elaborated in the following sections.

2.4.1. Device-Level Reliability Assessment

One of the most important steps in guaranteeing the overall reliability of power electronic-based power systems is the device-level reliability assessment. This assessment aims to evaluate the failure rates (λ) of various components such as capacitors and semiconductors. One of the key methods used for this evaluation is stress-strength analysis, which involves assessing the stress levels experienced by the components and comparing them to their strength thresholds. To guarantee they function at the intended strength level, capacitors and semiconductors must be made

to withstand applied stresses over a given lifetime, such as electrical loading and thermal cycling.

Figure 2-5 depicts the standard framework for estimating the failure rate of components through stress-strength analysis. According to this procedure, variations in conditions resulting from uncertainties related to manufacturing, operations, and models cause deviations in both the designed strength and applied stress. Therefore, the difference between the stress and strength levels for every device can be used to determine the possibility of failure.

The process of failure rate estimation begins with the failure identification stage, in which, critical components within the power electronic system are identified, along with their dominant failure mechanisms. This step is essential for focusing subsequent analysis efforts on the most critical aspects of the system. Following the failure identification, the mission profile is translated into thermal loading parameters. This involves determining the thermal stresses experienced by the components under different operating conditions, considering factors such as temperature, voltage, and current flow. An electro-thermal model is often employed to accurately represent the thermal behavior of the components. Once the thermal loading parameters are established, the thermal cycling interpretation stage begins. Here, the thermal loading is decomposed into an equivalent set of simple stress reversals to analyze the cyclic thermal stresses endured by the components. A cycle counting algorithm is then used to quantify the number of stress cycles experienced by each component.

The junction temperatures of power switches have a major impact on their longevity. Variations in high-loading currents may put stress on die-attach solder and wire bonding, possibly resulting in failures. To estimate the lifespan, the number of cycles to failure can be estimated using the Coffin Manson equation [110], which is dependent on temperature variations. The determined temperature ranges are then compared by cross-referencing them with the constant amplitude loading data that is currently available [111]. The Number of thermal cycles to failure can be represented as follows:

$$N_f = A \cdot \Delta T_j^\alpha \cdot \exp\left(\frac{E_a}{k_b \cdot T_{jm}}\right) \quad (2.1)$$

Where N_f represents the number of cycles leading to failure, A is a constant, ΔT_j , T_{jm} denote the swing and mean values of the junction temperature. k_b stands for the Boltzmann constant and E_a is activation energy.

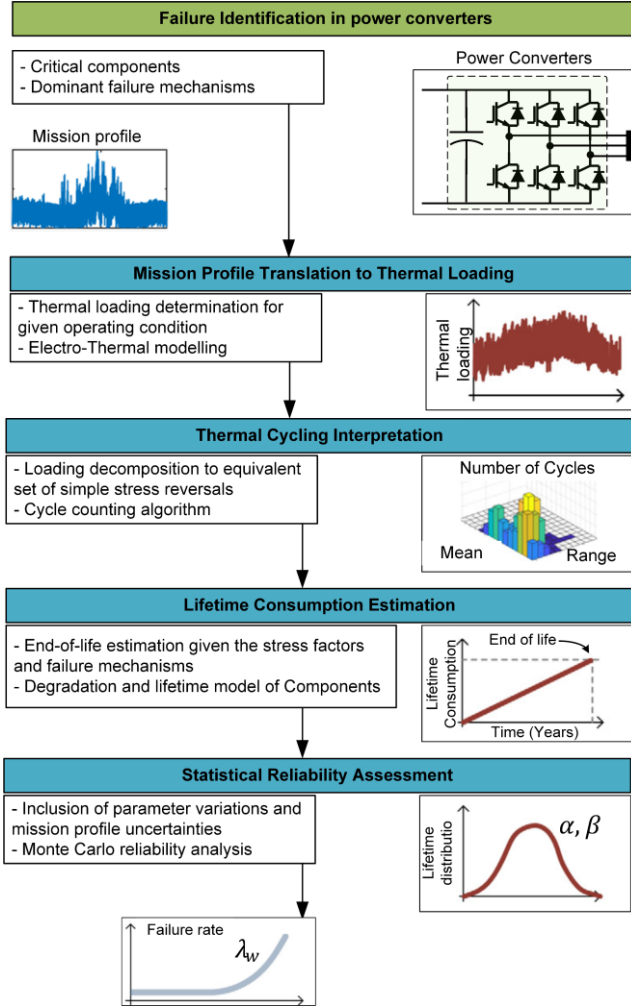


Figure 2-5. Stress-strength analysis for failure rate estimation in design for reliability in power electronic-based power systems to be used in device-level risk assessment [35].

Based on thermal cycling data, the lifetime consumption estimation stage predicts the remaining useful life of the components. This estimation considers the degradation mechanisms and lifetime models specific to each component, allowing designers to assess the expected end-of-life performance. The lifetime model for capacitor banks is related to the time until failure under specific temperature (T_h) and voltage (V) conditions and can be expressed as [111]:

$$L = L_{ref} \cdot 2^{\frac{T_{h,ref} - T_h}{n_1}} \cdot \left(\frac{V}{V_{ref}} \right)^{-n_2} \quad (2.2)$$

where n_1 and n_2 are manufacturer-provided parameters, V_{ref} is the reference voltage, L_{ref} is the capacitor's rated lifetime under the reference hotspot temperature, and $T_{h,ref}$ is the reference hotspot temperature.

Finally, the statistical reliability assessment stage evaluates the reliability of the components using probabilistic methods. Variations in parameters and uncertainties in the mission profile are considered using techniques such as Monte Carlo reliability analysis. This approach relies on the mission profile, enabling the estimation of component wear-out models. Consequently, following the bathtub curve model depicted in Figure 2-6, the failure rate can be categorized into three primary phases: the Burn-In Phase, the Useful Lifetime and the wear-out or Aging phase. The Burn-In phase which experiences the Infant Mortality is usually ignored. During the useful Lifetime, where the failure rate remains constant and the power system studies is performed in this phase, the reliability $R(t)$ can be expressed as:

$$R(t) = e^{-\lambda t} \quad (2.3)$$

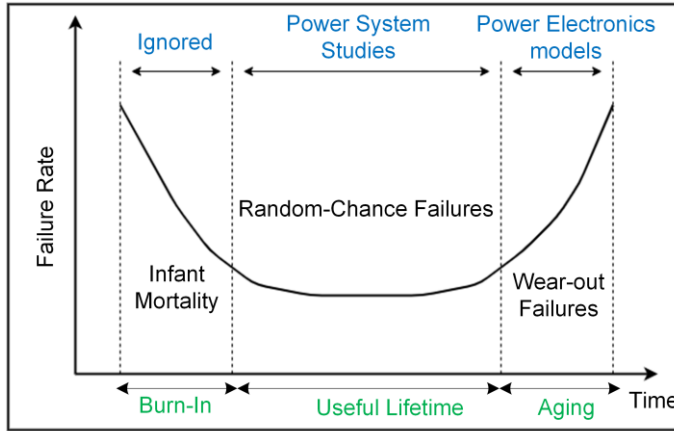


Figure 2-6. The bathtub curve representing the failure rate of an asset over time.

In contrast, during the wear-out phase, the failure rate ceases to be constant and experiences a significant increase attributed to the wear-out of the components. The failure rate can be represented by Weibull distribution function as follows [112]:

$$\lambda(t) = \frac{\beta}{\alpha^\beta} \cdot t^{(\beta-1)} \quad (2.4)$$

Where β and α are scale and shape factors, respectively.

2.4.2. Component-Level Reliability Assessment

In the component-level reliability assessment, the focus shifts from individual device failure rates to the overall reliability of components, such as power converters. This phase builds upon the failure rate estimations from the device-level assessment and integrates historical data to determine the reliability of each component. The primary objective here is to design each component optimally to achieve a desired B_x lifetime, where B_x represents the probability of failure after a certain period (usually in years), ensuring that the probability of failure remains below a specified threshold [13]. For instance, when aiming for a B_{10} lifetime, the goal is to ensure that the probability of component failure within a given timeframe is below 10%, indicating a 90% probability of survival. This reliability target is crucial for ensuring robustness and longevity of the microgrid system, particularly in demanding operational environments. Figure 2-7 provides a visual representation of how the failure probability of a component is determined and how the B_x level is established. This graphical illustration helps in understanding the relationship between component reliability and the probability of failure over time, enabling engineers to make informed decisions regarding component selection and design optimization.

To achieve the desired B_x lifetime, various factors must be considered, including mission profiles, environmental conditions, and stress levels experienced by the components during operation. By carefully analyzing these factors and integrating them into the design process, engineers can optimize component design to withstand operational stresses and extend their operational lifespan.

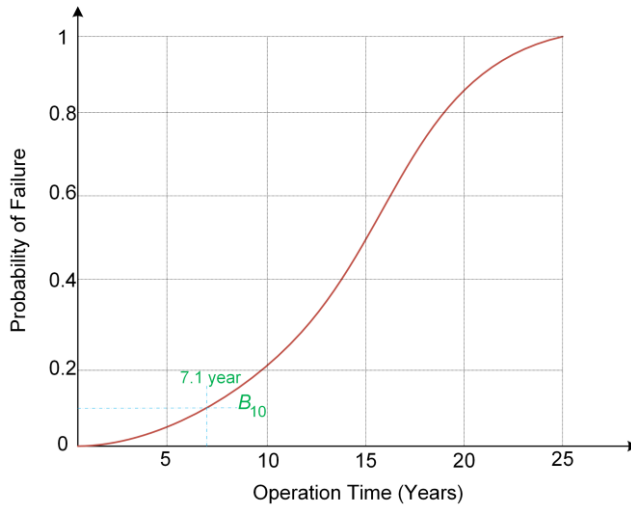


Figure 2-7. Failure Probability of a sample component and B_{10} level.

This criterion helps designers in selecting the most suitable components during the design phase to ensure the desired lifetime for each component. Following this reliability-driven approach, if the B_x lifetime fails to meet the minimum requirements,

the design process will be reiterated with the selection of new devices. For example, in the design of power converters, various capacitors and power switches will be examined to identify the optimal design solution for the converter. Figure 2-8 illustrates the Design for Reliability framework for power converters in microgrids. This framework comprises all three hierarchical levels, starting with the estimation of failure rates, followed by determining the B_x lifetime for each converter, and concluding in estimating the reliability indices at the system level.

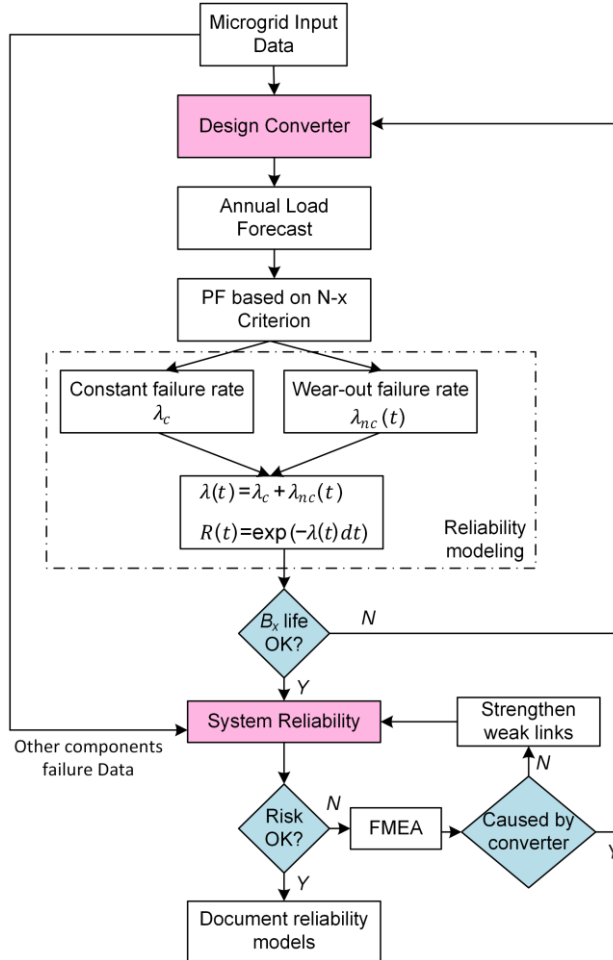


Figure 2-8. Design for reliability framework in MicroGrids, as outlined in [26], [112], [113].

Determining each component's availability within the system is the last step in the component-level analysis process. The computation of availability takes into account both the failure rates during the wear-out phase and the useful lifetime.

Overall, the component-level reliability assessment plays a crucial role in ensuring the long-term performance and durability of microgrid components. By incorporating reliability considerations into the design process, engineers can mitigate the risk of premature failures and enhance the overall reliability of the microgrid system.

2.4.3. System-Level Reliability Assessment

System-level reliability assessment in power systems is a crucial process aimed at ensuring the overall reliability and performance of the entire Micro-Grid system. This assessment involves evaluating the reliability indices of various components and subsystems within the power system to determine its overall robustness. The primary aim of system-level reliability assessment is to determine the reliability and availability of the entire power system under different operating conditions and scenarios. This assessment provides valuable insights into the system's ability to meet demand requirements, withstand disturbances and faults, and also recover efficiently from disruptions.

Before conducting system-level reliability assessment, individual component reliability analyses are performed at the component-level as explained previously. This involves assessing the reliability of key components such as power converters, generating units, transformers, and switchgear. Failure rate data, maintenance records, and historical performance data are analyzed to estimate component reliability indices. The next step involves creating a detailed model of the power system, including its topology, equipment configurations, operational parameters, and interconnections. Advanced simulation tools and techniques may be employed to simulate various operating scenarios and evaluate system performance. For instance, Failure Modes and Effects Analysis (FMEA) is conducted to identify potential failure modes of critical components and assess their potential impact on system reliability as depicted in Figure 2-8. This analysis helps prioritize mitigation strategies and preventive maintenance activities.

Various reliability indices are calculated to quantify the system's reliability and availability. These indices include Time-based Availability (A_t), Production-based Availability (A_p), Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE), Expected Energy Not Supplied (EENS), System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), and Customer Average Interruption Duration Index (CAIDI) [26], [113], [114].

The equations below illustrate the Time-based Availability (A_t) and Production-based Availability (A_p), commonly employed in assessing the reliability of renewable power plants such as PV systems and wind farms [109].

$$A_t = 8760 \left(1 - \frac{\text{Unavailable time}}{\text{Available time} + \text{Unavailable time}} \right) \quad (2.5)$$

$$A_p = \left(1 - \frac{\text{Lost production}}{\text{Actual energy production} + \text{Lost production}} \right) \quad (2.6)$$

Given the multitude of components within the system, in system-level reliability assessment, series and parallel components can be combined using reliability definitions to derive equivalent failure rates and repair rates. For instance, in a series connection of n components, from a reliability standpoint, if any one of the system components fails, the entire system fails. Therefore, the system's reliability R_s is calculated by multiplying the reliability of individual components as follows:

$$R_s = \prod_{i=1}^n R_i = e^{-\lambda_s t} \quad (2.7)$$

Therefore, the equivalent failure rate (λ_s) and repair time (μ_s) for series connection will be calculated as follows [21]:

$$\lambda_s = \sum_{i=1}^n \lambda_i \quad (2.8)$$

$$\mu_s = \sum_{i=1}^n \lambda_i \cdot \frac{\prod_{i=1}^n \mu_i}{\prod_{i=1}^n (\lambda_i + \mu_i) - \prod_{i=1}^n \lambda_i} \quad (2.9)$$

Where λ_i and μ_i are the failure rate and repair time of i^{th} component. The same procedure can be used for the parallel connection. The equivalent failure rate (λ_p) and repair time (μ_p) in parallel connection will be as follows [114]:

$$\mu_p = \sum_{i=1}^n \mu_i \quad (2.10)$$

$$\lambda_p = \sum_{i=1}^n \mu_i \cdot \frac{\prod_{i=1}^n \lambda_i}{\prod_{i=1}^n (\lambda_i + \mu_i) - \prod_{i=1}^n \lambda_i} \quad (2.11)$$

These equations are used in system-level reliability assessment and evaluating the reliability indices. By evaluating key reliability indices and performance indices, system operators and planners can identify potential vulnerabilities, implement targeted mitigation measures, and enhance the overall reliability and performance of the power system.

In conclusion, the concept of design for reliability has been introduced as a fundamental methodology for ensuring the long-term performance and durability of power systems and electronics. This approach emphasizes incorporating reliability considerations into the design phase to mitigate potential failure risks and enhance overall system robustness. The reliability assessment process includes three hierarchical levels: device-level, component-level, and system-level. At the device-level, failure rates of individual elements such as capacitors and semiconductors are estimated using stress-strength analysis and other methods. In the component-level

assessment, the reliability of each component, such as power converters, is determined based on estimated failure rates and historical data, aiming to achieve a desired B_x lifetime. Finally, at the system-level, reliability indices are calculated by aggregating the reliability of individual components, considering their series and parallel connections, to assess the overall reliability of the system.

Chapter 3. Power System Dynamic Failures: Stability Issues

3.1. Introduction

In the first Chapter, it was discussed that addressing the impact of dynamic performance on the overall risk of microgrids is often neglected, highlighting the importance of bridging dynamic performance with static performance. As previously discussed, dynamic performance can limit the normal functionality of equipment or cause transient instability issues due to a variety of stability phenomenon that can occur in both short-term and long-term. Therefore, to develop and propose a comprehensive design guideline, at first, it is necessary to mathematically model these stability issues and illustrate how they affect the microgrid operation. This Chapter introduces these stability challenges through root cause analysis and time domain simulations to identify stability causes. Next, this analysis allows for the definition of criteria and stability margins as dynamic failures. These dynamic criteria will then be incorporated into risk assessment modeling in the next chapter to demonstrate their impact on the overall risk of microgrids. It is possible to develop a more robust and reliable design guideline for microgrids that can be used for both the planning and operating phases by bridging the gap between dynamic and static failures.

3.2. Analysis of Stability Issues: Timeframes and Causes in Microgrids

Understanding the timescales of stability issues is crucial for comprehensively analyzing the dynamics of microgrids. These stability phenomena vary significantly, ranging from milliseconds to minutes including both short-term and long-term perspectives. As part of this PhD project, the objective is to identify and address different stability issues and dynamics within microgrids. It is essential to recognize the varying timescales of these stability challenges and recognize the applicable dynamics in risk assessment, design, and operation of microgrids. For instance, voltage and frequency stability, two fundamental aspects of microgrid operation, show dynamics spanning from milliseconds to minutes. Voltage stability involves maintaining acceptable voltage levels over longer timescales, while frequency stability involves regulating grid frequency within narrow bounds, potentially requiring faster responses to disturbances. Frequency deviations can occur due to sudden changes in generation or load, faults, or inadequate control mechanisms, potentially leading to cascading failures and blackouts if not addressed properly. Some of the most important timescales for the dynamics and controls of the power system have been compiled in Figure 3-1 [115]. As it can be seen, voltage stability issues typically appear over relatively longer timescales, ranging from seconds to minutes, as they involve gradual changes in system conditions and responses. Voltage

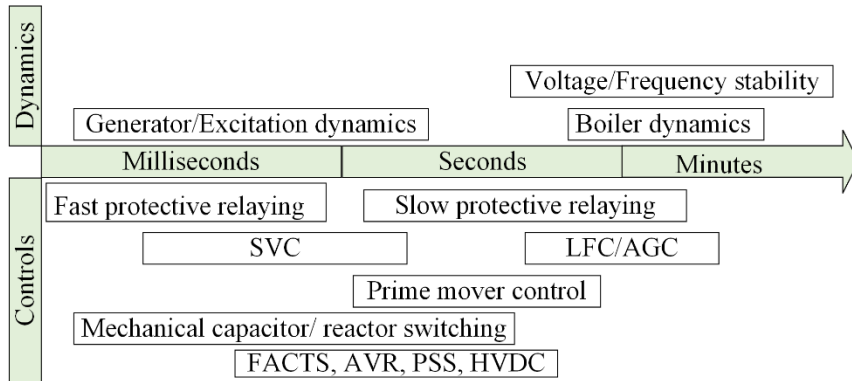


Figure 3-1. Schematic representation illustrating various timescales of power system dynamics and controls [115]

stability may occur due to large load changes and loss of generating units, in which, the voltage magnitude or angle fluctuate significantly and may cause unstable operation in microgrids. Frequency stability issues, while also occurring over similar timescales, may implies faster dynamics in certain cases, such as the rapid frequency deviations following the loss of a large generator or a significant load imbalance.

Smaller time constants are usually found in control loops operating locally in a generator at lower system levels in power system control designs than in control loops operating at higher system levels. For instance, the Power System Stabilizer (PSS), which dampens the generator voltage angle swing, reacts in less than a second on average. Secondary voltage control, on the other hand, works over a period of seconds or minutes to set the reference values of the voltage controlling devices. As a result, a power system with several decoupled control loops running on various timescales. Longer timescale stability problems, especially those involving minutes, will be examined in this PhD project, as their significant impact on loss of loads and instable operation of microgrids.

As outlined in the first chapter, the PES TR66 [12] has outlined stability challenges into control system and power supply and balancing categories. From another perspective, considering timescales and causes, microgrid stability can be classified into three primary categories: small signal, transient, and voltage stability, as per Table 3-1. Small signal stability concerns originated from factors like feedback controllers, minor load changes, system damping, and power limitations of distributed generators (DGs), which may result in limitations in components and sources. Consequently, in this PhD project one area of analysis will explore stability limitations arising from bidirectional converter power transfer in hybrid microgrids, caused by converter characteristics that impact microgrid stability under certain operational conditions. Meanwhile, transient stability issues arise during events like islanding, loss of DG, large load steps, or faults, impacting voltage angle stability. The thesis will specifically investigate transient stability concerns, focusing on the effects of large load steps or loss of DGs on system instability, particularly regarding voltage angle stability. In addition to small signal and transient stability, voltage stability is a

Table 3-1. Stability issues and the most common root causes [116]

Microgrid Stability		
Small signal stability	Transient stability	Voltage stability
• Feedback controller • Small load changes • System damping • Power limit of DGs • Interaction between converters	• Islanding • Loss of Distributed Generators (DGs) • Large load steps • Faults	• Reactive power limit • Load dynamics • Under voltage load shedding • Tap changers and Voltage Regulations

crucial aspect influenced by various factors such as reactive power limits, load dynamics, under voltage load shedding, and tap changers along with voltage regulations. Load dynamics, including sudden changes in demand or the addition of new loads, can disrupt voltage stability by changing the balance between generation and consumption. Under voltage load shedding is a protective measure employed to maintain grid stability by shedding non-critical loads during voltage drops to prevent system collapse.

3.2.1. Analysis Methods for Microgrid Stability

Each of stability issues categorized in Table 3-1, requires specific analysis methods to identify and mitigate potential instability. This section provides a comprehensive explanation of these stability types and the common analysis methods used for them. State-space analysis is a primary method for analyzing small signal stability [117]. It includes eigenvalue analysis, which involves determining the eigenvalues of the system matrix derived from linearizing the system equations around an operating point. The system is stable if all of the eigenvalues have negative real parts. This method is particularly useful for identifying the modes of oscillation and their damping. Participation factor analysis is another technique within state-space analysis, identifying the contribution of each state variable to a particular mode and helping pinpoint critical components or parameters affecting stability [118].

Frequency-domain analysis is another approach for small signal stability [119], [120]. methods based on impedance divide the system in half and use methods like phase or gain margins and the General Nyquist Criterion to derive stability conditions from the impedance ratio of both halves. The complex torque coefficient method is used to analyze interactions between mechanical and electrical systems in terms of torque and angle dynamics. Frequency scan techniques involve scanning the system over a range of frequencies to identify resonance conditions or stability margins.

Additionally, root cause analysis identifies the underlying causes of instability by tracing back through the system dynamics and interactions that lead to small-signal instabilities.

On the other hand, transient stability analysis methods can be broadly classified into four main categories: time-domain simulations [121], transient energy functions [122], curve fitting approaches [123], and machine learning techniques [124].

Time-domain simulations can be classified into two main methods: Direct Integration methods and Predictive methods. Direct Integration methods solve the differential equations that represent the power system dynamics directly over a time span to observe the system's transient response. This is one of the most accurate methods but computationally intensive [125]. Predictive methods use the current state of the system to predict future behavior and assess stability. An example is the recursive approach that adjusts the system's kinetic energy based on ongoing measurements.

Transient Energy Function (TEF) methods are also classified into two main groups: Transient Energy Analysis and Energy Margin Calculation. Transient Energy analysis evaluates the system's transient stability by calculating the system's energy state before and after a disturbance. It involves the use of energy functions to determine whether the system will return to a stable equilibrium point [126]. Energy Margin calculation measures the margin of stability by comparing the post-disturbance energy state to a predefined threshold. If the energy exceeds this threshold, the system is considered unstable [127].

Curve Fitting Approaches use Polynomial Curve Fitting and Ellipse Fitting methods for transient stability analysis [128]. Polynomial Curve Fitting methods fit a polynomial curve to the system's state variables (like rotor angles or speeds) over time and use this curve to predict future states and stability. This can be useful for real-time stability assessment. While Ellipse Fitting is an advanced method where the trajectory of the system's state variables is fitted into an ellipse to predict out-of-step conditions and instability.

Machine learning (ML) techniques are increasingly used for stability analysis in microgrids due to their ability to handle complex, nonlinear systems and large datasets. Supervised learning, unsupervised learning, and reinforcement learning are some of these methods. Supervised learning methods such as neural networks and support vector machines are used for classification and prediction of stability issues. Unsupervised learning techniques, including clustering and dimensionality reduction, help in identifying patterns and anomalies without labeled data. Reinforcement learning is employed for adaptive control and real-time stability management. These ML techniques can enhance the accuracy and efficiency of stability assessments and control strategies in microgrids [129], [130].

Finally, P-V and Q-V curve analysis are common methods used to assess voltage stability by plotting power versus voltage curves [131]. These curves help in understanding how voltage levels change with varying loads or generation and in identifying critical points where voltage instability might occur. Continuation power flow (CPF) is an advanced method that tracks the system's voltage profile as load increases, helping identify the point at which voltage instability occurs and providing valuable information for planning and operational purposes [132]. Time-domain simulation is also used for voltage stability to observe how voltage levels change over time following disturbances, aiding in understanding the dynamic behavior of the voltage and identifying potential stability issues. Table 3-2 provides a concise overview of the analysis methods for each stability type.

Table 3-2. Analysis methods for stability assessment in MicroGrids.

Stability Type	Analysis Methods
Small signal stability	<u>State-space analysis</u> : Eigenvalue analysis, Participation factor analysis.
	<u>Frequency-domain analysis</u> : Frequency scan techniques, complex torque coefficient method, and impedance-based methods.
	<u>Root cause analysis</u>
Transient stability	<u>Time-domain simulations</u> : Direct Integration methods, Predictive methods.
	<u>Transient Energy Function</u> : Transient Energy Analysis, Energy Margin Calculation.
	<u>Curve Fitting Approaches</u> : Polynomial Curve Fitting, Ellipse Fitting.
	<u>Machine Learning Techniques</u> : Supervised learning, Unsupervised learning, Reinforcement learning.
Voltage stability	<u>P-V and Q-V curve analysis</u>
	<u>Continuation power flow (CPF)</u>
	<u>Time-domain simulation</u>

The diverse stability challenges as outlined include small signal, transient, and voltage stability issues, each with distinct origins and impacts on microgrid operations. These dynamics complexly influence the reliability of microgrids, potentially necessitating load curtailment, shedding, or even disconnection of power sources to mitigate instability risks. As microgrids continue to evolve and integrate renewable energy sources, understanding and addressing these stability challenges in risk assessment and design remain vital for ensuring the robustness and resilience of microgrids in the case of dynamic operating conditions.

3.3. Dynamic Risk Induced by Stability Issues

According to the PES TR66 [12] stability classification, different stability problems on different timescales affect the dynamic performance of microgrids, which consequently impacts the overall risk of the system. Each stability problem requires thorough examination to identify its root causes and determine how they influence system functionality. Certain stability issues can be incorporated into risk assessment analyses based on the results of these analyses and their influence on dynamic risk. This PhD thesis concentrates on three of these problems due to restrictions. Initially, inherent characteristics of bidirectional converters during operation will be examined. These characteristics, which come under the PES TR66 Power Supply and Balance Stability classification, may cause instability or inadequate performance of DC-link voltage in microgrids, with effects ranging from milliseconds to minutes. Transient stability is another area of focus for this PhD project. Microgrids may experience transient stability problems as a result of loss of generating units or large load steps,

as identified in Table 3-1. This instability appears as voltage angle fluctuations, which endangered the dynamic performance of the system.

Finally, frequency deviations from standard operating values may result from an imbalance between load and generation in some off-grid microgrids without secondary frequency control. In order to regulate the frequency within acceptable levels in the absence of secondary frequency control, system operators need for load shedding or curtailment. In summary, by requiring additional load shedding or curtailments to maintain stability, these stability constraints add dynamic risk to the system and consequently impact overall microgrid risk. These studies have produced certain stability constraints and margins, which will be used in the microgrid redesign and risk assessment model.

In this PhD study, a hybrid microgrid (HMG) will be selected as the test system for all analyses, as it aligns with the aim of proposing a multi-domain stability-oriented design guideline. The choice of a hybrid microgrid as the test system for this research was driven by several compelling reasons that align with the objectives of this study. Hybrid microgrids, which integrate both ac and dc subgrids, offer a flexible framework for exploring the complex interactions and dynamics present in modern power systems.

Firstly, hybrid microgrids embody the convergence of diverse energy sources, including renewable energy technologies like photovoltaic (PV) systems and wind turbines, as well as conventional generation units such as microturbines and fuel cells. This diversity makes HMGs an ideal testbed for evaluating the impact of integrating various energy sources on system reliability and stability. The presence of both ac and dc subgrids in HMGs allows for the investigation of unique stability issues and dynamic failures specific to each type of subgrid, thereby providing comprehensive insights that would not be possible with a purely ac or dc system.

Secondly, the growing adoption of hybrid microgrids in real-world applications highlights their relevance and importance. As the global energy landscape shifts towards more sustainable and resilient power systems, understanding the behavior and optimization of HMGs becomes increasingly critical. By selecting a hybrid microgrid as the test system, this research addresses practical challenges and contributes valuable knowledge that can be applied to the design and operation of future power systems.

Therefore, for all future case studies, a hybrid microgrid, as shown in Figure 3-2, will be employed. Each subgrid has two sources that supply power to the loads in that subgrid. An interlinking converter (IC) connects the dc and ac subgrids. In this figure, $P_{dc1}, P_{dc2}, P_{ac1}, P_{ac2}$ are active power of dc and ac sources, respectively. P_{ic} is the transferred power through interlinking converter and P_{Ldc}, P_{Lac} are dc and ac loads.

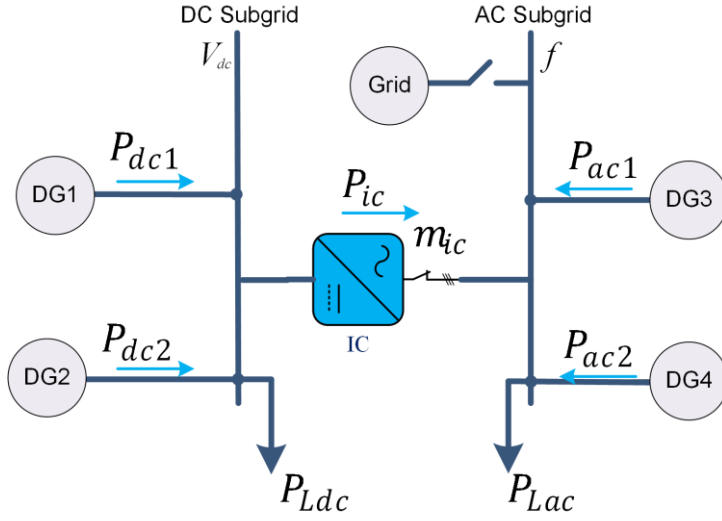


Figure 3-2. Schematic diagram of hybrid microgrid with an interlinking converter (IC) including two sources in each Subgrid, all controlled using droop method.

3.3.1. Interlinking Converter (IC) DC-link Voltage Stability

The Interlinking Converters (ICs) with capability of transferring power in both rectifying and inversion mode, plays a crucial role on stable and reliable operation of hybrid microgrids. Precise and robust control strategies are required to ensure proper IC operation in order to maintain dc-side voltage stability during transients and steady-state operation. However, some research has shown that current control schemes ignore the influence of the instantaneous power in the AC filter inductor and instead depend on approximating the power balance between the ac and dc subgrids [62], [63], [133]. These studies have revealed that during operation close to nominal capacity in rectifying mode, the IC's dc-link voltage may become unstable. This instability originates from the non-minimum phase behavior of the IC and will be explained in further detail. Figure 3-3 represent schematic diagram of a sample IC used in the hybrid microgrid under study (Figure 3-2) along with its control system which links the ac subgrid to the dc subgrid. Depending on the power status of distributed generators (DGs) and loads, the IC can transfer power in both rectifying and inversion modes; as a result, the IC needs to be stable in both operating modes.

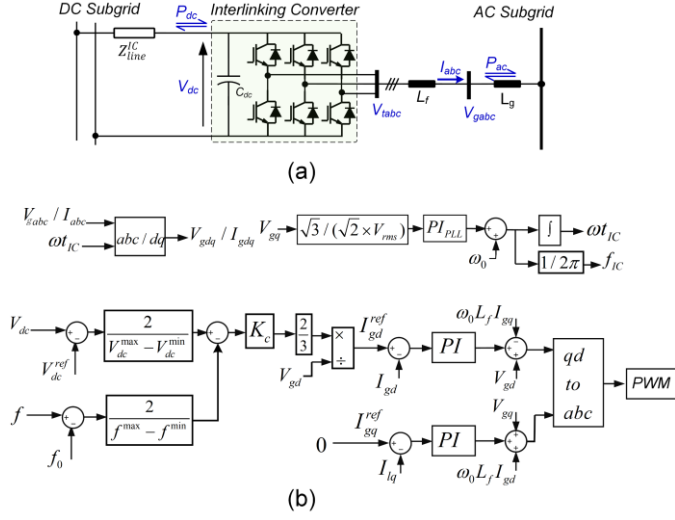


Figure 3-3. A schematic representation of an example interlinking converter along with its control system within hybrid microgrids. (a) Topology, (b) Controllers [J1].

3.3.1.1. Mathematical Modeling

Previous studies have thoroughly studied a precise nonlinear model of the IC [62], [133]. This section outlines the IC's mathematical model, which is intended to help find the least amount of stability margin needed to guarantee steady IC operation. The following is a possible formulation for the IC's power balance equation:

$$\frac{1}{2}C_{dc}\frac{d}{dt}(V_{dc}^2) = P_{dc} - P_{ac} \quad (3.1)$$

The first term denotes the energy stored in the dc-link capacitor (C_{dc}), and V_{dc} is the voltage across the capacitor. As shown in Figure 3-3, P_{dc} and P_{ac} stand for the transferred dc and ac powers, respectively. Because the power balance equation is nonlinear with respect to V_{dc} , the energy stored in the capacitor (W) can be used as a state space variable, as shown below:

$$\frac{dW}{dt} = P_{dc} - P_{ac} \quad (3.2)$$

The power in the ac-side can be expressed as given in

$$P_{ac} = \frac{3}{2}(V_{gd} \cdot I_{gd} + V_{gq} \cdot I_{gq}) \quad (3.3)$$

Where the ac-side currents (I_{abc}) and voltages (V_{gabc}) are represented by dq -frame components I_{gd}, I_{gq} and V_{gd}, V_{gq} , respectively. Since the stored energy (W_L) in the ac-

side filter (L_f) is zero in steady-state operation and has a small magnitude in relation to other variables, it is typically ignored in traditional models. This simplification results from an assumption that the energy stored in the ac-side filter is insignificant when compared to other parts of the system and it can be ignored, especially in steady-state circumstances. Because of this, the expression for ac-side power is usually written without taking the energy stored in the ac-side filter into consideration. However, this assumption may reduce the stability margin and cause stability issues under certain operating conditions. Thus, in order minimize the possibility of this issue, the expression of P_{ac} can be rewritten as follows:

$$P_{ac} = \frac{3}{2} (V_{gd} \cdot I_{gd} + V_{gq} \cdot I_{gq}) + \frac{dW_L}{dt} \quad (3.4)$$

The expression dW_L/dt is the ac filter's instantaneous power, and it can be calculated as [117]:

$$W_L = \frac{3}{4} L_f (I_{gd}^2 + I_{gq}^2) \xrightarrow{der} dW_L/dt = \frac{3}{2} L_f \left(I_{gd} \cdot \frac{dI_{gd}}{dt} + I_{gq} \cdot \frac{dI_{gq}}{dt} \right) \quad (3.5)$$

By substituting (3.4) and (3.5) into (3.2), it results:

$$\frac{dW}{dt} = P_{dc} - \frac{3}{2} V_{gd} I_{gd} - \frac{3}{2} V_{gq} I_{gq} - \frac{3}{2} L_f \left(I_{gd} \frac{dI_{gd}}{dt} + I_{gq} \frac{dI_{gq}}{dt} \right) \quad (3.6)$$

In addition, the control system of the IC is shown in Figure 3-3, which uses a normalized droop approach to control how power is transferred between the dc and ac subgrids. This control system's basic idea, which comes from [134], states that the power transferred by the IC will be zero when the normalized AC and DC powers are in equilibrium. The power flow through the IC is driven by changes in AC/DC loads, which result in differences in normalized voltage and frequency.

The normalization of the dc voltage (V_{pu}) on dc-side and the frequency (f_{pu}) on the ac-side can be obtained using equations (3.7) and (3.8). This normalization process is essential for controlling the dc voltage and ac frequency.

$$V_{pu} = \frac{2}{V_{dc}^{max} - V_{dc}^{min}} (V_{dc} - V_{dc}^{ref}) \quad (3.7)$$

$$f_{pu} = \frac{2}{f^{max} - f^{min}} (f - f_0) \quad (3.8)$$

Where $V_{dc}^{min}/V_{dc}^{max}$ and f^{min}/f^{max} , respectively, stand for the minimum and maximum values of dc voltage and frequency, while V_{dc}^{ref}/V_{dc} and f_0/f stand for the reference/operating values.

The IC's reference current (I_{gd}^{ref}) can be obtained in the following ways:

$$I_{gd}^{ref} = \frac{2}{3V_{gd}} K_c \cdot (V_{pu} - f_{pu}) \quad (3.9)$$

The droop gain, K_c , represents the portion of transferred power through the IC. It should be noted that equation (3.9) presents a general expression. In cases where the hybrid microgrid is equipped with a single interlinking converter, the proportional-integral (PI) controller becomes necessary instead of utilizing the proportional gain K_c . However, in scenarios involving multiple ICs, stability can be ensured by only employing the proportional gain K_c without the need for the PI controller [134].

The reactive power on the ac-side can also be calculated by:

$$Q_{ac} = \frac{3}{2} (V_{gd} \cdot I_{gq} - V_{gq} \cdot I_{gd}) \quad (3.10)$$

By setting V_{gq} to zero, in accordance with equations (3.6) and (3.10), the control of the DC-link voltage and reactive power becomes feasible through I_{gd} and I_{gq} , respectively. Consequently, this enables the determination of the control inputs V_{td} and V_{tq} which are derived as given below:

$$V_{td} = V_{gd} - \omega_0 L_f I_{gd} + \left(k_p + k_i \int dt \right) \cdot (I_{gd}^{ref} - I_{gd}) \quad (3.11)$$

$$V_{tq} = V_{gq} + \omega_0 L_f I_{gq} + \left(k_p + k_i \int dt \right) \cdot (I_{gq}^{ref} - I_{gq}) \quad (3.12)$$

Where, ω_0 and L_f are the reference frequency and ac filter inductance, k_p and k_i are the proportional and integral gains, and V_{gd} / V_{gq} are the dq-frame components of V_{gabc} voltage.

The frequency (ω_{IC}) of the ac voltage is obtained through a phase-locked loop (PLL), leading to the derivation of the state equation of the PLL as follows:

$$\frac{d\omega_{IC}}{dt} = \omega_0 + k_{p,PLL} \cdot V_{gq}^{pu} + k_{i,PLL} \cdot \int V_{gq}^{pu} dt \quad (3.13)$$

For a more thorough understanding of the behavior of the system, including the instantaneous power of the inductance, equation (3.6) can be linearized as follows at the operating point (I_{gd}^0, I_{gq}^0):

$$\frac{dW}{dt} = P_{dc} - \frac{3}{2} V_{gd} I_{gd} - \frac{3}{2} L_f \left(I_{gd}^0 \frac{dI_{gd}}{dt} + I_{gq}^0 \frac{dI_{gq}}{dt} \right) \quad (3.14)$$

In the aforementioned equation, it is assumed that V_{gq} is zero due to the operation of PLL. Using equations (3.1) and (3.4) and taking into account the zero value for ac-

filter power in steady state operation, P_{dc} can be used in place of I_{gd}^0 . The formula for I_{gd}^0 is thus:

$$I_{gd}^0 = P_{dc}/1.5V_{gd} \quad (3.15)$$

Using the Laplace transform in (3.14) and replacing I_{gd}^0 results in (3.16), where Laplace operator is represented by "s".

$$W(s) = \frac{P_{dc}(s)}{s} - \frac{(\frac{3}{2}V_{gd} + \frac{L_f P_{dc}}{V_{gd}}s)}{s} I_{gd}(s) - \frac{3}{2}L_f I_{gq}^0 s I_{gq}(s) \quad (3.16)$$

Equation (3.16) illustrates that considering the dynamics of the AC-side filter leads to a "zero" in the transfer function of $W(s)/I_{gd}(s)$, demonstrating a notable impact on system behavior. This zero indicates a critical point in the response characteristics, highlighting the importance of incorporating ac-side filter dynamics for a comprehensive understanding of the system dynamics and stability. The "zero" is depicted as:

$$Z = -1.5V_{gd}^2/L_f P_{dc} \quad (3.17)$$

Changes in P_{dc} in relation to the mode of operation and P_{dc} magnitude affect the "zero"s position. The "zero" appears on the left side during inversion mode, which is marked by positive P_{dc} and guarantees the system stability. Conversely, a Right Half-Plane Zero (RHPZ) happens in rectifying mode with negative P_{dc} . As P_{dc} gets closer to the IC's rated capacity, the system dynamics in this case become nonminimum phase, which could reduce the phase margin. An eigenvalue analysis can be conducted

Table 3-3. Properties and parameters of an interlinking converter and its associated control system.

Symbol	Simulation
$P_{nominal}$	10 kVA
V_{dc}	180 V
V_{ac}	110 V
f_0	50 Hz
$V_{dc}^{min}, V_{dc}^{max}$	175,185 V
K_c	8000
f^{min}, f^{max}	49,51 Hz
L_f	4.5 mH
C_f	190 μ F
K_p, K_I	8,120
$K_{p,pll}, K_{I,pll}$	40,1000

to illustrate the influence of AC-filter dynamics and the consequent "zero" in the transfer function. The parameters of the IC and control system can be found in Table 3-3.

A frequency domain analysis of the IC has been carried out, taking into consideration the impact of the ac filter inductor as specified by the previously mentioned equations. The magnitude and phase variations for a range of P_{dc} values, from 0 to +1 p.u in inversion mode and 0 to -1 p.u in rectifying mode, are shown in Figure 3-4. This figure illustrates when a positive phase is added to the system, it will increase the stability margin for positive P_{dc} . On the other hand, the corresponding zero in equation (3.17) adds negative phase margin to the system during the rectifying mode of operation, which is identified by negative P_{dc} values. The system stays stable for positive P_{dc} values, while in rectifying mode, the stability margin decreases as P_{dc} gets closer to nominal values, which could lead to an unstable dc voltage operation of the IC.

Table 3-4 provides a detailed insight into the variation of phase margin and gain margin for different values of P_{dc} . As indicated in the table, when the IC transferred power from the ac side to the dc side exceeds -0.5 p.u, the system operates under undesirable conditions. The system becomes unstable when P_{dc} reaches to -0.93 p.u.

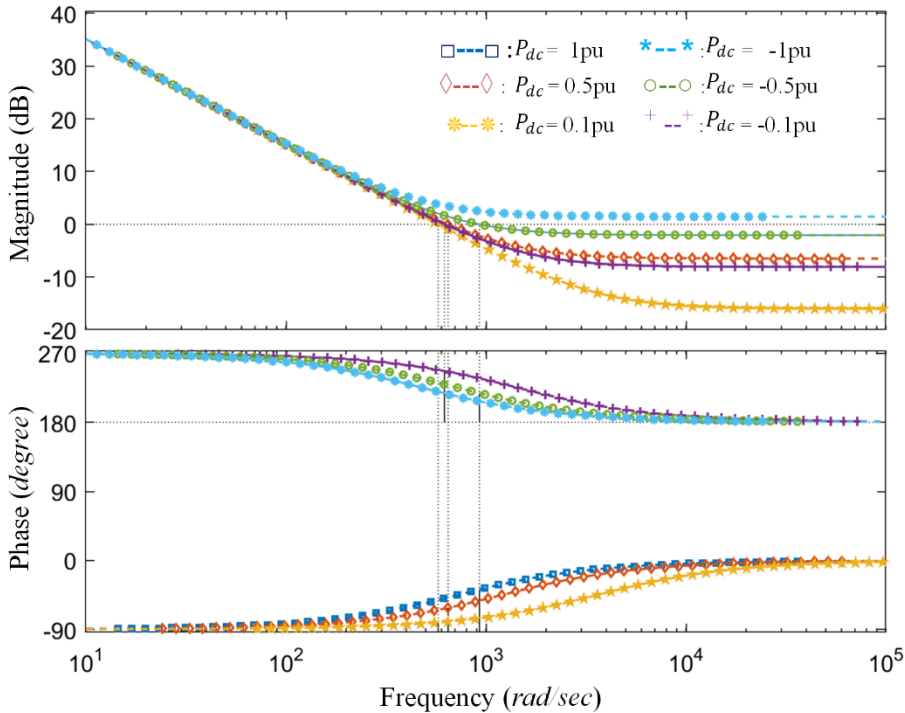


Figure 3-4. System frequency response for varying P_{dc} functioning in both inversion and rectifying modes [C2].

Because of the impact of non-minimum phase zero, the IC must have a specified stability margin in its rectifying mode of operation in order to operate in a stable condition. The dynamic stability margin poses significant constraints on the supply of dc loads in the event of power shortages or failures in dc sources, consequently increasing the overall risk of the microgrid, particularly within the dc subgrid.

Table 3-4. Variation of the phase margin and gain margin for different values of P_{dc} obtained via the interlinking converter [C2].

$P_{dc}(p.u.)$	Phase Margin ($^{\circ}$)	Gain Margin (dB)
1	142	-
0.5	113	-
0.1	95	-
0	74	-
-0.1	60	9
-0.5	46	6
-0.8	32	4
-0.85	26	3
-0.9	18	1
-0.93	Unstable	
-1		

Additionally, by adjusting P_{dc} , Figure 3-5 shows how the root locus of the dominant eigenvalues moves. The dominating modes shift to the left side of the s-plane when P_{dc} is raised in the inversion mode from 0 to +1 p.u. This results in an increase in damping, which keeps the system operating in a stable condition.

On the other hand, in the rectifying mode of operation, an increase in P_{dc} causes the dominant modes to shift towards the right half-plane, which causes instability in the system. For example, similar to the frequency domain results, the dominant modes become very close to the origin when the transferred power reaches $P_{dc} = -0.93$ pu, and the system becomes unstable. Therefore, in order to prevent instability, it is essential to operate the IC within a restricted stability boundary. These analyses show that in order to guarantee stable operation of bidirectional converters in hybrid microgrids, it is necessary to define the stability margin in rectifying mode.

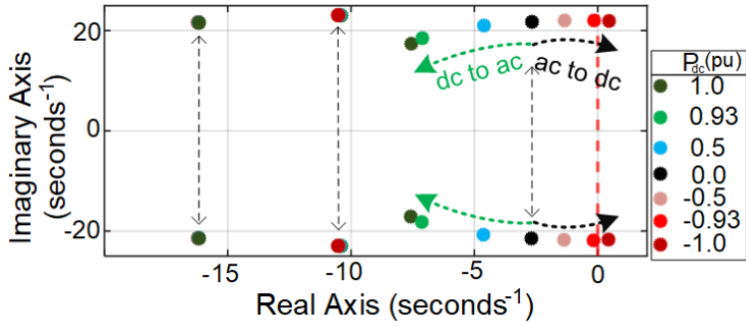


Figure 3-5. Impact of P_{dc} variation on loci of dominant modes for the system specified in Table 3-3 [J1].

3.3.1.2. Time Domain Simulation

The frequency domain and root locus analysis have demonstrated that when the IC operates close to the nominal power in rectifying mode, the presence of a zero in the transfer function of $W(s)/Igd(s)$ causes the dc voltage to operate in unstable condition. Two case studies that feature both the inversion and rectifying modes of operation for the IC have been carried out in the time domain simulations to further illustrate this instability. Below, the two case studies are elaborated:

a) Operation in the Inversion Mode

In this case study, 10 kVA IC is analyzed under various load conditions, assuming the need to transfer power from the dc subgrid to the ac subgrid. Each subgrid has a maximum power capacity of 20 kW, or 2 p.u considering the IC capacity as based power ($S_b = 10 \text{ kVA}$). According to this, the ac and dc load changes over a 4-second interval are detailed in Table 3-4. During the simulations, it is assumed that the dc load remains constant at 1 p.u (10 kW), while the ac load increases from 1 p.u up to 3 p.u in different intervals.

Table 3-5. AC and DC load changes in p.u over the designated period of time

Load		Time (s)				
		0	1	2	3	4
Inversion mode	AC load (p.u)	1	2	2.5	2.93	3
	DC load (p.u)	constant= 1				
Rectifying mode	AC load (p.u)	constant= 1				
	DC load (p.u)	1	2	2.5	2.93	3

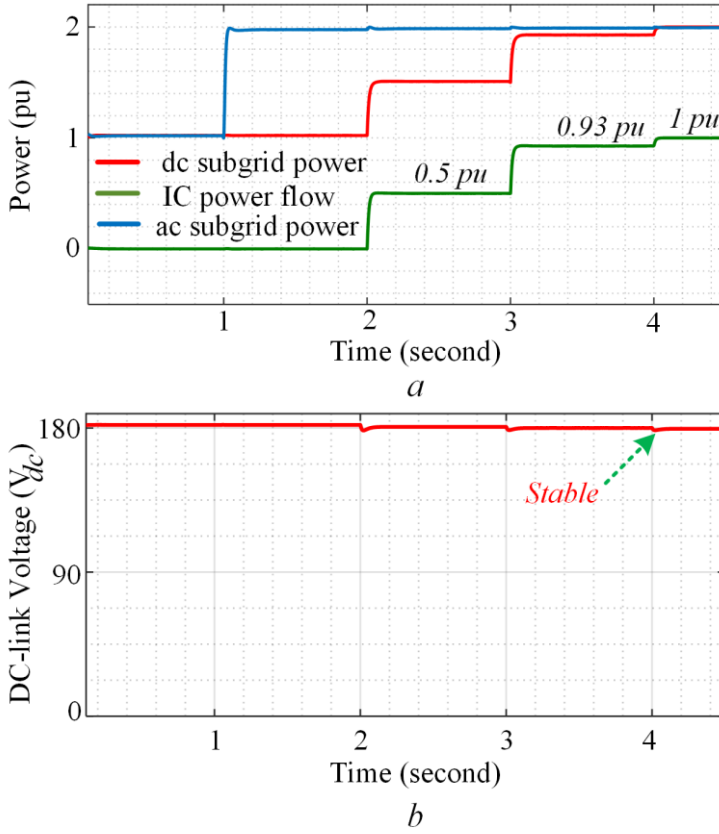


Figure 3-6. Dynamic behavior of DC-link voltage and power distribution between dc and ac subgrids, along with interlinking converter power flow during inversion mode operation, illustrated in (a) Power distribution and (b) DC voltage fluctuations. [J1].

Figure 3-6 depicts the power sharing and DC link voltage variation corresponding to the load changes. Initially, both ac and dc subgrids supply their loads at 1 p.u each, with zero power transferred by the IC. At $t=1$ sec, the ac load increases to 2 p.u, causing the ac subgrid to operate at nominal capacity. Subsequently, the ac load is overloaded to 2.5 p.u at $t=2$ sec, resulting in a transfer of 0.5 p.u power through the IC from the dc subgrid. Despite this, the DC link voltage remains stable according to Figure 3-6 (b). At $t=3$ sec, the ac load is further increased to 2.93 p.u, forcing the IC to increase the transferred power to 0.93 p.u while still maintaining stable DC link voltage. Finally, at $t=4$ sec, the ac load reaches 3 p.u, and the IC successfully transfers the required nominal power (1 p.u) in the inversion mode without causing instability in the DC link voltage. Thus, the IC demonstrates its capability to transfer its rated capacity (10 kVA or 1 p.u) while ensuring the stability of the DC link voltage during operation in the inversion mode.

b) Operating in Rectifying Mode

In this scenario, the ac load remains constant at 1 p.u over a 4-seconds period, while the dc load is incrementally increased to 3 p.u, as outlined in Table 3-5. Consequently, the IC converter transfers power from the ac subgrid to the dc subgrid, operating in rectifying mode. The stability of the DC link voltage is then assessed under these conditions.

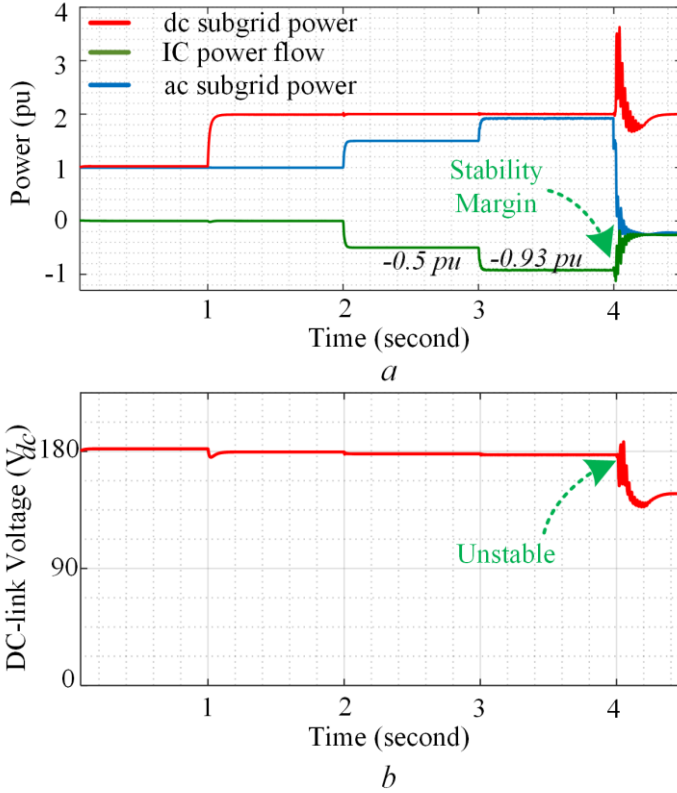


Figure 3-7. Dynamic behavior of DC-link voltage and power distribution between dc and ac subgrids, along with interlinking converter power flow during rectifying mode operation, illustrated in (a) Power distribution and (b) DC voltage fluctuations [J1].

Figure 3-7 (a) and (b) illustrate the active power variations of the IC, ac and dc subgrids, and the changes in DC link voltage, respectively. At $t=1$ sec, the dc load rises to 2 p.u, causing the dc subgrid to operate at a nominal power of 2 p.u. Subsequently, at $t=2$ sec, the dc load increases to 2.5 p.u, prompting the IC to transfer -0.5 p.u of excess power from the ac to the dc side. During this period, the ac subgrid supplies 1.5 p.u of loads. As the dc load further escalates to 2.93 p.u at $t=3$ sec, the IC continues to provide the required excess power from the ac side, with the DC link voltage remaining stable, as shown in Figure 3-7 (b). However, when the dc load

reaches 3 p.u at $t=4$ sec, the DC link voltage becomes unstable, resulting in the HMG operating in an unstable condition.

Hence, as demonstrated by root cause and frequency domain analysis as well as time domain simulations, it becomes evident that defining an appropriate stability margin is critical to guarantee the IC's stable operation in rectifying mode. The outcomes suggest that establishing a stability margin of 0.93 enables the hybrid microgrid to maintain stable conditions. In fact, this stability margin indicates that in rectifying mode of operation, the transferred capacity of the interlinking converter is restricted to 0.93 per unit to guarantee stability.

3.4. Transient Angle Stability (TAS) in AC Subgrid

The presence of power electronics and renewable generation uncertainties make microgrids more vulnerable than conventional power systems. Because of this, microgrids can become unstable even in the event of small interruptions. Transient voltage stability is particularly important, as shown by the stability classification in [116]. Transient stability issues can be caused by a wide range of events, including loss in renewable energy sources, islanding, faults, and large load steps. In this section, the impact of large load changes in the ac subgrid on transient angle stability (TAS) will be analyzed. The lower inertia in microgrids and improper control parameters tuning in microgrids may put the sources into an unstable operation similar to the conventional electrical machines. Thus, the unstable operation of the microgrid under large load steps will be investigated first, followed by the determination of stability constraints to be included in the risk assessment model. Considering a single machine connected to the infinite bus with line impedance X_l , the power-angle equation can be obtained as given below [135]:

$$P = \frac{|E| \cdot |V|}{X_l} \cdot \sin(\delta) = P_{max} \cdot \sin(\delta) \quad (3.18)$$

Where E is the electric machine internal voltage, V is the voltage magnitude of the infinite bus, and the δ is the angle between E and V . The graphical representation of power-angle of sample electric machine is shown in Figure 3-8. Any changes in the ac load or loss of one generating unit in a multi-machine configuration result in fluctuations in the input power. Considering the initial steady-state operating point at P_{m1}, δ_0 , when a sudden change in the input power occurs, the rotor accelerates, and the power angle increases. The angle accelerates and reaches the maximum value of δ_2 , swinging back to δ_1 , before settling down at the final operating point (P_{m2}, δ_1). In accordance with the Equal Area Criterion (EAC), which is widely used for analyzing the transient stability in power systems and in order to operate in stable condition the positive acceleration area (A2) must be equal to or greater than the negative decelerating area (A1) [135]. Figure 3-9 depicts the variations in angle (δ) for two distinct operating conditions: one stable and other unstable. If the area A2 exceeds A1, δ will converge to a stable operating condition. Conversely, if A2 is smaller than A1, the system will become unstable.

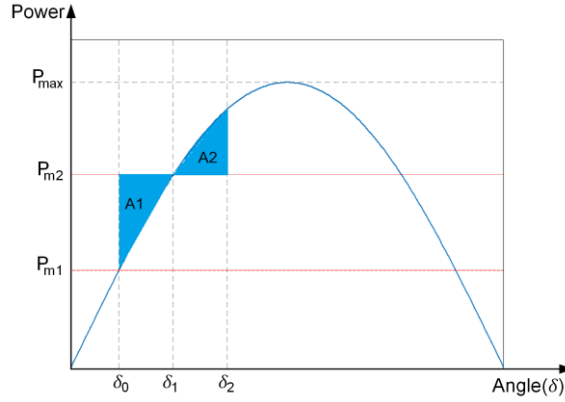


Figure 3-8. Power angle curve for a sample machine during variations in input power [J2].

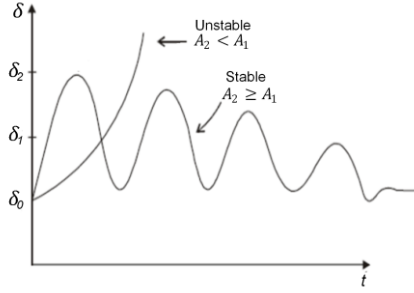


Figure 3-9. Variation of angle for two different operating conditions

3.4.1. Mathematical Modeling of Angle Stability

According to equal area criterion and Figure 3-8, when the input power increases and sets in P_{m2} , stable operating circumstances require that: $Area A_2 = Area A_1$.

Or:

$$\int_{\delta_0}^{\delta_1} (P_{m2} - P_{max} \sin(\delta)) d\delta = \int_{\delta_1}^{\delta_2} (P_{max} \sin(\delta) - P_{m2}) d\delta \quad (3.19)$$

Where P_{max} is the maximum power of the machine. Substituting $P_{m2} = P_{max} \sin(\delta_1)$ into equation (3.19) and doing some calculations yields:

$$(\delta_2 - \delta_0) \sin(\delta_1) + \cos(\delta_2) - \cos(\delta_0) = 0 \quad (3.20)$$

When $A_1 = A_{2,max}$, the new mechanical power (P_{m2}) can change as much as possible without compromising the system's instantaneous stability and synchronism. In other words, the angle δ_2 must be equal to: $\pi - \delta_1$. Thus, by replacing δ_2 in equation (3.20), the maximum critical power angle can be found as follow:

$$(\pi - \delta_1 - \delta_0)\sin(\delta_1) + \cos(\pi - \delta_1) - \cos(\delta_0) = 0 \quad (3.21)$$

The maximum permitted sudden changes in the machine's input power can be obtained using (3.22), in which δ_{cr} represents the critical power angle and it is equal to $\delta_{cr} = \delta_1$.

$$P_m^{cr} = P_{max}\sin(\delta_{cr}) \quad (3.22)$$

P_m^{cr} indicates the maximum allowable input power changes of a machine without losing stability. This criterion limits the machine's input power fluctuations, which is crucial for ensuring stable and steady system operation. Maintaining the stability of the synchronous operation, preventing excessive power angle deviations, and ensuring that EAC keeps the system within acceptable bounds. Understanding this criterion can be considered as a safety measure in practice by preventing sudden fluctuations in mechanical power and maintaining steady and reliable system operation. Time domain simulation results will illustrate this instability problem and show unstable operations under particular conditions in the following section.

3.4.2. Time Domain Simulations

In hybrid microgrids, the Equal Area Criterion (EAC) traditionally used for synchronous machines can be effectively adapted through the implementation of Virtual Synchronous Generators. VSGs emulate the dynamic characteristics of traditional synchronous generators by utilizing power electronics to mimic inertia (J) and damping (D), which are essential components of the swing equation. This equation governs the mechanical and electrical power balance, enabling the analysis of transient stability by comparing the accelerating and decelerating power areas during disturbances. By setting the control parameters of power electronic converters to replicate these characteristics, hybrid microgrids can maintain stability and robustness akin to conventional power systems, making EAC a valuable tool for assessing and enhancing system stability in response to dynamic changes.

Therefore, in order to investigate the transient angle stability challenges in microgrids, DG3 and DG4 in the ac subgrid of HMG depicted in Figure 3-2 are replaced with two Virtual Synchronous Generators (VSG). Additionally, the previously discussed a 10 kVA Interlinking Converter (IC) is connected to the ac terminal and is involved in power and energy management program. The dc subgrid is represented as a constant voltage source linked to the IC, as the focus is on analyzing transient stability issues in the ac subgrid.

The overall diagram of the model is shown in Figure 3-10. Figure 3-10 (a) illustrates the connection of two VSGs to the ac terminal as power sources. VSG1 and VSG2 have nominal powers of 10 kW and 15 kW, respectively. The control diagram of the VSG is shown in Figure 3-10 (b) [134], [136]. It is assumed that there is no power exchange between the main grid and the ac subgrid. Two ac loads are supplied by the VSGs along with power transferred through the IC from the dc side. The sources and

control parameters used in the time domain simulation study are summarized in Table 3-6. The relevant parameters and the control diagram for the IC remain the same with those presented in Table 3-3 and Figure 3-3, respectively.

For the purpose of transient stability analysis, three Case studies have been considered:

- a) Case Study 1: It will examine the unstable angle operation of VSG2 resulting from exceeding the allowable input power changes.
- b) Case Study 2: It will demonstrate how effective energy management alongside the utilization of available energy sources can contribute to stable operation of the system.
- c) Case Study 3: It will explore the impact of gradual load changes as opposed to large load steps, as well as the ability of sources to generate their maximum allowable power without encountering stability issues.

The remainder of this section will present the time domain simulation results and establish the criteria for dynamic stability to ensure the power angle remains within stable conditions.

Table 3-6 Sources and control parameters for the ac microgrid utilized for time domain simulation [J2].

Parameters	Value
Virtual Synchronous Generators (VSGs)	
ω^*	314.159 rad/s
P_{VSG1}^*	10 kW
Q_{VSG1}^*	3 kVAR
P_{VSG2}^*	15 kW
Q_{VSG2}^*	5 kVAR
V_{DC}	180 V
V^*	110 V
L_f	2.8 mH
C_f	250 μ F
f_s	8000 Hz
m	0.002
n	0.003
J_{VSG1}	0.1 $kg.m^2$
D_{VSG1}	0.08 N.m.S
J_{VSG2}	0.15 $kg.m^2$
D_{VSG2}	0.05 N.m.S
Z_{line1}	3.8 mH
Z_{line2}	2.5 mH
K_{pv}, K_{iv}	0.7,15
K_{pi}, K_{ii}	3.5,180

3.4.2.1. Case Study 1: Unstable Operation of the System

In this case study, a constant 18 kW ac Load1 (Z_{load1}^{ac} : 18 kW) is assumed to be supplied by the VSGs and the IC. The operating point of each VSG is 5 kW and the IC provide remaining 8 kW load, in accordance with the power and energy management strategy. The operating conditions is depicted in Table 3-7. At $t=5$ sec, an IC failure occurs, leading to its disconnection from the grid. In this situation, the VSG1 output power is maintained fixed at 5 kW, and the VSG2 must supply the load by increasing its power from the 5 kW to 13 kW. Based on equations (3.21) and (3.22) the critical operating angle and therefore the maximum allowable input power are obtained as: $\delta_{cr} = 55.55^\circ$, $P_m^{cr} = 12.19 \text{ kW}$.

Figure 3-11 (a) and (b) illustrate the variation in active powers of the sources and IC, as well as the three-phase current of the VSG2, respectively. As it can be seen from this figure, a large and sudden increase in the input power of the VSG2, leads to significant fluctuations with large magnitude in the power and current due to the exceeding of the maximum allowable input power ($P_m^{cr} = 12.19 \text{ kW}$). Figure 3-11 (c) represents the instability in power angle of VSG2 after disconnecting the IC from the grid. The deviation of the power angle from the operating point has resulted in instability within the system.

This investigation shows that in order to keep the system stable under certain operating conditions, the generating units power must be restricted to the designated values. From a reliability standpoint, more load is lost as a result of this dynamic criteria. As a result, risk assessment frameworks need to address these kinds of dynamic failures and quantify how they affect the overall risk. Utilizing methods that allow for the integration of time series inputs with varying time resolutions in risk assessment facilitates the incorporation and mitigation of stability issues. Should these dynamic failures, in addition to static failures, exceed acceptable reliability thresholds, accurate system redesign becomes necessary to mitigate the impact of both dynamic and static performance limitations.

Table 3-7. Operating status of loads and generations within the ac subgrid in Figure 3-10 for Case study 1 [J2].

Sources	Capacity (kW)	Z_{load1}^{ac} : 18 kW constant, Z_{load2}^{ac} : Disconnected	
		Initial Operating Point (kW)	New Operating Condition (kW) at $t=5\text{sec}$
VSG1	10	5	Unchanged
VSG2	15	5	5+8=13
IC	10	8	Failed

3.4.2.2. Case Study 2: Stable Operation of the system

In the preceding case study, it was illustrated how abrupt changes in the input power of generating sources can lead to angle stability issues in the system. This instability arose from exceeding the maximum allowable input power. However, in this case study, it will be demonstrated how the contribution of other generating sources can

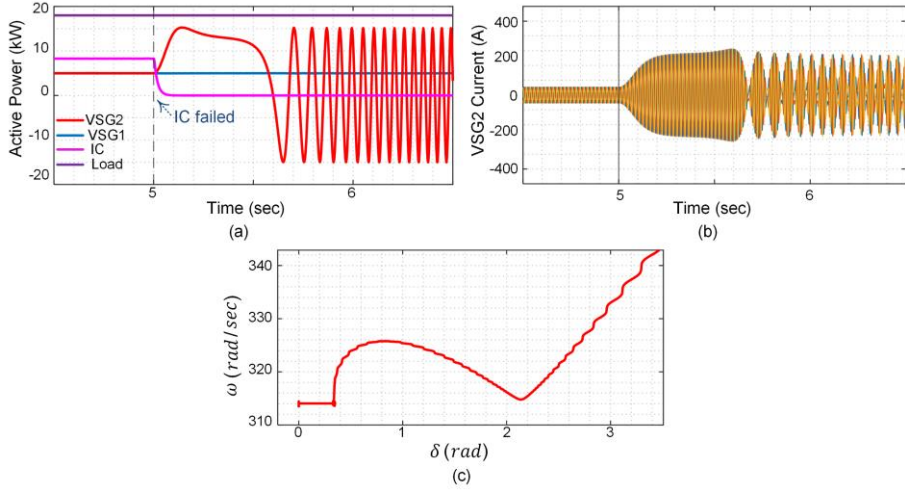


Figure 3-11. Time domain simulation results when IC fails at $t=5$ sec. (a) Active Power of sources and load, (b) VSG2 current, (c) $\omega - \delta$ characteristics of VSG2.

enhance the system's performance in the event of significant disturbances. The initial operating conditions are similar to the previous study, and the interlinking converter (IC) will again be disconnected at $t=5$ sec. However, in this study, it is assumed that VSG1 is permitted to adjust and increase its power up to 7 kW (it is assumed that the connected renewable energy source has sufficient power to contribute to the power management). The time domain results are depicted in Figure 3-12. According to Figure 3-12 (a), the power of VSG1 experiences a change from 5 kW to 7 kW with minimal oscillations. Consequently, the required power from VSG2 decreases to 11 kW compared to the 13 kW required in the previous study. Since this increment in input power is smaller than the critical input power ($P_m^{cr} = 12.19 \text{ kW}$), the current of the VSG2 remains stable, as depicted in Figure 3-12 (b), operating at the new setpoint. The oscillations in angular speed versus power angle for VSG2 and VSG1 are illustrated in Figure 3-12 (c) and (d), respectively. In this scenario, the power angle eventually returns to the stable equilibrium point after some oscillations.

This study demonstrated that with sufficient generating power in the system, angle stability can be effectively managed, ensuring the system operates in a stable condition.

3.4.2.3. Case Study 3: Stable Operation with Gradual Load Increment

The control systems in microgrids are designed to transfer the maximum permissible power without encountering instability issues. This study tries to demonstrate another facet of stable operation within the system, achieved through a gradual increment of load. In other words, we examine how the power angle varies in response to these incremental load changes. It is assumed that the IC is disconnected and the two VSGs equally supply the 10 kW ac Load1. Then, at $t=5$

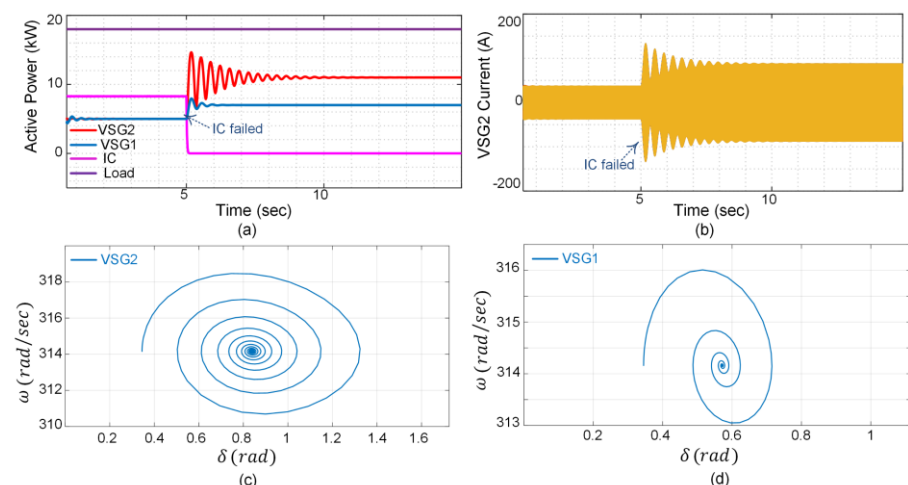


Figure 3-12. Simulation results depicting the behavior upon interlinking converter failure at $t=5$ sec and VSG1 contribute to the load flow. (a) Active Power Sources, (b) VSG2 current, (c) $\omega - \delta$ characteristics of VSG2, (d) $\omega - \delta$ characteristics of VSG1 [J2].

sec, ac load2 (Z_{load2}^{ac}) is connected to the grid following the specified load characteristics in Table 3-8. Considering fixed 5 kW power for the VSG1, the input power of the VSG2 starts to increase according to the Figure 3-13 (a), reaching to its maximum capacity (15 kW) at $t=20$ sec without losing the stability. The power angle changes for both VSGs are shown in Figure 3-13 (b), indicating stable operation for the gradual load increment.

Table 3-8. Operating status of loads and generations within the ac subgrid in Figure 3-10 for Case study 3.

Z_{load1}^{ac} : 10 kW constant, Z_{load2}^{ac} : $\begin{cases} \frac{10}{15}(t-5) & 5s \leq t \leq 20s \\ 10 & 20s \leq t \end{cases}$			
Sources	Capacity (kW)	Initial Operating Point (kW)	New Operating Condition (kW) at $t=5s$
VSG1	10	5	Unchanged
VSG2	15	5	Increases gradually
IC	10	Disconnected	Disconnected

Thus, it is clear from these results that, depending on the situation, suddenly high load variations or the loss of generating units may result in unstable conditions for other generating units. System operators are required to respond quickly in such circumstances. This may include shifting the load to different sources or, in more extreme circumstances, reducing or disconnecting a portion of the load. In order to ensure a more reliable and stable operating condition, it is imperative that these stability issues must be addressed, modeled within the framework of risk assessment,

and their impact evaluated. The system must then be redesigned to minimize these effects.

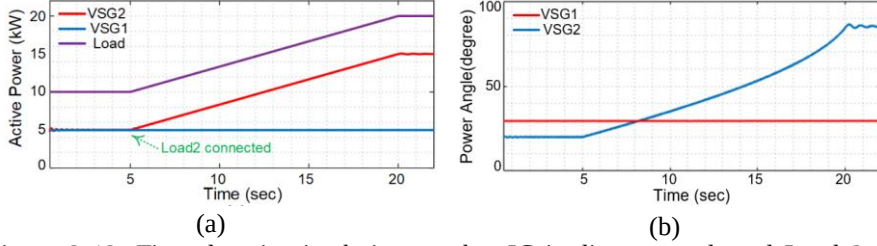


Figure 3-13. Time domain simulation results: IC is disconnected, and Load 2 is connected at $t=5$ sec. (a) VSG1 and VSG2 Active Power, (b) Power angle (δ)

3.5. AC Subgrid Frequency Stability

As outlined earlier in this chapter, frequency stability poses a significant challenge in microgrids and can span from several seconds to minutes. Various grid codes have established operating conditions that restrict frequency variations for renewable energy sources. Consequently, microgrids are permitted to operate within specific frequency limits, and if these limits are exceeded, the microgrid must be disconnected. To address this issue, most microgrids are equipped with suitable frequency control mechanisms. Figure 3-14 depicts three primary control units and their respective time intervals during a system disturbance. Initially, the inertia response uses the machines' stored kinetic energy to mitigate the imbalance through inertia control until the primary control is fully functional. In microgrids relying on power electronics, the system's inertia response has been reduced to 1-10 seconds, resulting in a significantly higher rate of change of frequency (RoCoF) [137] and larger frequency deviations, as highlighted in red in Figure 3-14, particularly with high penetration of Renewable Energy Sources (RES). If the inertia alone cannot restore the frequency to its nominal value, the primary and secondary control mechanisms engage in frequency regulation. The primary control operates within 10-30 seconds, while the secondary control spans from 10 to 30 minutes.

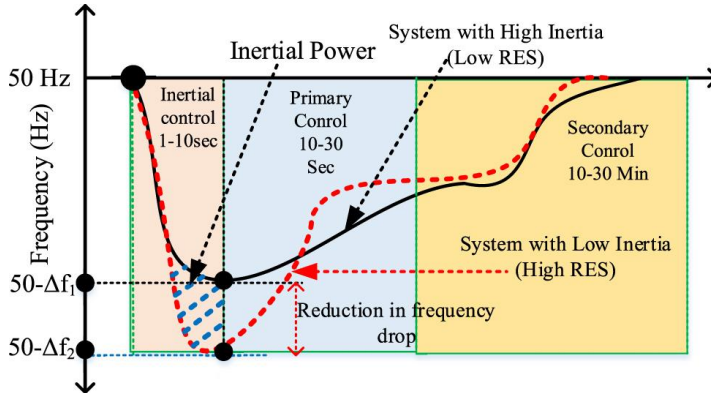


Figure 3-14. Frequency response time intervals during a disturbance [138].

Any changes in the input power of the sources result in deviations in the frequency and the rate of frequency changes depends to the droop gain parameters in the control loop. In the subsequent section, the mathematical models for the ac subgrid frequency and the dc subgrid voltage, incorporating the droop control for the sources, will be examined. Subsequently, the variations in frequency attributed to changes in system variables and inputs will be assessed.

3.5.1. Mathematical Modeling

Similar to the previous section, a hybrid microgrid shown in Figure 3-2 is used to mathematically model the variations in frequency and dc voltage. As a matter of simplicity, this model considers all sources to have a capacity of 10 kW and ignores line impedances.

The only control variable in the dc subgrid that can regulate the active power of the converters is the dc voltage. The droop control is considered as a primary control in adjusting the frequency and the dc voltage in hybrid microgrids according to changes in the active power. Considering conventional droop control method, the dc power of each source (DG1 and DG2) in dc subgrid can be determined as [139]:

$$\begin{aligned} P_{1dc} &= P_{1dc}^* - \frac{1}{n1} (V_{dc} - V_{dc}^*) \\ P_{2dc} &= P_{2dc}^* - \frac{1}{n2} (V_{dc} - V_{dc}^*) \end{aligned} \quad (3.23)$$

where P_{1dc} and P_{2dc} are the dc active power of DG1 and DG2, respectively, considering P_{1dc}^* and P_{2dc}^* as their references. V_{dc} is the dc subgrid voltage with reference to V_{dc}^* and $n1, n2$ are the droop gains for the $V - P$ characteristics.

In addition, the power balance equation in the dc subgrid can be expressed as follows:

$$P_{1dc} + P_{2dc} - P_{ic} = P_{Ldc} \quad (3.24)$$

Where the P_{ic} and P_{Ldc} are the IC transferred power and the load demand, respectively.

In the ac subgrid, similar to the dc side, the ac power output of each source can be determined as follows, considering the used droop control method:

$$\begin{aligned} P_{1ac} &= P_{1ac}^* - \frac{1}{m1} (f - f^*) \\ P_{2ac} &= P_{2ac}^* - \frac{1}{m2} (f - f^*) \end{aligned} \quad (3.25)$$

where P_{1ac} and P_{2ac} are the ac active power of DG3 and DG4, respectively, and considering P_{1ac}^* and P_{2ac}^* as their references. f is the ac subgrid frequency with reference to f^* and $m1, m2$ are the droop gains for the $f - P$ characteristics.

The power balance equation in the ac subgrid can be obtained as:

$$P_{1ac} + P_{2ac} + P_{ic} = P_{Lac} \quad (3.26)$$

As described in section 3.3, in order to regulate the power exchange between the subgrids, a normalized droop model has been used for the control of the IC. Therefore, considering the per unit values of V_{pu} and f_{pu} as shown in equations (3.7) and (3.8) the droop characteristic of the interlinking converter will be obtained as:

$$P_{ic} = m_{ic}(V_{pu} - f_{pu}) \quad (3.27)$$

Where the P_{ic} is the exchanged power of the IC and m_{ic} is the droop gain and indicates the amount of power transferred through the IC. By substituting V_{pu} and f_{pu} into equation (3.27) and calculating f and V_{dc} in accordance with other parameters, the matrix-vector equation can be obtained using:

$$A \begin{pmatrix} f \\ V_{dc} \end{pmatrix} = B \quad (3.28)$$

where the coefficient matrix A and vector matrix B are defined as below:

$$A = \begin{pmatrix} \frac{1}{m1} + \frac{1}{m2} & \frac{1}{n1} + \frac{1}{n2} \\ -\frac{1}{m1} - \frac{1}{m2} - \frac{m_{ic}}{0.5(f^{max} - f^{min})} & \frac{m_{ic}}{0.5(V_{dc}^{max} - V_{dc}^{min})} \end{pmatrix} \quad (3.29)$$

$$B = \begin{pmatrix} -P_{Ldc} - P_{Lac} + P_{1dc}^* + P_{2dc}^* + P_{1ac}^* + P_{2ac}^* + \dots \\ P_{Lac} - P_{1ac}^* - P_{2ac}^* - \frac{m_{ic}(f^{max} + f^{min})}{f^{max} - f^{min}} + \dots \end{pmatrix} \quad (3.30)$$

$$\begin{pmatrix} \dots + \left(\frac{1}{m1} + \frac{1}{m2}\right)f^* + \left(\frac{1}{n1} + \frac{1}{n2}\right)V_{dc}^* \\ \dots + \frac{m_{ic}(V_{dc}^{max} + V_{dc}^{min})}{V_{dc}^{max} - V_{dc}^{min}} - \left(\frac{1}{m1} + \frac{1}{m2}\right)f^* \end{pmatrix}$$

The variation in the frequency of the ac subgrid and the voltage of the dc subgrid depends on the droop gains of the sources, their operational limits, as well as the reference and operational values of the active power.

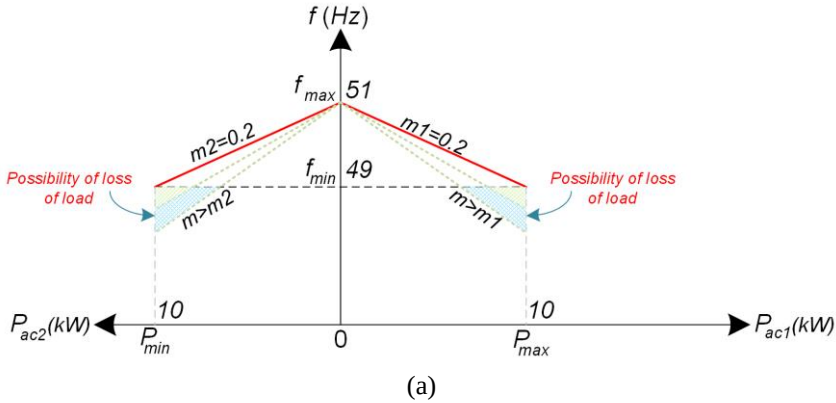
For simplicity, the droop characteristics of parallel sources in each subgrid can be aggregated, leading to the following rewritten equations for frequency and voltage:

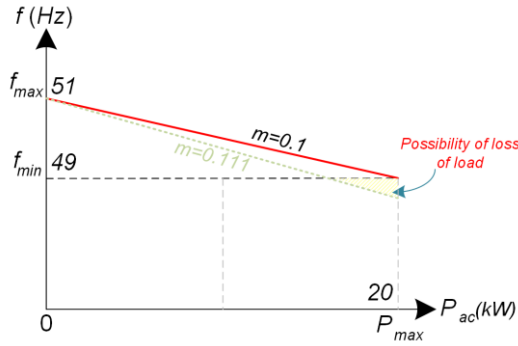
$$f = f^* - \frac{m_1 m_2}{m_1 + m_2} (P_{ac} - P_{ac}^*), \quad P_{ac} = P_{ac1} + P_{ac2}, \quad P_{ac}^* = P_{ac1}^* + P_{ac2}^* \quad (3.31)$$

$$V_{dc} = V_{dc}^* - \frac{n_1 n_2}{n_1 + n_2} (P_{dc} - P_{dc}^*), \quad P_{dc} = P_{dc1} + P_{dc2}, \quad P_{dc}^* = P_{dc1}^* + P_{dc2}^* \quad (3.32)$$

The droop characteristics for frequency ($f - P$) and dc voltage ($V_{dc} - P$) control in a hybrid microgrid, as illustrated in Figure 3-10 are depicted in Figure 3-15 and Figure 3-16, respectively. Assuming all sources have a capacity of 10 kW and droop gains of $m_1 = m_2 = 0.2$, with frequency boundaries set between 49-51 Hz, Figure 3-15 (a) demonstrates that as the droop gains increase, without secondary frequency control, sources operating close to nominal power will cause the frequency to drop to the minimum value of 49 Hz. In such instances, corrective actions are necessary to return the frequency to standard operating values, increasing the likelihood of load loss. Large changes in droop gains necessitate higher load shedding, thereby elevating the microgrid's risk. Figure 3-15 (b) shows this scenario using an equivalent model for ac sources, where the droop gain is set to 0.1. A similar phenomenon is observed in the dc subgrid, with changes in dc voltage depicted in Figure 3-16 (a) and Figure 3-16 (b). Considering equal droop gains $n_1 = n_2 = 1$ and allowing ± 5 V deviation for dc voltage, changes in droop gains, coupled with the absence of secondary control, amplify the probability of load loss when operating near nominal capacity.

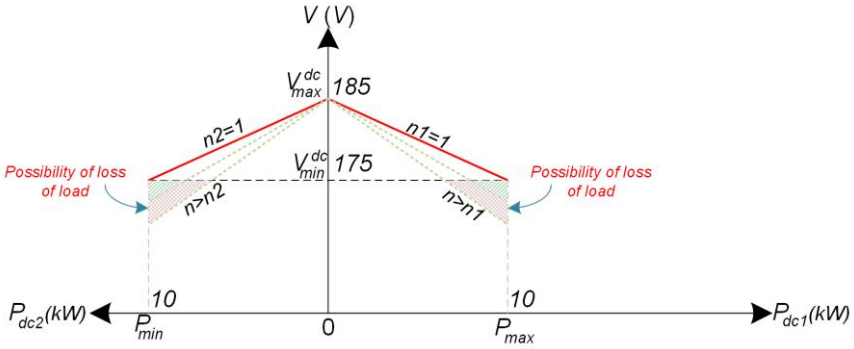
Microgrid stability is largely dependent on the dc voltage and frequency control mechanisms, particularly in situations when secondary control systems are nonexistent or inefficient. There are inherent risks associated with using droop controls to control frequency and voltage levels, especially when operating near nominal capacity. In the absence of backup controls to mitigate deviations, variations in droop gains may result in heightened risk exposure, increased chances of load shedding, and ultimately, and raised probability of load loss. The lack of strong strategies for voltage and frequency regulation highlights the significance of putting in place efficient secondary control mechanisms to improve the stability and reliability of microgrid operations and to reduce the possible impact of risks associated with droop control.



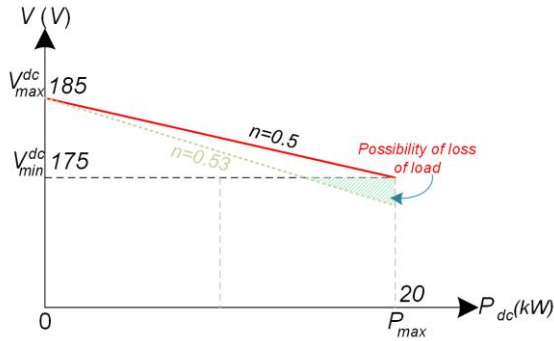


(b)

Figure 3-15. Control of droop through frequency droop with active power sharing in ac subgrid. (a) $f - P$ for two sources, (b) $f - P$ for equivalent model



(a)



(b)

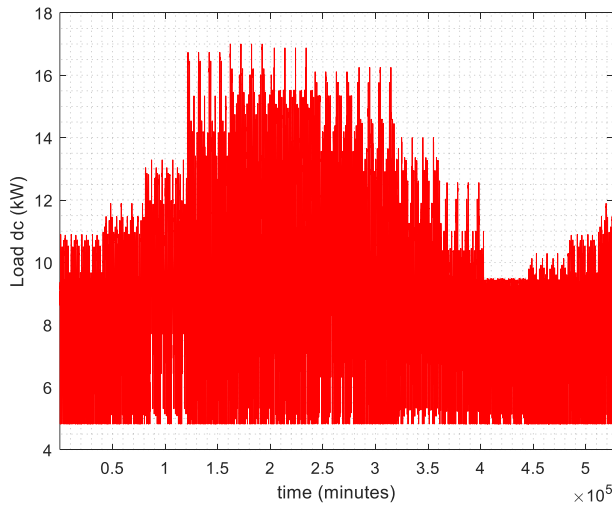
Figure 3-16. Control of droop through voltage droop with active power sharing in dc subgrid. (a) $V_{dc} - P$ for two sources, (b) $V_{dc} - P$ for equivalent model

3.5.2. Case Studies (Off-Grid Operation)

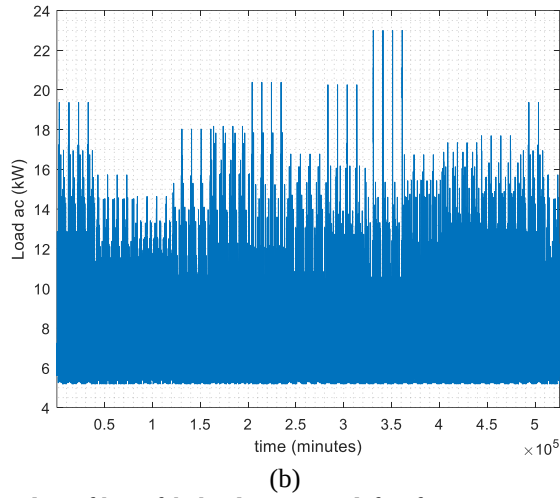
To investigate the dynamics of frequency and dc voltage in response to load fluctuations, time domain simulations were conducted using the microgrid parameters given in Table 3-6. For the frequency stability study, it is assumed that the hybrid microgrid is operating in off-grid condition and the grid is disconnected from the ac subgrid in Figure 3-2.

The simulation used the load profiles of the dc and ac subgrids, which are shown in Figure 3-17 with minute-level resolution. Employing an equivalent model for both subgrids, each was set to supply 20 kW of power, with droop gains assumed to be $m_1=0.1$ and $n_1=0.5$. These simulations provided insights into the dynamic behavior of the system under various operating conditions by allowing an analysis of how changes in load affected the frequency and dc voltage within the microgrid.

Figure 3-18 (a) shows the frequency fluctuations observed in the ac subgrid. Particularly, in certain operating scenarios, the frequency dips below the minimum acceptable threshold for several minutes. In the absence or ineffectiveness of secondary control mechanisms, this situation necessitates load shedding to restore the frequency to a permissible level. Such dynamic failures significantly raise the risk profile of the microgrid and mitigate its overall reliability. Prolonged durations of operation under underfrequency conditions may ultimately require the disconnection of a substantial portion of the load, further worsening the reliability challenges. Similarly, Figure 3-18 (b) illustrates the variation in dc voltage within the dc subgrid. Situations where the voltage falls below the minimum standard value happen, and they are comparable to the frequency fluctuations in the ac subgrid. This highlights a higher probability of load loss in the dc subgrid, emphasizing the importance of efficient control systems and stability measures in microgrid operations.



(a)



(b)
Figure 3-17. Load profiles of hybrid microgrid for frequency stability study with minute time resolution. (a) dc subgrid annual load profile, (b) ac subgrid annual load profile.

Therefore, the results showed that how the frequency and dc voltage stability which are controlled by droop method, may be affected by improper droop gains. The acceptable ranges that these parameters must operate within to guarantee grid stability and appropriate functionality are determined by this stability analysis. It is possible to identify critical thresholds and possible instabilities that could put in risk the stability and reliability of the microgrid system by analyzing the dynamics of frequency and dc voltage.

In conclusion, this chapter presented a thorough investigation of stability issues in microgrids and highlighted the complicated relationships resulting from different stability problems. The investigation started by outlining the stability issues related to the IC's DC link voltage, emphasizing its constraints in rectifying mode because of its non-minimum phase behavior. In addition, a stability margin was carefully established for the IC in order to outline its limitations. After that, transient stability problems were discussed with an emphasis on the effects of large load variations or DG loss on voltage angle stability. The findings highlighted the necessity of resolving temporary stability concerns by pointing to the possibility of system instability under specific circumstances. The chapter also covered DC voltage and frequency stability in a hybrid microgrid, which highlights the complexity of the issues related to stability in microgrids.

These dynamic failures could result in loss of load and increased microgrid risk. Different approaches, including eigenvalue analysis, root cause analysis, and time domain simulations, were used to investigate these stability issues and distinguish between short- and long-term stability concerns. Crucially, the stability margins and constraints found will be essential inputs for the ensuing risk assessment model, which will enable a comprehensive assessment of microgrid reliability.

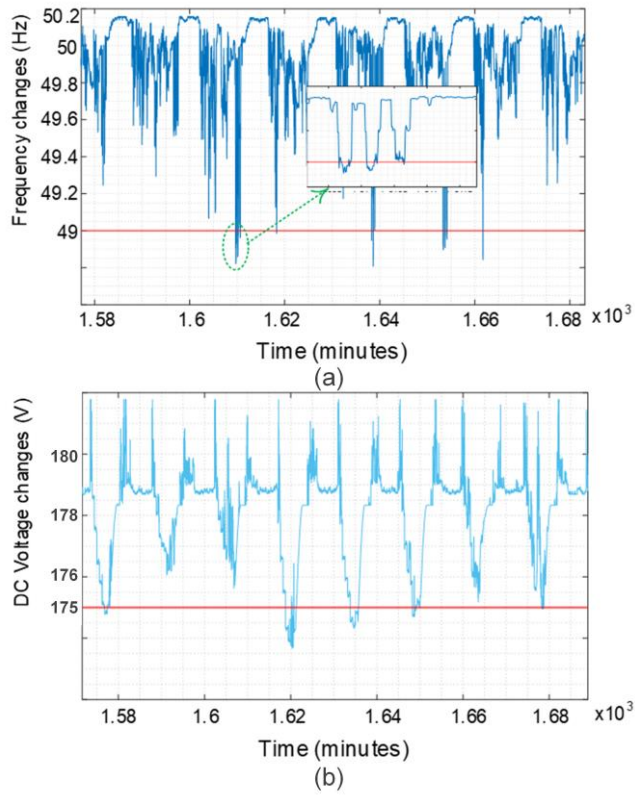


Figure 3-18. Hybrid microgrid variables (see Figure 3-2) response to load variations. (a) Frequency fluctuation in the ac subgrid, (b) DC voltage variation in the dc subgrid

Chapter 4. Multi-Domain Design Framework for HMGs Integrating Reliability and Stability Simultaneously

4.1. Introduction

A study of several dynamic failures and stability issues was conducted in the previous chapter, which demonstrated how stability problem-related limitations may cause problems with a continuous supply of load and prediction. In such scenarios, in addition to static failures resulting from component failures, dynamic failures increase the risk of failures in microgrids. As a result, this chapter presents a new multi-domain design guideline model that simultaneously addresses static and dynamic failures. To develop and propose an innovative risk assessment model for microgrids, it is imperative to begin with analyzing conventional risk assessment methodologies. This involves presenting key reliability indices and exploring various numerical and simulation-based approaches utilized for risk analysis. In this chapter, methodologies such as Capacity Outage Probability (COPT), Monte Carlo Simulation, Markov Chain method, and State Enumeration Model will be investigated. Subsequently, a stability-oriented risk framework will be introduced to evaluate both dynamic and static reliability metrics, followed by the proposal of design guidelines for microgrids during the planning and operational phases.

4.2. Conventional Risk Assessment Methodologies

In order to guarantee the reliability and resiliency of microgrids, risk assessment is essential since it offers vital insights into probable failures and consequences. Traditional risk assessment models provide basic frameworks for assessing the probability and effects of different operational issues and failures in microgrid systems. By using a variety of methodologies and analytical techniques, these models evaluate the reliability of individual parts as well as the system as a whole, enabling customers to make well-informed decisions about the design, operation, and maintenance of the system. This section explores an investigation of these traditional risk assessment models, looking at their prominent characteristics, working principles, and uses with respect to microgrid reliability. A comprehensive set of reliability indices, or numerical measures of different aspects of the system's performance and reliability, are the results of the risk assessment models. These indices provide important details about the system's overall operational resilience by reflecting information regarding the system's ability to withstand potential failures or disturbances, providing insights into its overall operational resilience [26], [140]. By

incorporating various factors like failure probabilities, outage durations, restoration times, and system availability, they provide a comprehensive understanding of the system's resilience and efficiency in maintaining uninterrupted and reliable operation. The general procedure of obtaining the reliability indices in power systems is illustrated in Figure 4-1.

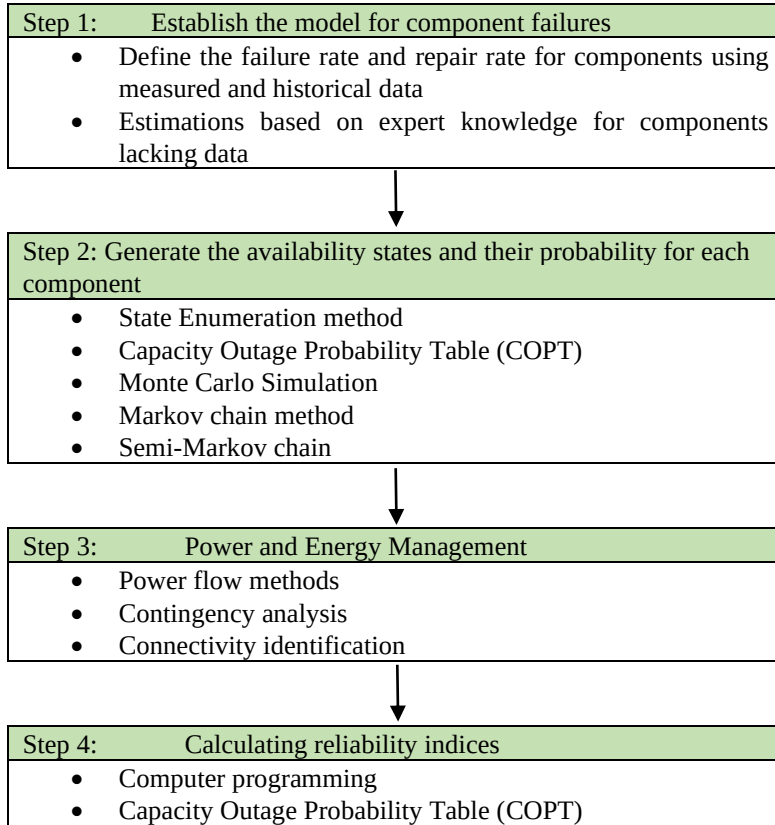


Figure 4-1. General approach for obtaining the reliability indices in power systems.

As illustrated in Figure 4-1, the first step in calculating the reliability indices is developing a framework for defining and calculating the probability that different system components can fail. For evaluating the system's reliability and predicting potential risks, this is essential. The data is gathered and examined from actual operations and maintenance records for components for which data is available. If not, engineering specialists can estimate component failure and repair rates using their knowledge and experience. In the second stage, the probability of failure for each component is calculated, or the availability states of these components is generated through analytical and numerical approaches. Then, various power and energy management methods can be used to determine the steady state operating conditions

for generation units and loads. Finally, by comparing the available energy with the load profiles, it becomes possible to determine the energy and time reliability indices. In the following different methods that are used to calculate the availability states (step 2) in risk assessment models will be discussed.

4.2.1. State Enumeration Method

State enumeration is a reliability assessment technique that involves enumerating system states until a certain failure order or probability threshold is reached. This method relies on expanding the following equation:

$$(A_1 + U_1)(A_2 + U_2) \dots (A_n + U_n) \quad (4.1)$$

Where A_i and U_i are the availability and unavailability of the i th component, respectively and n is the number of components in the system. The availability and unavailability terms are defined as given below:

$$A_i = \frac{\mu_i}{\mu_i + \lambda_i} \quad (4.2)$$

$$U_i = \frac{\lambda_i}{\mu_i + \lambda_i} \quad (4.3)$$

Constants λ_i and μ_i are the failure rate and repair rate of the i th component and these constants are obtained from the historical data and the service reports. The probability $P(s)$ that a state will occur in the system with N generating units is expressed as:

$$P(s) = \prod_{i=1}^{N_f} U_i \prod_{i=1}^{N-N_f} A_i \quad (4.4)$$

Where N_f represents the count of failed units, and $N - N_f$ represents the count of unfailed units in the state s . The procedure of calculating the reliability indices using this method is as follows:

1. After creating a multiple-step load model and enumerating each load level's state, the probability of the system state is determined.
2. Following the completion of the contingency analysis, an optimal power flow analysis is carried out to determine the necessary load curtailment in the chosen state in the event of a system malfunction. The chosen state is a failed one if the load curtailment is not zero. Only failed system states' probabilities and load reductions are noted.
3. Obtain and measure the risk indices using the following equations:

$$PLC = \sum_{i=1}^{N_L} \left(\sum_{s \in F_i} P(s) \right) \frac{T_i}{T} \quad (4.5)$$

Where PLC is the Probability of load curtailments, F_i is the set of all failed system states at the i th load level, T_i is the i th load level's duration (measured in hours), and N_L is the total number of load levels. T is the load curve's total duration (in hours). For system development planning, the duration is typically one year, while for operation planning, it can be any duration (weeks, months, or seasons). The Expected energy not supplied (EENS) can be obtained using the following equation:

$$EENS = \sum_{i=1}^{N_L} \left(\sum_{s \in F_i} P(s) \cdot C(s) \right) \cdot T_i \quad (4.6)$$

where $C(s)$ refers the curtailed load in state s in MW.

The expected frequency of load curtailments (EFLC) is another measure that can be determined using the state enumeration technique. The mathematical representation of this indices can be written as:

$$EFLC = \sum_{i=1}^{N_L} \sum_{s \in F_i} \left(P(s) \sum_{j=1}^{m(s)} \lambda_j \right) \frac{T_i}{T} \quad (4.7)$$

Where the total number of transition rates departing state s is denoted by $m(s)$ and λ_j is the j th departure rate of the components in state s .

Finally, the average duration of load curtailment (ADLC) can be obtained using:

$$ADLC = \frac{PLC \times T}{EFLC} \quad (4.8)$$

The reliability indices of each bus or the system as a whole can be assessed using any of the reliability indices. The state enumeration method works well with constant failure rates, and it is less appropriate for wear-out failures. However, it is a dependable method for analyzing constant failures within a system. Because of its thorough enumeration approach, which enables it to precisely calculate the probabilities of every possible system state, it is especially effective for small to medium-sized systems. Systems with discrete states benefit from this method, which ensures accurate analysis. Its drawback, however, is that it becomes computationally unfeasible for large-scale systems with many states due to the exhaustive enumeration's growing complexity and resource requirements.

4.2.2. Capacity Outage Probability Table (COPT)

A probabilistic depiction of a power system's generating units is offered by the Capacity Outage Probability Table (COPT) technique, which lists all potential states of available generating capacity along with the associated probabilities of occurrence. Analytical or numerical methods like state enumeration, Markov analysis, or Monte

Carlo simulations can be used to find these probabilities. By using contingency analysis or power flow, the available capacity for each state can be determined. Although COPT can be used with systems of different sizes, larger systems need computer programming, while smaller systems can list states manually. The general representation of the COPT model can be written as given Table 4-1.

Table 4-1. The Capacity Outage Probability Table (COPT) general model [141]

j	Available capacity (G_k)	Capacity outage	Individual Probability (p_k)	Cumulative probability
1	G_1	0	p_1	$\sum_{k=1}^{N_{COPT}} p_k$
2	G_2	$G_1 - G_2$	p_2	$\sum_{k=2}^{N_{COPT}} p_k$
...	...	...	...	...
N_{COPT}	$G_{N_{copt}}$	$G_1 - G_{N_{copt}}$	$p_{N_{copt}}$	$p_{N_{copt}}$

When combined with a designated load model, COPT allows the calculation of reliability indices by representing the probabilistic model of generating capacity. Depending on the needs of the analysis and the availability of data, different load models, such as constant, hourly, or daily peak load models, can be used. Hourly and daily peak load models, for example, provide load representations in a chronological order that are useful for evaluating historical system performance but less useful for long-term predictive analysis. An example of hourly load profile which is used for the IEEE Reliability Test System (RTS) is illustrated in Figure 4-2 [142]. When examining capacity-related failures and outages in large-scale systems with numerous components and capacity restrictions, COPT is especially helpful. It is ideally suited for capacity-related risk assessment tasks because its methodology centers on estimating the likelihood of capacity failures or shortages.

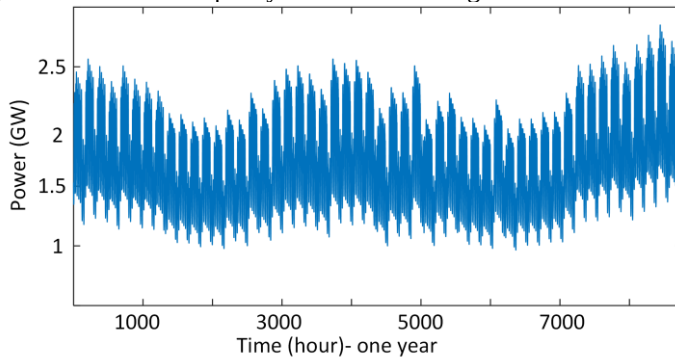


Figure 4-2. Time series load profile in hour resolution used in IEEE Reliability Test System (RTS) [142].

Some of the reliability indices that can be derived from the COPT model, considering the constant load model, include the Loss of Load Expectation (LOLE) and the Expected Energy Not Supplied (EENS), formulated as follows:

$$LOLE = \sum_{j=1}^{N_{copt}} \frac{\max(0, L - G_j)}{L - G_j} \cdot p_j \cdot T \quad (4.9)$$

$$EENS = \sum_{j=1}^{N_{copt}} \max(0, L - G_j) \cdot p_j \cdot T \quad (4.10)$$

Where j denotes the number of rows in COPT, T is the duration of the study, p_j and G_j stand for the capacity available at row j of COPT and the individual probability, respectively. L denotes the load's value.

In this method, if the load is characterized using either the Load Duration Curve (LDC) or the Daily Peak Load Variation Curve (DPLVC), the reliability indices mentioned earlier can effectively measure the system's risk. The primary distinction between these two load models lies in their representation of peak loads: the LDC employs hourly peak load data, whereas the DPLVC utilizes daily peak load data. A typical load duration curve is shown in Figure 4-3, where the load levels are sorted according to their magnitude and the length of time that each load level lasts. Then, using the formula $P_i = T_i / T$, where T_i is the load level duration and T is the total observation period, these durations can be translated into probabilities of occurrence for each load level.

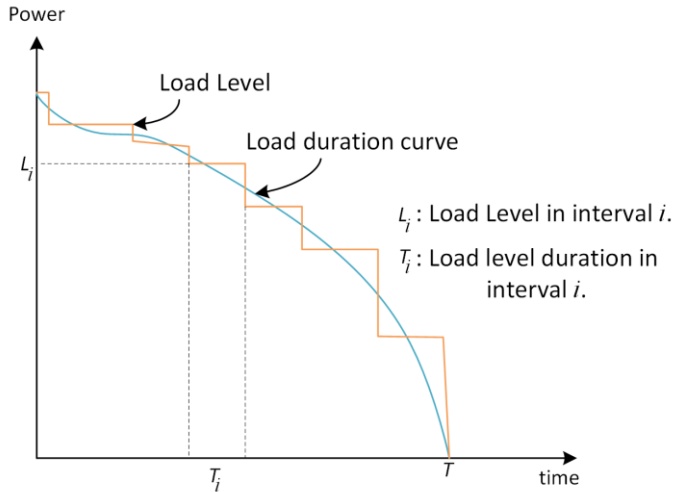


Figure 4-3. An example of Load Duration Curve (LDC) in a power system.

Therefore, the reliability indices can be obtained as:

$$l_{ij} = \begin{cases} 0 & L_j \leq G_j \\ 1 & L_j > G_j \end{cases} \quad (4.11)$$

$$LOLE = \sum_{j=1}^{N_{copt}} \sum_{i=1}^{N_{LDC}} p_i \cdot p_j \cdot l_{ij} \cdot T \quad (4.12)$$

$$EENS = \sum_{j=1}^{N_{copt}} \sum_{i=1}^{N_{LDC}} p_i \cdot p_j \cdot \max(0, L_i - G_j) \cdot T \quad (4.13)$$

Where N_{LDC} is the number of load levels, N_{copt} is the number of rows in *copt*, p_j is the individual probability in the j th row of the DLC, G_j is the available capacity in the j th row of *copt*, and T is the study time frame. L_i is the i th load level in the LDC. P_i is the probability of the i th load level.

The COPT method works well with large-scale systems that have a lot of components and capacity constraints. Its disadvantage, though, is that it might miss some failure modes or system dynamics, particularly those associated with wear-out failures, which might restrict how thorough and precise evaluation can perform.

4.2.3. Monte Carlo Simulation

Under some conditions, carrying out a thorough analytical assessment of power system reliability can be difficult. Numerous possible failure states or the substantial influence of higher failure scenarios on system reliability could be the source of this complexity [143]. Furthermore, it might be necessary to collect more specific data, like probability distributions related to load curtailment, or to include actual system behaviors, like the protection systems' operational sequences. Monte Carlo simulation provides a workable solution to these problems. With the use of computer-generated scenarios, this simulation technique replicates the behavior of the system and extracts probabilistic reliability indicators. Monte Carlo simulation offers a flexible way to study system reliability by simulating a variety of system parameters and behaviors, such as load and generation patterns and operational conditions. It is important to note that Monte Carlo simulation has uses outside of power system reliability analysis, demonstrating its applicability in a variety of domains. Three main simulation approaches used in Monte Carlo are described in this section as below:

(a) State Sampling method

This approach creates a representative sample of system states in order to evaluate the system's performance and behavior using probability [144], [145]. Rather than listing every possible state of the system, which may not be feasible for large-scale systems, this method selects a subset of states at random according to how likely it is to occur. The characteristics of each component are represented by a uniform distribution from 0 to 1. Considering success and failure as two states for each component and assuming

that each component fails independently, each component can be identified by its state (S_i) and failure probability (PF_i). In addition, using the uniform distribution function (U_i) which produces a random number between 0 and 1, the state of each component can be defined as:

$$S_i = \begin{cases} 0 & U_i \geq PF_i \\ 1 & 0 \leq U_i < PF_i \end{cases} \quad (4.14)$$

Defining State 0 as a success State and State 1 as a failure state, the state matrix of a system with n components is represented using:

$$S = (S_1, S_2, \dots, S_n) \quad (4.15)$$

Assuming that the probability $P(S)$ and reliability index function $F(S)$ are present in each system state, the mathematical expectation of the index function $E(F)$ for every system state can be found by [142]:

$$E(F) = \sum_{S \in m} F(S)P(S) \quad (4.16)$$

Where m represents the set of states in the system.

The probability $P(S)$ is derived from the following equation:

$$P(S) = \frac{n(S)}{N} \quad (4.17)$$

where $n(S)$ is the number of occurrences of state S and N is the number of samples. Some advantages and disadvantages of the state sampling approach are:

Advantages:

1. **Simplification:** It simplifies the modeling process by representing component states with probability distributions, making it easier to incorporate uncertainties.
2. **Flexibility:** This approach allows for flexibility in modeling complex systems with multiple components and failure states.
3. **Independence:** Assuming independent component failures enables straightforward simulation of system behavior without complex dependencies.
4. **Versatility:** It can be applied to various systems and scenarios, offering a versatile tool for reliability analysis in different domains.

Disadvantages:

1. **Assumptions:** The approach relies on the assumption of independent component failures, which may not always hold true in real-world systems.
2. **Accuracy:** Depending on the accuracy of the probability distributions assigned to component states, the simulation results may deviate from actual system behavior.

3. Computational Complexity: Implementing the State Sampling Approach in Monte Carlo simulations can be computationally intensive, particularly for large-scale systems with numerous components.
4. Interpretation Challenges: Interpreting the results of Monte Carlo simulations based on the State Sampling Approach requires careful consideration of the underlying assumptions and uncertainties, which may pose challenges for practical application.

(b) State Duration Sampling method

In the Monte Carlo simulation, the State Duration Sampling Approach is used to sample the states of system components over time in order to model their behavior [146]. This approach uses failure and repair rates to sample each component's state over time in a probabilistic manner. Iteratively sampling the states of every component and advancing time based on the shortest sample duration are how the simulation moves forward. This methodology permits the evaluation of dependability and performance metrics across time, as well as the consideration of dynamic changes in system states. Figure 4-4 presents the flowchart detailing the implementation of this approach for calculating reliability indices. At first, the initial state of each component is determined. Subsequently, based on whether each component is in an up state (equal to 1) or a down state (equal to 0), the duration of each component's state is sampled using various distribution functions such as the exponential distribution. For example, the following equations illustrate the generation of the up (T_{iup}) and down (T_{idown}) duration states for each component i , using the exponential distribution function [147]:

$$T_{iup} = -\frac{1}{\lambda_i} \ln(U_{id}) \quad (4.18)$$

$$T_{idown} = -\frac{1}{\mu_i} \ln(U_{iq}) \quad (4.19)$$

where U_{id} and U_{iq} are uniform distribution function which produces a random number between 0 and 1 for each component i . The failure and repair rates of each component i are represented by λ_i and μ_i , respectively. This process is iterated until all states are filled within the given time span (T) and the specified number of samples (N). For instance, if hourly time resolution is considered over a 30-year period and set $N=300$, the length of the array for each component would be $30 \times 8760 \times 300 = 78,840,000$. In the subsequent step, once the state durations for each component are acquired, if the component functions as a generating source, this state matrix can be convolved with the generation profile of sources, resulting in the generation profile. For other components such as cables and transformers responsible for power transmission, the chronological system state transition process can be determined based on the series or parallel connection of these components, effectively combining the chronological states of the components. Ultimately, by comparing the system's availability capacity with the load profile, various reliability indices such as Loss of Load Expectation

(LOLE), Loss of Load Frequency (LOLF), Expected Energy Not Served (EENS), Loss of Energy Expectation (LOEE), and others can be derived.

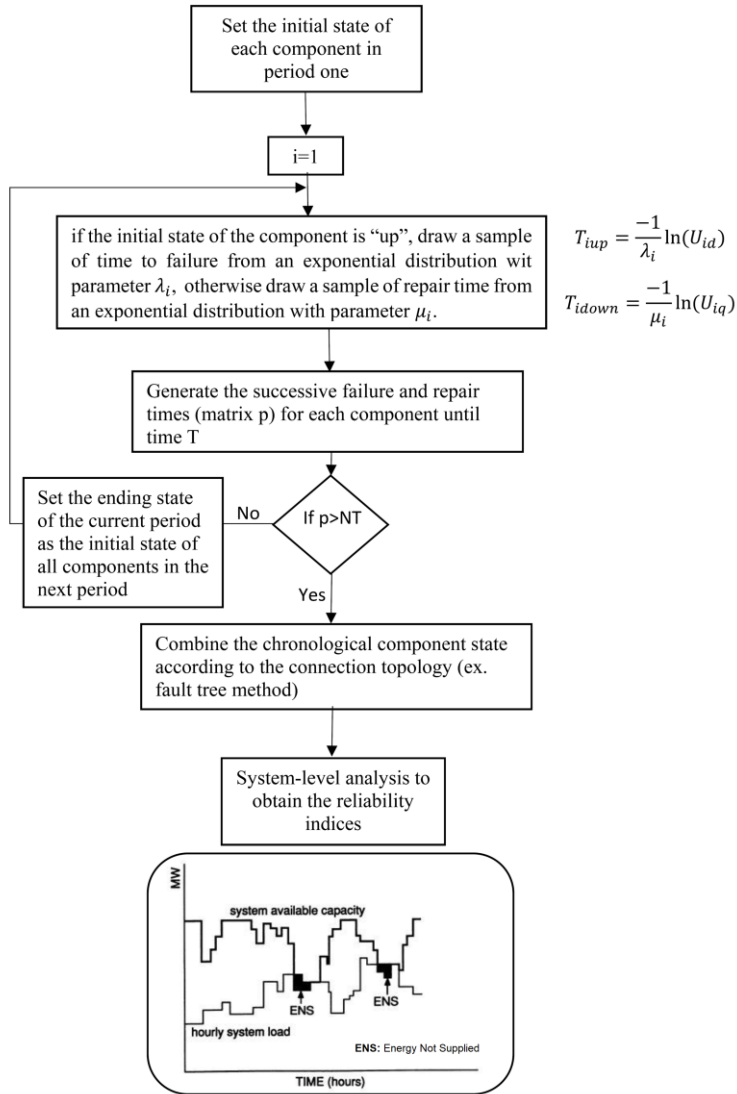


Figure 4-4. Flowchart illustrating the implementation of the state duration sampling method for power system analysis [142].

The state enumeration method has some advantages and disadvantages which are summarized here:

Advantages:

1. Flexible Time Resolution: This method can accommodate different time resolutions, ranging from seconds to hours or even daily, allowing for detailed analysis of system behavior.
2. Non-Constant Failure Rates: It is capable of handling non-constant failure rates, making it suitable for systems with varying reliability characteristics over time.
3. Scalability: The method is well-suited for large-scale systems with numerous components, as it can efficiently model and simulate complex system configurations.
4. Accuracy: By utilizing component state duration distribution functions, such as exponential distributions, the approach can provide accurate estimations of reliability indices by capturing the dynamic behavior of system components.

Disadvantages:

1. Computational Intensity: Implementing the State Duration Sampling Approach can be computationally intensive, especially for large-scale systems, due to the need to simulate numerous component states over extended time periods.
2. Complexity: The method may involve complex calculations and simulations, particularly when considering diverse component behaviors and interactions within the system.
3. Resource Intensive: It requires significant computational resources, including processing power and memory, to execute simulations effectively, potentially limiting its applicability for resource-constrained environments.
4. Sensitivity to Assumptions: The accuracy of results may be sensitive to the assumptions made regarding component failure distributions and system dynamics, requiring careful consideration and validation of input parameters.

(c) System State Transition Sampling

This method involves determining the chronological sequence of states for system components based on their respective state duration distributions. This method employs probability distributions to model the duration of each component's states, allowing for the generation of realistic system behavior over time. Mathematically, the process involves sampling from the state duration distribution functions for each component. Considering the state duration distribution function for component i as $f_i(t)$, where t is time, the sampling process generates random durations $t_1, t_2, \dots, t_N$ for each component [147], [148]. N is the number of samples. Following the transitions between component states, the chronological sequence of system states can be built once the state durations have been established. This includes taking into account each component's up and down states as well as their corresponding durations. A simple example for this method can be a two-state component (e.g., up/down). The transition from one state to another occurs based on the sampled durations and the current state of the component. If the current state is up and the sampled duration

corresponds to the up state, the component remains up for that duration before transitioning to the down state. This process is repeated for all components in the system until the desired time span is covered. The resulting sequence of system states represents a simulated scenario of the system's behavior over time, incorporating the dynamic interactions between components. By simulating multiple scenarios and aggregating the results, reliability indices such as LOLE, LOLF, and EENS can be calculated to assess the system's reliability under various conditions. This method is not applicable for non-exponential distributed components. In addition, it focuses on state transition of whole system rather than component states.

4.2.4. Markov Chain method

The Markov chain method is a probabilistic modeling approach that models changes in system states and is used to assess system reliability. It is assumed that the current state alone, rather than the chain of events leading up to it, determines the probability of transitioning to a future state. Systems with discrete states and Markovian properties, where transition probabilities between states allow for an accurate representation of the system dynamics, benefit greatly from this approach. This method is suitable for a small to medium systems. Because the Markov method is based on a state-space diagram, which offers a graphical means of illustrating different states and the transitions among them, it is also known as the state-space approach. Figure 4-5 shows the state space diagram using the Markov model for a power system consisting of four power generations. According to this method, if the system has N generating units, the number of possible states will be 2^N , showing the Markov chain impractical for systems with a large number of generating units.

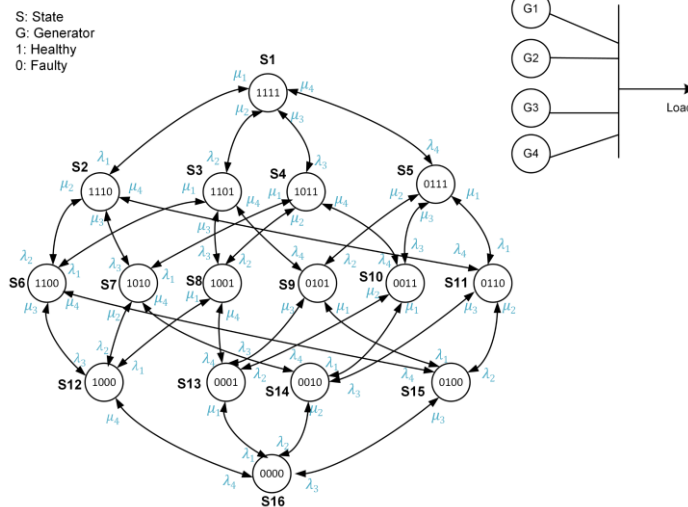


Figure 4-5. Markov model for four power generation units to assess the power system reliability.

Additionally, the Markov chain method calculates the probability of each state, and the outcomes of these states must be evaluated using power flow techniques. After constructing the state space diagram for each system, similar to Figure 4-5, the failure rate (λ_i) and repair rates (μ_i) can be expressed as a set of differential equations. Subsequently, the probability distribution for each state can be determined by solving these differential equations along with the initial conditions. Figure 4-6 illustrates the typical states and their transitions between them.

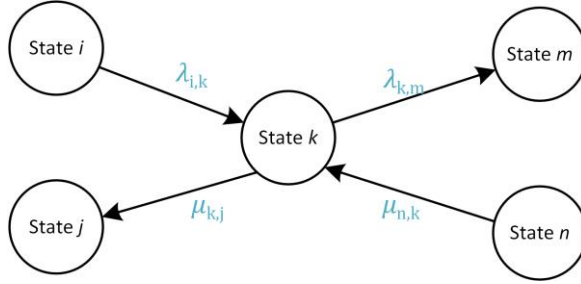


Figure 4-6. A typical state used for Markov equations.

Accordingly, the differential equation for the probability in state k can be written as [149]:

$$\frac{dP_k}{dt} = \sum_i \lambda_{i,k} P_i + \sum_n \mu_{n,k} P_n - \left(\sum_j \mu_{k,j} + \sum_n \lambda_{k,n} \right) \times P_k \quad (4.20)$$

4.2.5. Semi-Markov method

The semi-Markov chain method extends the Markov chain approach to handle systems with non-Markovian properties and non-exponential distributions. It allows for more flexibility in modeling complex system behaviors by relaxing the assumption of memory lessness and incorporating various types of state transitions [150]. This method is suitable for systems where the time spent in each state follows non-exponential distributions and requires modeling continuous or discrete states with varying transition probabilities. The transition probabilities between various states in the Semi-Markov method rely on both the current state and the amount of time spent in it. This is how the Semi-Markov method is expressed:

$$P_{ij}(t) = \lim_{\Delta t \rightarrow 0} \frac{P(X(t + \Delta t) = j | X(t) = i)}{\Delta t} \quad (4.21)$$

where $X(t)$ represents the state of the system at time t , $P_{ij}(t)$ is the probability that the system transitions from state i to state j in time t .

The probability of remaining in the same state i for time t , denoted by $P_{ii}(t)$, can be expressed as:

$$P_{ii}(t) = P(X(t) = i | X(0) = i) \quad (4.22)$$

The probability distribution function for the time spent in state i before transitioning to another state is denoted by $f_i(t)$. It represents the probability that the system remains in state i for exactly t units of time before transitioning to another state. With these definitions, the transition probabilities $P_{ij}(t)$ can be written as:

$$P_{ij}(t) = P_{ii}(t) \times f_i(t) \times p_{ij} \quad (4.23)$$

Where p_{ij} is the probability of transitioning from state i to state j without considering time. This formulation enables a more realistic evaluation of performance and reliability by capturing the time-dependent behavior of the system. Table 4-2 provides a comprehensive comparison of different risk assessment models commonly used in power system reliability analysis.

Table 4-2. Comparison of risk assessment models for power system analysis.

Method	Applicability	Scale	Methodology	Advantage	Disadvantage
Monte Carlo Simulation	Wear-out and constant failures	Large and small-scale systems	Random sampling for scenario simulation	Flexible for complex systems	Computationally intensive
State Enumeration Method	Effective for constant failures	Small to medium-scale systems	Exhaustive enumeration of system states	Accurate for simple systems	Infeasible for large systems
Markov Chain Method	Wear-out and constant failures	Small to medium-scale systems	Probabilistic modeling of state transitions	Simple and efficient analysis	Limited to Markovian systems
Semi-Markov Chain	Wear-out failures; non-Markovian systems	Medium-scale systems	Extends Markov models for non-exponential distributions	Flexibility in modeling complex behaviors	Requires sophisticated analysis
COPT	Capacity-related failures	Large-scale systems	Focuses on capacity shortage probabilities	Tailored for capacity-related risk assessment	Limited capture of failure modes

In this PhD project, the risk assessment model will primarily utilize the Monte Carlo Simulation and State Duration Sampling methods due to their enhanced accuracy, applicability to large-scale systems, and compatibility in analyzing risk across different time scales, ranging from seconds to hours. By integrating stability issues into the proposed model, both short-term and long-term dynamics can be effectively captured and translated within the Monte Carlo framework. This approach enables a comprehensive evaluation of system reliability and risk under various operating conditions, contributing to a robust assessment of power system performance and resilience.

4.3. Proposed stability-Oriented Risk Assessment Methodology

In the previous chapter, the effects of stability problems and resulting dynamic failures were examined, and it was shown how certain dynamic failures could result in a loss of load. These problems have the potential to raise the risk in real power grids and push risk indices above their desired levels. This diversity results from dynamic failures, in which power system operators are forced to disconnect loads or power generators in order to maintain a stable and dependable system operation due to both short- and long-term constraints. The overall system risk is significantly affected by these dynamic failures. Additionally, the traditional approaches were discussed and used in risk assessment in the section 4.2, explaining how to determine the availability states of components and calculate the corresponding reliability indices. These techniques demonstrate how failures of equipment in power systems cause energy loss and consequent demand-side load shedding. These risk assessment techniques, are useful in assessing these static failures. Therefore, it is crucial to take into account the implications of both dynamic and static characteristics at the same time, especially in power electronic-based power systems, which are more vulnerable than traditional power systems. These risk models highlight the necessity of taking preventative action during the system's design and operation phases. To effectively mitigate risks and strengthen system resilience, it is imperative to acknowledge these complexities.

In order to measure the static and dynamic risk indices, this PhD project proposes a new multi-domain design method that incorporates the traditional reliability assessment model and various stability challenges. It then suggests the most effective techniques to plan and design microgrids in a way that minimizes the system risk. Figure 4-7 provides a visual representation of the proposed approach, which integrates both reliability and stability considerations in the assessment of microgrids. The method consists of two main components: a conventional risk assessment model, primarily addressing static performance evaluation, and a stability issues model, which incorporates dynamic performance.

4.3.1. Conventional Method

The availability and probability states of components, which are established based on either constant or non-constant failure rates, form the core of the traditional risk assessment model. These states can be produced using a variety of techniques, including State Enumeration, Monte Carlo simulations, and Markov chain analysis, as described in the previous section. Because Monte Carlo simulation can produce component availability states at different time resolutions, from seconds to hours, it has been selected for this PhD project. This method makes it easier to include stability concerns in the risk assessment process, both in the short and long term.

The next stage involves convolving the generated availability states with the power mission profiles to determine the power generation profile of the generating units (such as PV, wind, and fuel cells). These mission profiles may fluctuate around a constant value, or they may show significant fluctuations, as observed in PV and wind turbine units. As a result, time series power flow analysis and calculation of risk indices for the HMG are made possible by the units' generated generation profiles.

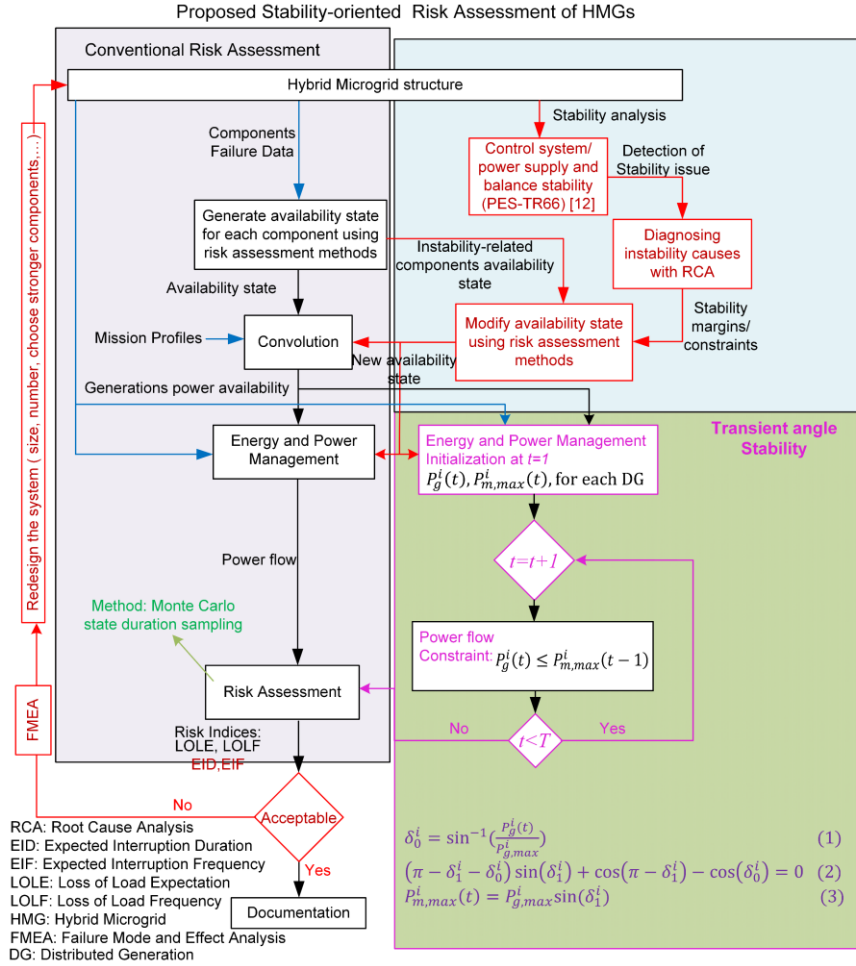


Figure 4-7. Proposed multi-domain risk assessment model incorporating the stability issues within hybrid microgrids (HMGs) [J1-J2].

The system architecture, source types, and control mechanisms are some of the factors that affect how energy and power management strategies are designed and implemented. The power and energy management strategy used in this project are described as the following:

In order to guarantee optimal power generation, non-dispatchable sources like wind and photovoltaic (PV) generators (if exist) use Maximum Power Point Tracking (MPPT) control and run at their nominal power levels. When there are uncertainties or power outages, dispatchable sources take over and supply the loads. Within the hybrid microgrid, each subgrid is responsible for providing power to its assigned load. If there is a power shortage, the necessary energy is transferred via the interlinking converter. These operational constraints are integrated into the load flow and control

strategies of the hybrid microgrid. The results of the power and energy management strategies determine the amount of load losses by comparing the generation profile with the load profiles.

Finally, as depicted in Figure 4-7, based on load losses, the system's overall risk will be calculated. The frequency, duration, and quantity of unsupplied loads can be assessed using a variety of risk indices [26], [134]. Numerous risk indices are provided by the risk assessment methods; for this project, two significant indices are used: Loss of Load Expectation (LOLE) and Loss of Load Frequency (LOLF), are selected as the risk indices in relation to the size of the HMG. The mathematical representations of these indices are provided as given below [26], [151]:

$$LOLE = \sum_t P_t \times T_t \quad (4.24)$$

$$LOLF = \sum_t P_t \quad (4.25)$$

Where P_t is the probability of occurrence of a particular outage scenario in a given time period and T_t is the duration of the outage associated with the scenario t .

Using the State Duration Sampling Method as one of the Monte Carlo simulation approaches, the LOLE and LOLF can be estimated as [21], [142]:

$$LOLE = \frac{1}{N} \cdot \sum_{i=1}^N LLD_i \quad (4.26)$$

$$LOLF = \frac{1}{N} \cdot \sum_{i=1}^N LLO_i \quad (4.27)$$

Where N represents the number of sampling years, LLD_i represents the duration of load loss, and LLO_i is the loss of load occurrence. The superimposed margin model provides a direct means of obtaining LLD_i and LLO_i .

4.3.2. Proposed Analysis Method

The proposed multi-domain model can be explored through two distinct parts: the new risk assessment model and the risk-based redesigning of the microgrid during the planning and operational phases. The subsequent sections will provide detailed explanations of both parts.

4.3.2.1. New Risk assessment model

The influence of dynamic failures has either been disregarded or not directly addressed in any of these models; instead, they only take into account the system's static failures. As a result, as shown in Figure 4-7, the proposed model integrates a variety of stability issues into the risk assessment framework. A technical report PES-TR66 [12] offers guidelines on how to incorporate different stability issues in HMGs.

Following the identification of the HMG's stability problems, Root Cause Analysis (RCA) methods including eigenvalue analysis, root locus analysis, and time-domain simulations can be used to determine the causes of instability. Thus, multiple stability constraints and margins are derived for each stability issue.

The relevant components affected by the identified instability issue have their availability status changed in the ensuing phase. This is accomplished by merging the availability state generator models with the stability margins/constraints. As it was mentioned, in the previous chapter, system risk is increased because the interlinking converter's DC-link voltage places a stability constraint on its operation when it is in the rectifying mode.

As a result, the IC availability state, and the IC stability margin (S_m) are integrated. The IC availability state's margins change from $[-P_n, P_n]$ kVA to $[-P_n \times S_m, P_n]$ kVA as a result, in which P_n is the nominal power of the IC. This suggests that when in rectifying mode, the IC's transferring power should not exceed $P_n \times S_m$ kVA in order to ensure the IC operates steadily. After making modifications to the component availability states, the power unit's convolution and/or conventional energy management strategy can make use of the updated availability states. New risk indices covering both the dynamic and static failures of the HMG are then produced. This part has been highlighted with the light blue frame in Figure 4-7. Since this method is general, various stability issues exhibiting similar characteristics and behaviors can be examined and assessed within this framework.

Furthermore, the methodology for handling stability problems resulting from transient intervals, sudden changes in load, or the loss of generating units that could cause the system to become unstable is suggested in Figure 4-7 with light green frame. This method incorporates real-time simulation results into the risk assessment model and can handle a range of time resolutions, from seconds to hours. Transient voltage angle stability has been identified as a major concern in HMGs and the mathematical modeling and time domain simulations results was conducted in detailed in the previous chapter. As illustrated in Figure 4-7, the model uses detailed equations to determine the maximum allowable input power changes for each generating unit in the ac subgrid for each time interval. This computed value establishes a limit for the ensuing time frame. It may be necessary to increase the power of other units beyond their permitted input power limit in the event of abrupt changes in the load or generating unit failures. In these situations, extra power from the dc subgrid or other ac side sources helps to meet the load demand without going over the maximum power of the ac sources. To keep the HMG operating steadily, some of loads may need to be curtailed if surpassing the power limit of the ac sources is about to happen.

By incorporating dynamic failures into the risk assessment model, the proposed model introduces two novel metrics as follows:

- (1) Expected Interruption Duration (EID)
- (2) Expected Interruption Frequency (EIF)

The mathematical representation of these two indices will be as follows:

$$\begin{aligned}
EID &= LOLE + (\text{dynamic performance}) \quad \text{hr/year} \\
&= \frac{1}{N} \cdot \sum_{i=1}^N LLD_i + \frac{1}{N} \cdot \sum_{j=1}^k \sum_{i=1}^N ULD_i^j
\end{aligned} \tag{4.28}$$

$$\begin{aligned}
EIF &= LOLF + (\text{dynamic performance}) \quad \text{occ/year} \\
&= \frac{1}{N} \cdot \sum_{i=1}^N LLO_i + \frac{1}{N} \cdot \sum_{j=1}^k \sum_{i=1}^N ULO_i^j
\end{aligned} \tag{4.29}$$

Where k represents the number of distinct stability issues, while ULD and ULO denote the unsupplied load duration and occurrence, respectively. The EIF and EID indices encompass both static and dynamic performance aspects within the system. Consequently, the difference between the EID-LOLE and EIF-LOLF indices will determine how stability issues influence the overall risk in the system.

4.3.2.2. Redesigning the system based on risk analysis

When interconnected stability issues cause the risk indices to surpass acceptable thresholds, thereby requiring system redesign, a comprehensive methodology that incorporates both static and dynamic failure considerations is necessary. Several scenarios can be investigated based on the measured risk values after the risk within the Hybrid Microgrid (HMG) has been evaluated, taking into consideration both dynamic and static failures:

Scenario 1: If the overall system risk, considering dynamic performance, remains within acceptable thresholds, there may be no need for system redesign. This scenario implies that the current system configuration and operational strategies adequately manage the risk levels.

Scenario 2: In specific system setups and operational conditions, detecting and strengthening the critical component with more reliable components (component-level evaluation), especially those identified as contributing most to the overall risk, could be sufficient if the risk indices exceed acceptable thresholds. This procedure is efficient in both design and operation phase.

Scenario 3: This scenario suggests addressing dynamic failure influences by redesigning components, possibly changing their size or quantity to effectively mitigate overall risk. Here, the focus is on modifying elements directly impacting dynamic performance to enhance system stability.

Scenario 4: Offers an opportunity to reconsider the selection and integration of energy sources within the ac and dc subgrids. This involves optimizing the mix of energy sources to create a more sustainable grid structure, both during initial design and

subsequent operational phases. By strategically choosing energy sources, the system can better withstand potential failures and fluctuations.

In order to reduce the overall risk, possible system redesigns can therefore be investigated based on the results of the risk assessment and benchmarking against predetermined thresholds. These redesign approaches can be applied at different hierarchical levels and follow the Model-Based System Engineering (MBSE) principles [152], [153]. For example, in some cases, using stronger parts—like the capacitors and switches in power converters—that have longer lifespans could help reduce risk and bring it back to reasonable levels. This strategy is classified as a component-level intervention. On the other hand, in order to solve more widespread stability issues and enhance overall performance, solutions might need to be developed at the converter and system levels for more complicated systems and circumstances.

This redesign process starts with a sensitivity analysis to determine the critical converters that have the biggest impact on both dynamic and static risks. Then, more durable replacements are used for the components of such converter. Reconfiguring the size and quantity of critical equipment, like the interlinking converter, is a secondary solution in case that the risk assessment shows continuously elevated risk levels. Due to its direct influence on dynamic performance, this method enables the best possible selection and sizing of system components.

It also produces insightful data and metrics for different energy sources, making it easier to compare them with financial factors like the Levelized Cost of Energy (LCOE) metric [154], [155] that is employed during the microgrid design stage. Additionally, carefully choosing renewable energy sources can help to reduce elevated risks. The suggested methodology helps to choose the best energy sources for each unique project while taking dynamic failures into consideration by providing a methodical way to evaluate and examine various design scenarios. In the upcoming chapter, these redesign solutions will be explored further, accompanied by examples across various scenarios to illustrate their effectiveness.

This chapter, at first, explored traditional risk assessment techniques like state enumeration, Markov chain analysis, and Monte Carlo simulation and discussed their applications and limitations. A suggested multi-domain model was then presented, providing a thorough framework that takes into account the issues of stability and dynamic failure in hybrid microgrids. This model provides a comprehensive approach to risk assessment by combining stability and reliability assessments, allowing for proactive actions during the design and operation phases of HMGs.

In the design phase, the model facilitates the identification of potential risks associated with dynamic failures, allowing for the selection of appropriate components and energy sources to mitigate these risks. Additionally, the model's flexibility allows for the investigation of multiple redesign scenarios, guaranteeing that HMGs are prepared to successfully manage both static and dynamic challenges. Through this chapter, it becomes evident that the proposed multi-domain model serves as a valuable tool for enhancing the stability and reliability of HMGs in the face of evolving operational dynamics and uncertainties.

Chapter 5. Application of the Proposed Framework in Risk-Based Microgrid Design

5.1. Introduction

The importance of risk assessment, particularly in addressing both static and dynamic failures within design models of microgrids, was previously emphasized. In addition, in the previous chapter, a multi-domain design guideline was introduced to provide a comprehensive approach to microgrid design. This chapter explores the application of the proposed framework in risk-based microgrid design. This study will illustrate the importance of risk assessment in power electronic-based power plants by examining the dependability of a real wind farm. Then, utilizing the multi-domain design guideline and incorporating dynamic performance considerations, the impact of stability issues on HMG risk is investigated. Time-domain simulations and root cause analysis conducted in Chapter 3 revealed instances where stability issues such as interlinking converter DC-link voltage stability, transient angle stability, and frequency stability influence the overall HMG risk.

Following the exploration of static and dynamic failures impact, the chapter proceeds to propose potential solutions applicable in the microgrid design phase. The introduced risk-based design guideline is utilized to redesign the HMG with the aim of reducing the overall system risk. Solutions include redesigning the dominant converter through sensitivity analysis at the component level, reconfiguring interlinking converters in terms of quantity and size, and optimizing renewable energy sources. Through detailed investigations, the effectiveness of these proposed methodologies in mitigating risks and ensuring robust system performance across diverse operational scenarios for HMGs will be demonstrated.

5.2. Risk in Large Scale Power Plants: Practical Example

The first example is evaluation of the system-level reliability assessment for an onshore wind power plant under construction in Zaragoza, Spain, where the wind farm showcases a total capacity of 150 MW. It consists of 38 wind turbines, each with a capacity of 3.83 MW, intricately connected through feeders to a 30 kV medium voltage (MV) substation. Additionally, the power generated is transferred to the 220 kV national grid via a singular 150 MW power transformer. The schematic diagram of the wind power plant is depicted in Figure 5-1. To maintain a general overview, specific details such as the connection between WTGs in each feeder, cable sizes and lengths, protections, characteristics of circuit breakers, and disconnecter switches have not been included in the Single Line Diagram (SLD).

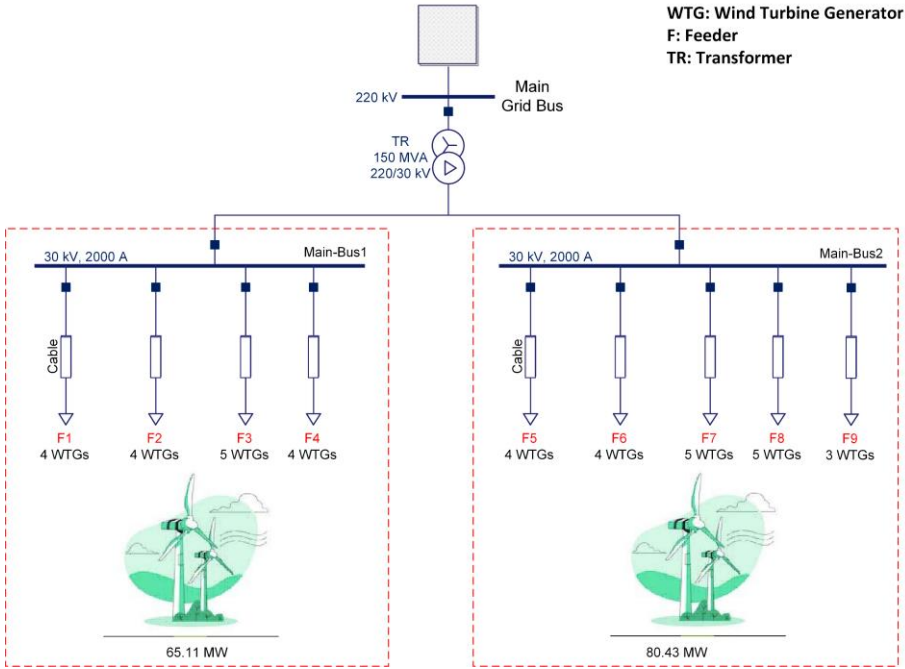


Figure 5-1. Single Line Diagram of Power Plant under study (150 MW Wind Farm).

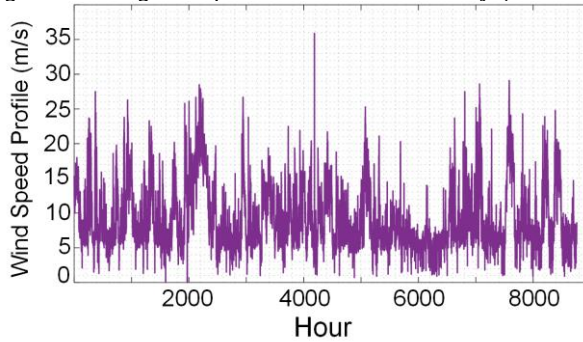


Figure 5-2. Wind Speed profile in hour resolution for one of the WTGs in Zaragoza.

Considering the wind speed profile depicted in Figure 5-2 and employing the Monte Carlo state duration sampling method (see Section 4.2.3), the reliability analysis was conducted to evaluate the 30-year lifespan of the entire wind power plant. In this study, three reliability indices—namely, full-time availability (A_{tf}), time availability (A_t), and production availability (A_p)—have been assessed. The definition of each index is as follows:

$$A_t = \frac{\text{Number of hours generating energy (hr)}}{\text{Total Time in consideration (hr)}} \quad (5.1)$$

$$A_{tf} = \frac{\text{Number of hours which all units are up (hr)}}{\text{Total Time in consideration (hr)}} \quad (5.2)$$

$$A_p = \frac{\text{Expected Output Energy (EOE) (KWh)}}{\text{Ideal Output Energy (IOE) (KWh)}} \quad (5.3)$$

The full-time availability variation for all buses over the 30-year lifespan is depicted in Figure 5-3. Initially, the full-time availability for all buses ranged between 98-100%. However, this availability gradually decreases over the years due to component wear-out. Specifically, for main Buses 1 and 2, the availability decreases to 75% and 70%, respectively, while for the grid main Bus at the point of interconnection to the grid, it drops to 52%. These reductions in availability highlight the impact of component degradation over time, illustrating the diminishing reliability of the power plant.

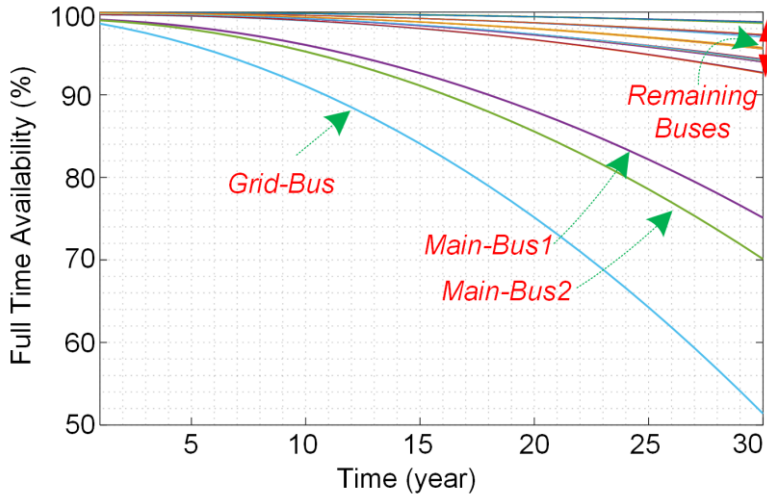


Figure 5-3 Full time availability for different buses for 30 years lifetime.

Furthermore, time availability represents the percentage of time during which the wind farm is capable of generating power. Figure 5-4 depicts the time availability for all buses over the 30-year period. Notably, at the grid bus, the time availability is approximately 97.96%, indicating that the power plant is offline for 178 hours. In other words, Figure 5-4 illustrates the total number of hours during which the power plant is unavailable across different buses. Figure 5-5 provides a visualization of the cumulative unavailable hours of the power plant over its 30-year lifespan. Initially, the unavailable hours are about 130 hours, but by the end of the lifespan, this figure increases to 180 hours. This trend highlights the gradual deterioration in reliability over time, emphasizing the importance of proactive maintenance and reliability improvement measures to mitigate downtime and optimize power generation efficiency.

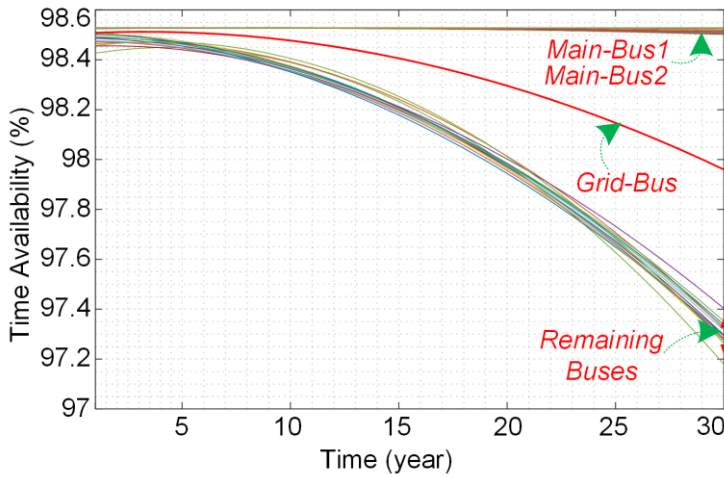


Figure 5-4 Time availability for different buses for 30 years lifetime.

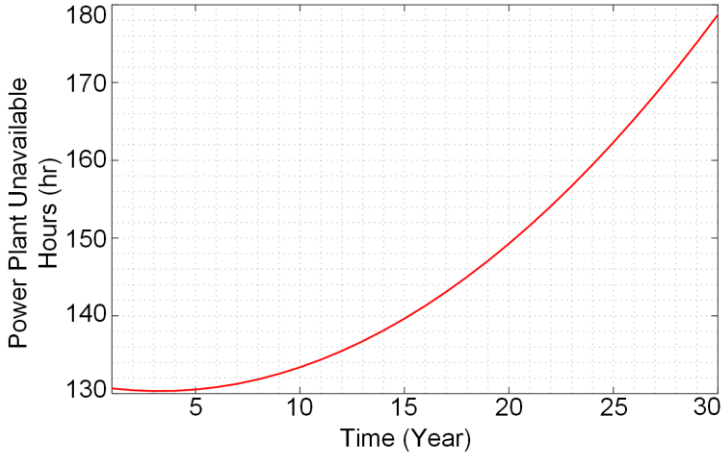


Figure 5-5 Power Plant Unavailable hours for 30 years lifespan (Grid-Bus).

Finally, production availability addresses the loss of energy in the power plant resulting from failures in its components. Figure 5-6 illustrates the production availability for all buses in $t=30$ year. For example, the production availability is calculated as 96.78% for the grid bus. This indicates that approximately 19.7 GWh of energy will be lost in the system due to failures, representing around 3.22% of the total produced energy. Understanding production availability is crucial for assessing the overall performance and efficiency of the power plant, as it quantifies the impact of failures on energy production. By identifying and mitigating the root causes of failures, operators can minimize energy losses and optimize the reliability and profitability of the wind farm.

The Ideal Output Energy (IOE), Expected Output Energy (EOE), and Energy Not Supplied (ENS) are depicted in Figure 5-7 and Figure 5-8, respectively. These figures

illustrate that the actual output energy deviates significantly from the ideal output energy and declines over time due to the aging of components. The Ideal Output

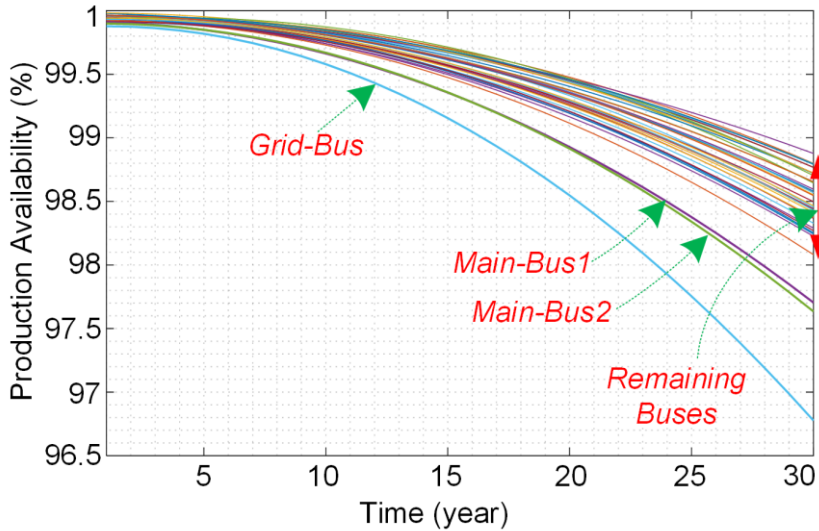


Figure 5-6 Production availability for different buses for 30 years lifetime.

Energy represents the theoretical energy production that would occur in the absence of any failures or disruptions in the wind turbine system. Conversely, the Expected Output Energy accounts for the impact of failures and component aging, providing a more realistic estimate of energy production under real-world conditions. The disparity between IOE and EOE underscores the importance of considering reliability factors when assessing energy generation capabilities.

Furthermore, the Energy Not Supplied (ENS) quantifies the amount of energy lost due to failures and downtime in the system. This metric highlights the economic and operational implications of the reliability issues, emphasizing the need for proactive maintenance and reliability improvement measures to minimize energy losses and optimize the overall system performance.

By analyzing these figures, stakeholders can gain valuable insights into the reliability and efficiency of the wind turbine system, enabling informed decision-making and targeted interventions to enhance the system reliability, minimizing downtime, and maximize energy production over the lifespan of the plant.

The estimated power losses due to thermal losses in the components like cables and power transformers, is around 2-3%. In addition, the loss of energy due to failures reaches to same percentages. Therefore, more accurate economic analysis will be possible by incorporating the impact of reliability into the system. Moreover, the preventive and corrective maintenance schedules can be performed based on the reliability analysis to avoid entering to wear-out phase before desired useful lifetime.

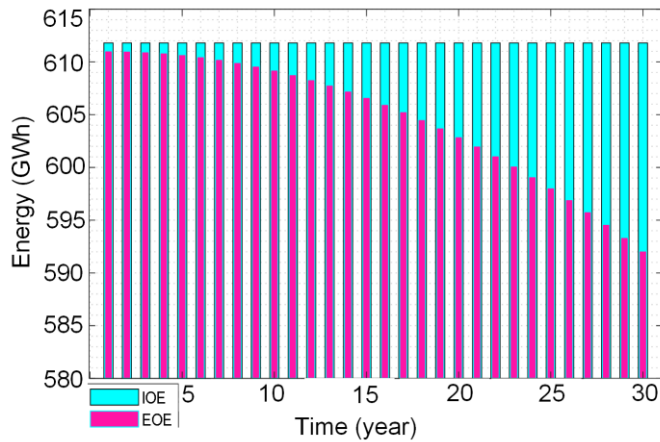


Figure 5-7 IOE and EOE in the Grid-Bus for 30 years lifespan for the power plant in Figure 5-1.

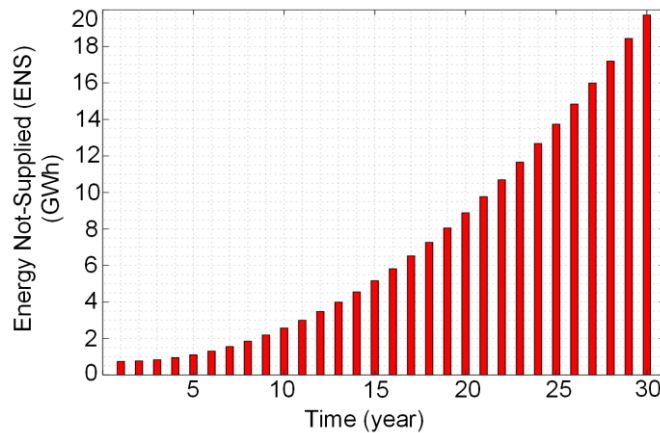


Figure 5-8 Energy Not Supplied in the Grid-Bus for 30 years lifespan for the power plant in Figure 5-1.

In conclusion, the reliability assessment conducted for the onshore wind farm has provided valuable insights into the performance, efficiency, and resilience of the power plant over its 30-year lifespan. Through comprehensive analysis of reliability indices such as full-time availability, time availability, and production availability, key findings have emerged regarding the impact of component failures, aging, and environmental factors on energy generation capabilities.

The study revealed a gradual decline in reliability over time, as evidenced by reductions in full-time availability and increases in downtime and energy losses due to component wear and aging.

Furthermore, the discrepancy between Ideal Output Energy (IOE) and Expected Output Energy (EOE) highlights the need for realistic assessment of energy generation

capabilities considering reliability factors. The Energy Not Supplied (ENS) metric quantifies the economic and operational implications of reliability issues, emphasizing the importance of minimizing downtime and energy losses to maximize the profitability and sustainability of the wind farm.

5.3. Risk Analysis Integrating Dynamic Stability

In the section 5.2, the significance of integrating risk considerations into the design of power electronic-based power systems was highlighted. The findings showed how static failures lead to energy loss and escalate the risk within the system. This section, in addition to incorporating static failures, will explore the impacts of dynamic failures stemming from stability issues. The test system for this study is the HMG introduced in Chapter 3. Two 10 kW and 15 kW Micro Turbines (MT) in the ac subgrid are linked to VSG1 and VSG2, respectively. There is no power exchange between the AC subgrid and the grid. A 10 kW Fuel Cell (FC) and a 10 kW PV system are integrated on the dc side. A 10 kVA Interlinking converter (IC) facilitates the connection between the dc and ac sides. Each subgrid supplies its loads independently in accordance with the requirements of power management, and power transfer through the IC only occurs when there is a power outage.

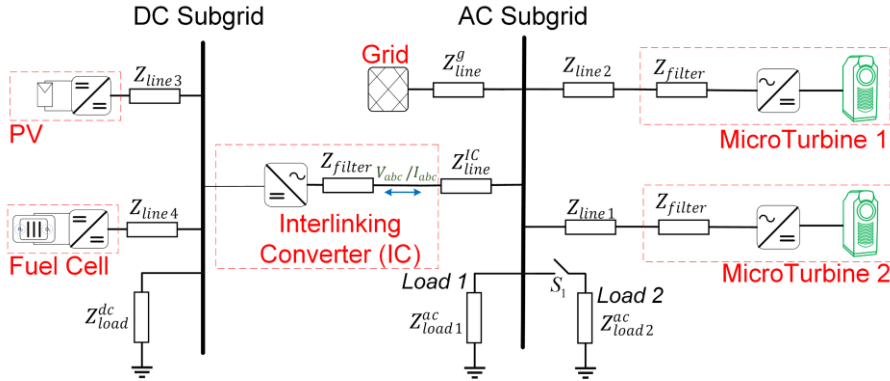


Figure 5-9 Single-line representation of a hybrid microgrid configuration including PV and Fuel Cell in dc side, two Microturbines in ac side and one Interlinking converter to connect dc and ac subgrid.

The cumulative load profiles for the dc and ac subgrids are depicted in Figure 5-10. Utilizing the Monte Carlo state duration sampling method allows for the utilization of various time resolutions in the risk assessment, with a minute-based resolution chosen for this study. This resolution is also suitable for conducting stability analysis. The failure data used for the power converters in the HMG is depicted in Table 5-1.

Table 5-1. Constant and non-constant failure rates, repair times of converters [J1].

Definition	Constant Failure rate	Repair rate	Weibull distribution factors	
	λ (10^{-5} f/hr)	μ (r/hr)	α (yr)	β
IC	4.55	0.007	20	3.8
PV	3.41	0.01	22	4
Micro Turbines 1 and 2	2.98	0.0125	22	3.5
Fuel Cell	4.85	0.0083	19	3.42

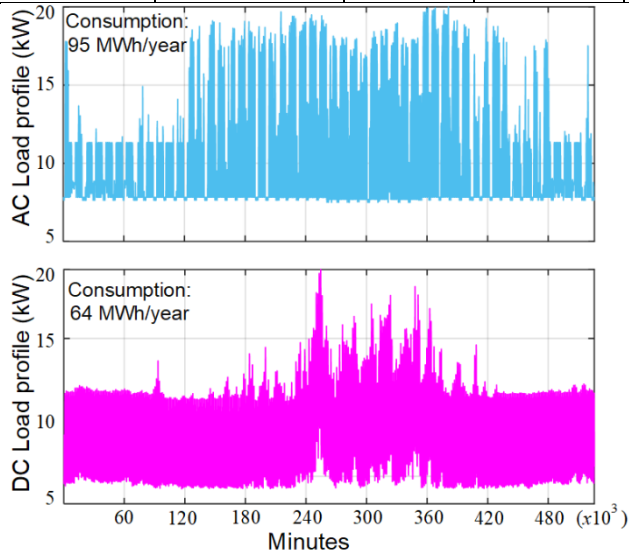


Figure 5-10. AC and DC subgrids load profile with minute resolution.

The total dc and ac loads consumption are 64 MWh/year and 95 MWh/year, respectively as shown in Figure 5-10. In addition, the PV annual irradiance profile is as shown in Figure 5-11.

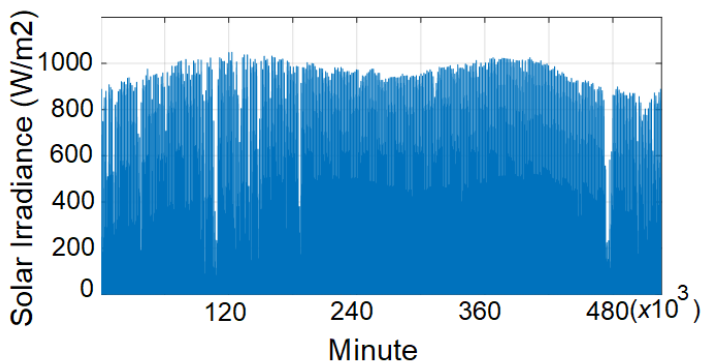


Figure 5-11. Solar Irradiance mission profile for PV with minutes time resolution.

Table 5-2 summarizes all the case studies that will be employed in this chapter for the risk assessment of the hybrid microgrid (HMG) using the proposed model from Chapter 4.

Table 5-2. An overview of all case studies for risk assessment of HMG in Figure 5-9.

Case Number	Type of Study
1	Interlinking Converter (IC) DC-link voltage impact on HMG risk
2	Impact of different load profiles on risk assessment
3	Impact of different solar irradiances profiles on risk assessment
4	Impact of transient angle stability (TAS) on HMG risk
5	Evaluating HMG risk with concurrent analysis of TAS and IC stability
6	Impact of Converters wear-out failure on risk of HMG
7	Frequency stability impact on HMG risk

5.3.1. Interlinking Converter (IC) DC-link Voltage Stability Impact on HMG Risk

In Chapter 3, through time domain simulations and root cause analysis, it was revealed that the interlinking converter's DC-link voltage can become unstable when operating close to its nominal power rating in rectifying mode. To ensure stable microgrid operation, a stability margin (S_m) was defined for the interlinking converter. For the tested HMG, the stability margin (S_m) was determined to be 0.93, indicating that the transferred power of the 10 kVA interlinking converter is limited to 9.3 kVA during rectifying mode operation. Utilizing this stability margin value of 0.93, the proposed risk assessment method outlined in Chapter 4 was applied to derive system-level risk indices for both subgrids and the overall HMG. The results, depicted in Figure 5-12, are based on the constant failure rates specified in Table 5-1, the load profiles shown in Figure 5-10, and solar irradiance data from Figure 5-11.

In Figure 5-12 (a), it is evident that the EID and LOLE reliability indices display significant disparities within the dc subgrid. This contrast primarily arises from the criteria regarding the IC stability margin. Specifically, the EID demonstrates a notable 32% increase when compared to LOLE. Additionally, the EIF exhibits a substantial 67% deviation from LOLF as illustrated in Figure 5-12 (b). Conversely, within the ac subgrid, these distinctions are marginal, amounting to only 6% for EID and LOLE, and 4% for EIF and LOLF. This small variation is explained by the IC stability margin criterion's dominance over the dc subgrid. In other words, the stability criteria of IC restrict the flow of power in rectifying mode from ac to dc subgrid during the power shortage.

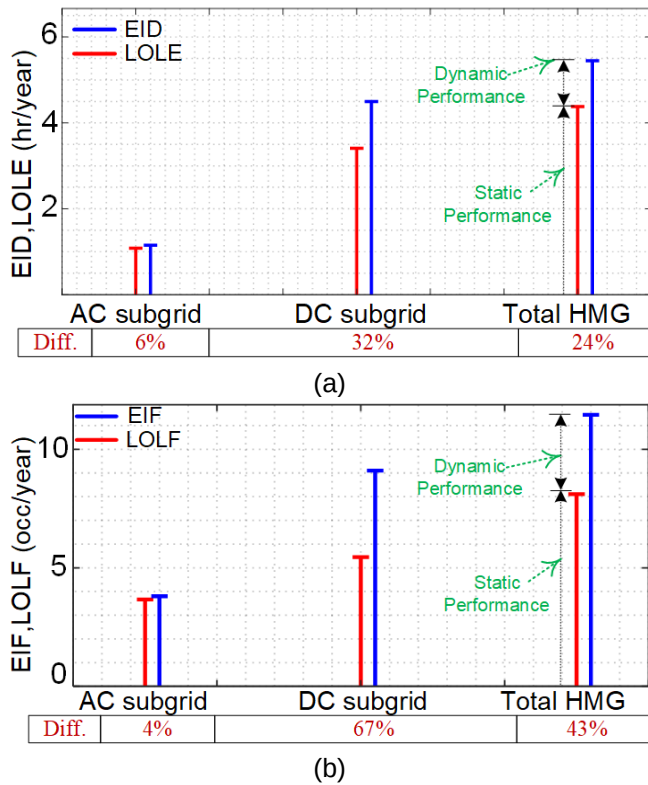


Figure 5-12. Subgrids and overall HMG System-level risk indices considering the impact of IC DC-link voltage stability. (a) EID and LOLE, (b) EIF and LOLF [J1].

Considering the comprehensive perspective of the entire HMG, these differences become more important. In particular, there is a notable 24% difference between EID and LOLE, and a substantial 43% difference between EIF and LOLF. These findings underscore the significant impact of dynamic failures arising from stability concerns across the whole microgrid system.

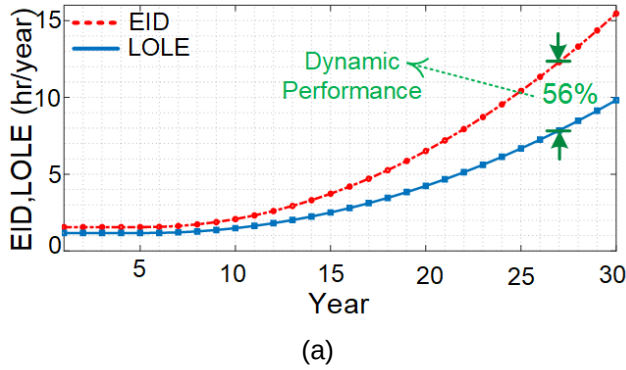
The previous results, as shown in Figure 5-12 were assumed constant failure rates for the power converters. However, it is important to note that in the real-world scenario, the failure rate of electrical equipment, including power converters, will increase over time. This increment can be attributed to various factors such as prolonged usage, environmental conditions, manufacturing defects, and inadequate maintenance practices. Consequently, the failure rates of power converters are expected to conform to the "bathtub curve" paradigm, as described in Chapter 2. This curve depicts the pattern of failure rates over the lifespan of a system, with an initial period of high failure rates (infant mortality), followed by a period of relatively low and constant failure rates, and finally, a phase of increasing failure rates (wear-out). The transition from constant failure rates to non-constant ones significantly impacts the overall risk profile of the system.

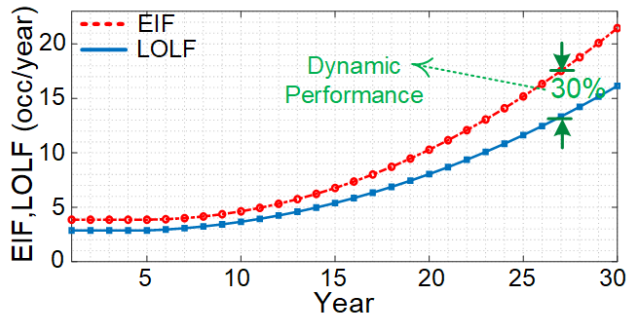
The failure rate ($\lambda(t)$) is represented using the Weibull distribution, as shown in equation (5.4). The relevant parameters defining the shape factor (α) and scale factor (β) are given in Table 5-1. This distribution is utilized to assess how the aging of converters is altering the risk landscape of the HMG.

$$\lambda(t) = \frac{\beta}{\alpha^\beta} \cdot t^{(\beta-1)} \quad (5.4)$$

Figure 5-13 shows the corresponding reliability indices for the full HMG over a 30-year period. Reliability indices show an observable increment as converter failure rates rise. Metrics rise noticeably over time when the IC DC-link voltage stability issue is included. The wear-out of converters leads to a significant increase in risk indices, highlighting that the system will be more vulnerable compared to a scenario where the failure rates are constant. As depicted in Figure 5-13 (a), the LOLE in the first year was 1.17 hr/year, increasing to 9.8 hr/year by the 30th year. Additionally, addressing stability issues and subsequently incorporating the impact of dynamic failures worsened this situation, starting from 1.55 hr/year and reaching 15.46 hr/year at the end of the lifespan.

Moreover, the risk assessments in Figure 5-13 (a) show that there is a 32% difference between LOLE and EID in the first year, and by the 27th year, the difference rises to 56%. With a 30% difference in the 27th year, this trend is reflected in both LOLF and EIF, as depicted in Figure 5-13 (b). These results reveal how the aging converters affect the dynamic risk. The EID to LOLE ratio shows a faster rise, suggesting a strong correlation between converter aging and stability problems. This result highlights the strong relationship between aging converters and increased dynamic risk related to their stability issues.





(b)

Figure 5-13. System-level risk indices of HMG incorporating the wear-out failure for power converters. (a) EID and LOLE, (b) EIF and LOLF [J1-C2].

5.3.2. Impact of Different Load Profiles on risk assessment

The generation and load profiles need to be combined to create the risk indices. Therefore, distinct load profiles will result in different risk indices, especially when stability issues are present. To demonstrate the impact of diverse load profiles on system risk, the load profile in the dc subgrid has been changed, depicted as "Load Profile 2" in Figure 5-14, and compared with the previous load profile ("Load Profile 1"). Notably, the load characteristics differ in terms of MWh and load peak distribution. The annual consumption of dc Load Profile 1 was 64 MWh, while it increased to 97.5 MWh for dc Load Profile 2. Comparing the cumulative distribution function (CDF) of dc loads, Figure 5-15 shows that dc Load Profile 2 surpasses 11.9 kW 50% of the time, while dc Load Profile 1 only reaches 5.7 kW. Therefore, using dc Load Profile 2 requires the IC to supply more power when it is in rectifying mode. By incorporating load profiles and considering the solar irradiance profile from Figure 5-11, the overall risk indices are depicted in Figure 5-16 for constant failure rates. As depicted in Figure 5-16 (a), the overall risk associated with Load Profile 2, for both dynamic and static performance, surpasses that of Load Profile 1. The increase in risk when using Load Profile 2 is significant, showing a 31% higher risk compared to Load Profile 1. In comparison with static performance and LOLE, the 24% difference escalates to 63% for EID. Similarly, the difference between EIF and LOLF demonstrates a noteworthy increase in the risk of the HMG when using Load Profile 2. Comparing EIF with LOLF, the previous 43% difference increases to 105% for Load Profile 2.

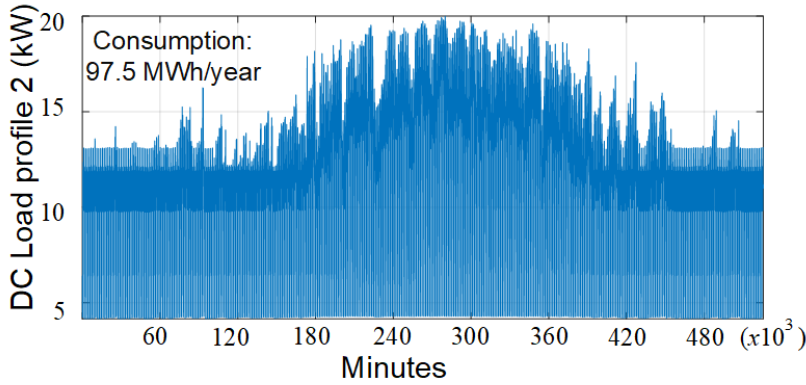


Figure 5-14. DC subgrid load profile with minute resolution (Load Profile 2) of the system in Figure 5-9 [J1].

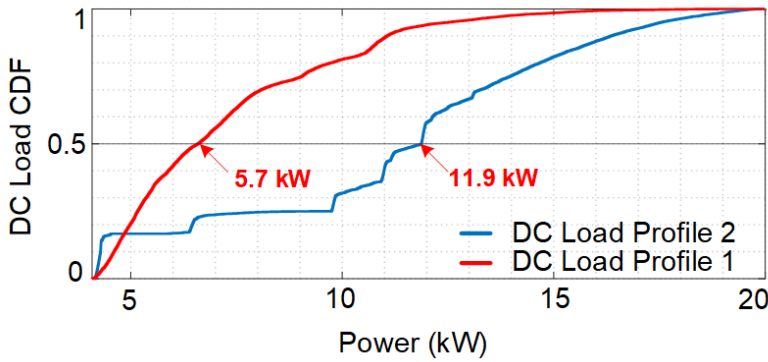
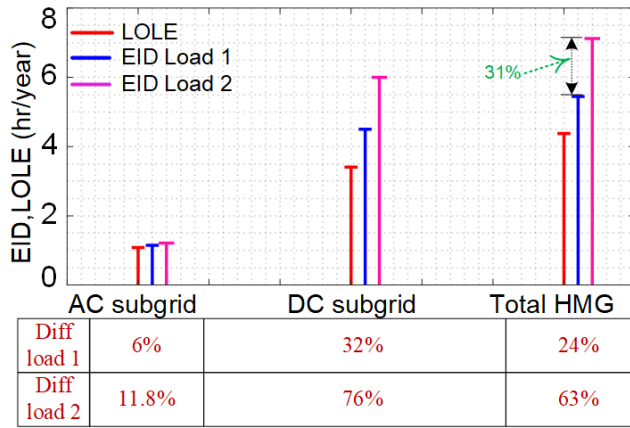
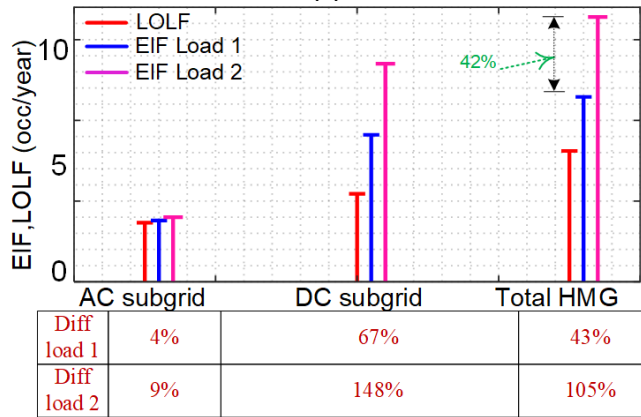


Figure 5-15. Cumulative distribution function (CDF) of dc load profiles of the system in Figure 5-9 [J1].

This study reveals that the risk indices may fluctuate within acceptable levels for both dynamic and static performance for specific load profiles and microgrids, eliminating the need for system redesign. This condition becomes clearer when considering the wear-out of power converters. Figure 5-17 compares the risk indices for two load profiles, indicating that, overall, DC Load Profile 2 results in higher static and dynamic risks compared to DC Load Profile 1. However, despite the EID being higher than LOLE for Load Profile 2, the overall risk at the end of the system's lifetime is significantly lower than the risks associated with Load Profile 1, with around 34% reduction in EID. This suggests that the risk outcomes of Load Profile 1 may fluctuate within standard margins, indicating no further need for optimal design for HMGs with this type of load. These risk indices vary for different load profiles, suggesting that even in the presence of stability issues, the risk of a microgrid may remain within an acceptable level.

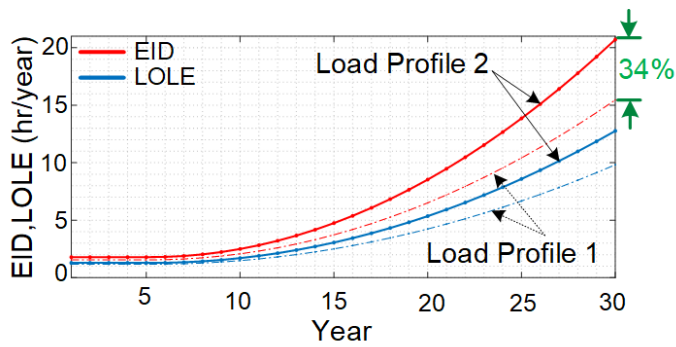


(a)

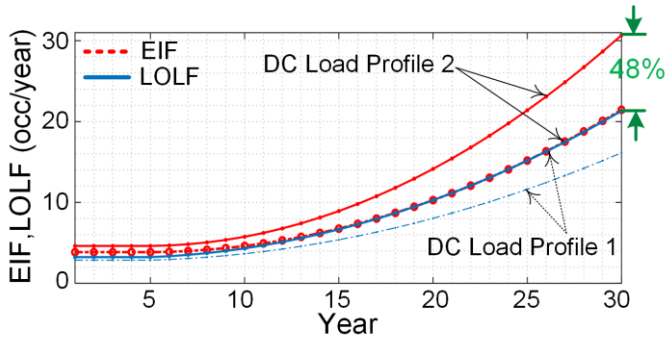


(b)

Figure 5-16. Subgrids and HMG (see Figure 5-9) System-level risk indices considering different dc load profiles. (a) EID and LOLE, (b) EIF and LOLF [J2].



(a)



(b)

Figure 5-17. System-level risk indices for DC Load Profile 1 (dash line) and DC Load Profile 2 (solid line) considering the wear-out of power converters of the system in Figure 5-9. (a) EID and LOLE, (b) EIF and LOLF [J2].

5.3.3. Impact of Different Solar Irradiance Profiles

As demonstrated above, the load profiles have a direct impact on the system's risk, potentially improving or worsening the overall risk in both subgrids and the overall HMG. Furthermore, the geographical location of the HMG and the corresponding non-dispatchable sources and their various mission profiles can also influence the power generation and consequently the system's risk profile. Thus, in this study, the solar irradiance depicted in Figure 5-11, labeled as "Solar Irradiance 1," has been replaced with Solar Irradiance 2, as illustrated in Figure 5-18. Solar Irradiance 2 exhibits a lower energy level measured in Watts per square meter (W/m^2) compared to Solar Irradiance 1.

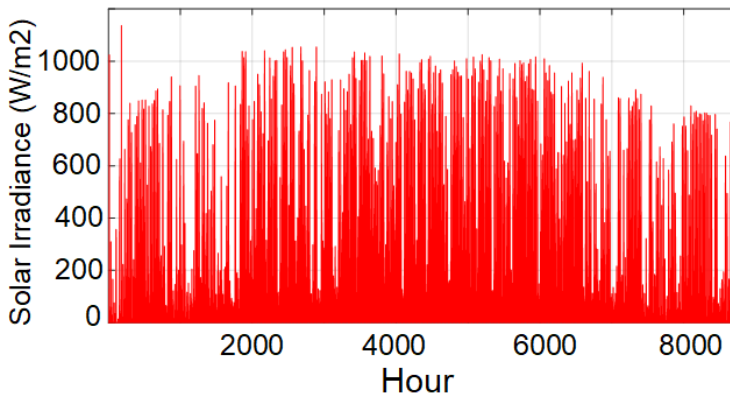


Figure 5-18. Solar Irradiance mission profile 2 for PV with minutes time resolution [J1].

Figure 5-19 compares the risk indices considering different solar irradiance profiles for the PV system in the dc subgrid of the HMG. Using solar irradiance with lower

energy, as depicted in Figure 5-19 (a), leads to an increase in both static and dynamic risk. Specifically, the static risk, measured by the LOLE, increases by 17% at the end of the 30-year lifespan when using Solar Irradiance 2, while for EID, it increases by 19%. However, the impact on the frequency of failure is much more pronounced. The number of failures due to a lack of generation increases significantly due to changes in the solar irradiance profile. As depicted in Figure 5-19 (b), the EIFs for the two solar irradiances show a 51% increment at the end of the 30-year lifespan, while this difference is 48% for LOLF. These results underscore the significant impact of the location and application of the HMG on the overall risk profile. In addition, this emphasizes how important it is to consider uncertainties resulting from different solar irradiance profiles as distinct sources of generation when designing systems and evaluating their overall risk.

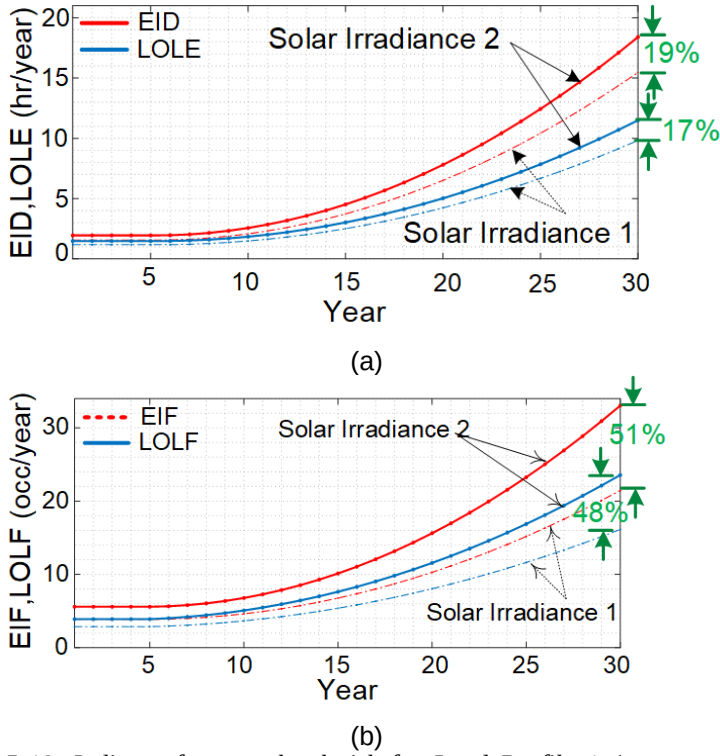


Figure 5-19. Indices of system level risk for Load Profile 1 (represented by dot marker) and Load Profile 2 (represented by square marker) employing the Solar Irradiance profile 1 shown in Fig. 9 (a). (a) EID and LOLE, (b) EIF and LOLF [J1]

In this section, the analysis of the interlinking converter DC-link voltage stability issue as a dynamic failure was thoroughly examined and incorporated into the risk assessment framework using the proposed stability-oriented risk model. The findings

highlight the intricate relationship between dynamic and static failures, revealing how the aging of converters can induce system instability and elevate the risk of load loss. Moreover, the findings highlighted the significant impact of load profiles on system risk. Certain load profiles may yield risk indices within acceptable thresholds, particularly when considering stability margins. However, in other scenarios, load characteristics may contribute to an increasing of overall risk and a degradation of dynamic performance. Therefore, load profiles emerge as pivotal determinants in the design of highly resilient microgrids.

Similarly, the examination of solar irradiance profiles underscores their critical role in system risk assessment. Variations in solar irradiance profiles can significantly impact system reliability and dynamic performance. Consequently, incorporating these factors into the design and evaluation of microgrid systems is imperative to ensure robust and resilient operation under diverse operating conditions.

5.3.4. Assessing the impact of Transient Angle Stability (TAS) on HMG Risk

Transient angle stability represents another critical stability issue that could potentially impact the risk profile of the hybrid microgrid. As detailed in Chapter 3, the vulnerability to instability arises from significant load variations or the sudden loss of generating units, which can destabilize the remaining units. Through time domain simulations conducted for the specific HMG under examination, stability criteria were established for the generating units within the ac subgrid. The forthcoming investigation will investigate the implications of transient angle stability on system risk. Given its expression within the ac subgrid, the effects of transient angle stability are expected to be particularly pronounced in comparison to those within the dc subgrid.

Therefore, using the data in Table 5-1, constant failure rates were applied to each converter in order to evaluate the impact of TAS and the ensuing dynamic performance on the overall system risk. The system-level reliability metrics for subgrids and the entire HMG are shown in Figure 5-20. The TAS criterion is the main cause of the notable differences in the EID and LOLE reliability indices that can be seen in the ac subgrid, as shown in Figure 5-20 (a). Significantly, Figure 5-20 (b) illustrates that EIF differs by 168% from LOLF and EID increases by 140% from LOLE. On the other hand, in the dc subgrid, these variations are negligible, at 7% and 14%, respectively, because the TAS criterion has a greater influence on the ac subgrid. With a 38% difference for EID compared to LOLE and a 34% difference for EIF compared to LOLF for the overall HMG, the differences are noteworthy and highlight the substantial impact of dynamic failures resulting from stability problems across the whole microgrid system.

The substantial differences in reliability indices within the ac subgrid show the pronounced impact of TAS on system risk, with EID showing a significant increase compared to LOLE, and EIF exhibiting a considerable difference compared to LOLF. These differences underscore the critical role of dynamic failures, particularly arising from stability issues, in driving overall risk levels within the microgrid. Furthermore,

the minimal differences observed in the dc subgrid emphasize the localized nature of TAS's impact, primarily affecting the ac subgrid components.

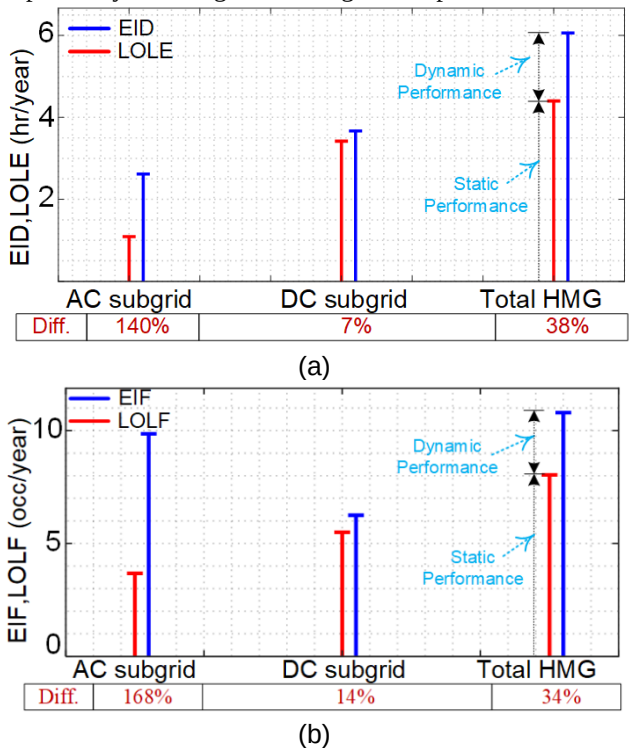


Figure 5-20. Subgrids and HMG System-level risk indices considering the impact of transient angle stability. (a) EID and LOLE, (b) EIF and LOLF [J2].

When comparing the risks associated with IC dc-link voltage stability and TAS, distinct differences emerge in their impacts on the microgrid's subgrids. For instance, the IC stability primarily affects the dc subgrid, while TAS has a more pronounced effect on the ac subgrid compared to the dc subgrid. The reliability indices, such as EID and EIF, show notable differences when considering each stability criterion. In the dc subgrid, where IC stability is the primary concern, the EID and EIF values are 32% and 67%, respectively, compared to LOLE and LOLF, according to Figure 5-12. Conversely, when TAS is considered, these values change significantly in the ac subgrid, with EID and EIF showing a substantial 140% and 168% increase compared to LOLE and LOLF, according to Figure 5-20. The differences in total HMG risk are also noteworthy. While the IC stability margin predominantly affects the frequency of losses, leading to a 43% difference between EIF and LOLF, TAS contributes more to the duration of load loss, resulting in a 38% difference between EID and LOLE.

5.3.5. Evaluating HMG Risk with Concurrent Analysis of TAS and IC Stability

In the previous studies, the impacts of IC DC-link voltage stability and transient angle stability on HMG risk were examined individually. In this study, the TAS criterion and the IC stability margin ($S_m = 0.93$) are simultaneously studied as two stability elements. Figure 5-21 shows how these factors interact collectively. In the dc subgrid, Figure 5-21 (a) shows that the EID increased by 32% relative to LOLE, and Figure 5-21 (b) shows that the EIF increased by 64% relative to LOLF. This highlights the significant impact of the IC stability margin, which limits the flow of power during rectifying mode from the ac subgrid to the dc subgrid, increasing the loss of the dc load. On the other hand, since the IC runs unrestricted in inversion mode, the reliability indices in the ac subgrid are close to situation that only TAS was considered (139% and 168% for EID and EIF relative to LOLE and LOLF, respectively). The difference increased to 60% for EID compared to LOLE and 66% for EIF compared to LOLF for the total HMG. These results underline how crucial it is to take

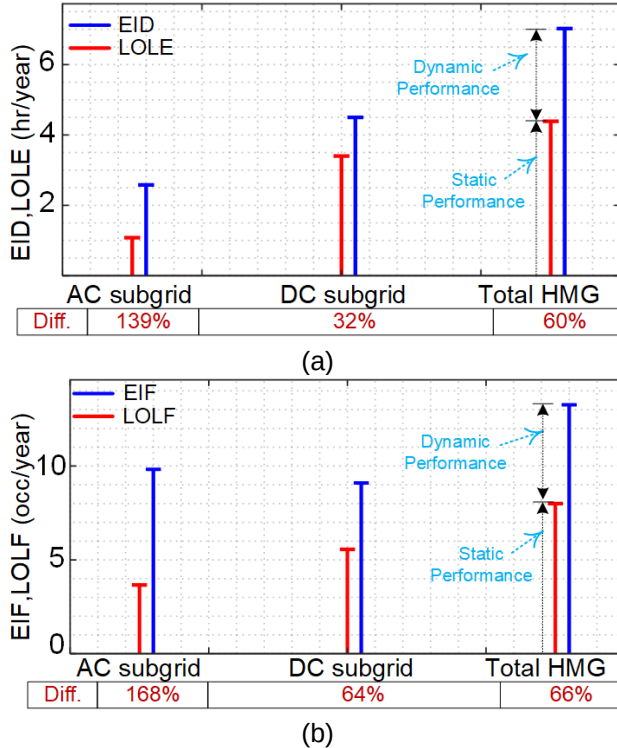


Figure 5-21. Risk indices at subgrids and HMG System levels taking into account the influence of TAS and IC stability margin. (a) EID and LOLE, (b) EIF and LOLF [J2].

stability impacts into account when designing and redesigning systems in order to lessen their effects, especially when the HMG's risk escalation surpasses conventional thresholds.

Therefore, compared to when these two stability issues were considered individually, the overall HMG experiences a higher risk level. Each stability issue impacts the risk in the subgrids, resulting in overall risks of 60% for EID compared to 24% of IC stability margin and 38% of TAS, and 66% for EIF compared to 43% and 34%.

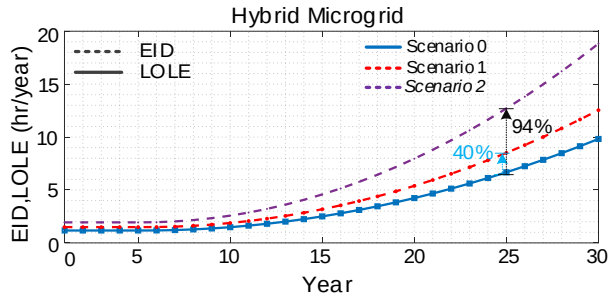
5.3.6. The impact of converters Wear-out Failure at Risk for HMG

So far, the analysis of TAS was based on constant failure rates. In section 5.2.1 it was shown that how wear-out failures of power converters affects the overall risk and increase it substantially. In this study, three distinct scenarios were analyzed, as outlined in Table 5-3, with the corresponding risk indices for the entire HMG depicted in Figure 5-22. The results reveal a significant increase in risk indices with increasing failure rates of the converters. In Scenario 1, where stability issues are disregarded, the LOLE commences at approximately 1.17 hr/year and steadily rises to 9.82 hr/year. Similarly, LOLF increases from 2.86 in the initial year to 16.14 at the end of the system's lifespan. Incorporating stability concerns, specifically TAS in Scenario 1 and TAS+IC in Scenario 2, leads to a notable surge in risk indices over time. For example, in Scenario 1, EID starts at 1.5 hr/year and escalates to 12.53 hr/year, whereas in Scenario 2, it begins at 1.94 hr/year and peaks at 18.82 hr/year.

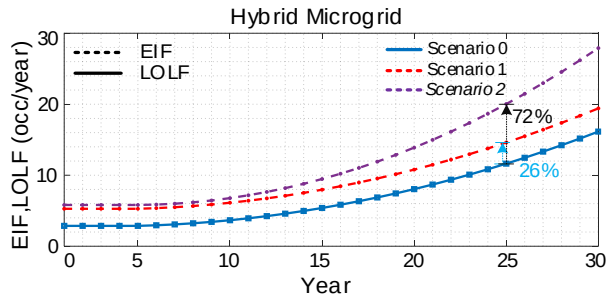
This study also demonstrates how aging of converters affect dynamic risk. A sharp rise in the EID to LOLE ratio suggests a close relationship between converter aging and stability problems. When compared to Scenario 1, where the difference is 40%, the gap between EID and LOLE in Scenario 2 reaches 94% by the 25th year, indicating a significant increase in the overall risk. Figure 5-22 (b) shows that in Scenario 2, the combination of TAS and IC stability margin results in a higher frequency of load loss, reaching 72% difference between EIF and LOLF compared to Scenario 1 with 26% difference. This result emphasizes how significantly the converter aging and the escalation of dynamic risk as a result of stability problems are correlated.

Table 5-3. Analyzing operating scenarios with regards to the impact of converter wear-out on HMG risk evaluation

Scenario 0	Scenario 1	Scenario 2
Without Stability issue	Only TAS's impact	Combined TAS and IC Impact



(a)



(b)

Figure 5-22. HMG system-level risk indices taking converter wear-out into account. (a) EID and LOLE, (b) EIF and LOLF (See Table 5-3 for Scenarios) [J2].

This study shows how risk indices can rise above acceptable levels in certain scenarios due to instability brought on by the loss of generating units or sudden large changes in load. Furthermore, these indices are made worse by taking into account the stability of the DC-link voltage of the interlinking converter. Therefore, it is imperative that microgrid designs address these issues and consider their impact on the overall design and planning process. The proposed model provides the opportunity to initially quantify the risk within the system and then determine whether redesigning the system is necessary based on predefined risk thresholds. If a redesign is considered necessary, the proposed model offers solutions to mitigate or alleviate the impact of both static and dynamic failures.

5.3.7. Frequency Stability Impact on HMG Risk

In Chapter 3 and Section 3.5, the issue of frequency stability was examined, revealing through mathematical modeling and time domain simulations that, in microgrids, the absence or failure of secondary control mechanisms can result in frequency exceeding acceptable operational limits under load changes. In such instances, to restore the frequency to an acceptable level from a reliability standpoint, it becomes necessary to shed a portion of the load. This additional load shedding introduces further losses into

the system and potentially impacts its overall risk profile. Consequently, this study highlights how frequency stability criteria can influence the risk of a hybrid microgrid. Using the same HMG configuration as depicted in Figure 5-1 and assuming constant failure rates for power converters, the system-level risk indices are presented in Figure 5-23. It is evident from this analysis that frequency stability has a pronounced impact on the ac subgrid, resulting in a 138% disparity between EID and LOLE, and a 155% increase in EIF compared to LOLF. In the dc subgrid, under circumstances where power needs to be transferred from the ac subgrid, increasing power injection from the ac side to the dc subgrid can lead to frequency deviations beyond acceptable levels. Consequently, certain segments of the dc subgrid may experience unsupplied loads, thereby initiating dynamic failures arising from frequency stability issues. However, the impact on dynamic performance in the dc subgrid is not as significant; EID is only 8% higher than LOLE, while EIF is 14% higher than LOLF. Overall, for whole microgrid, the frequency stability criteria result in a 38% increase in EID compared to conventional risk index LOLE (Figure 5-23 (a)), and a 34% higher risk for EIF compared to LOLF (Figure 5-23 (b)).

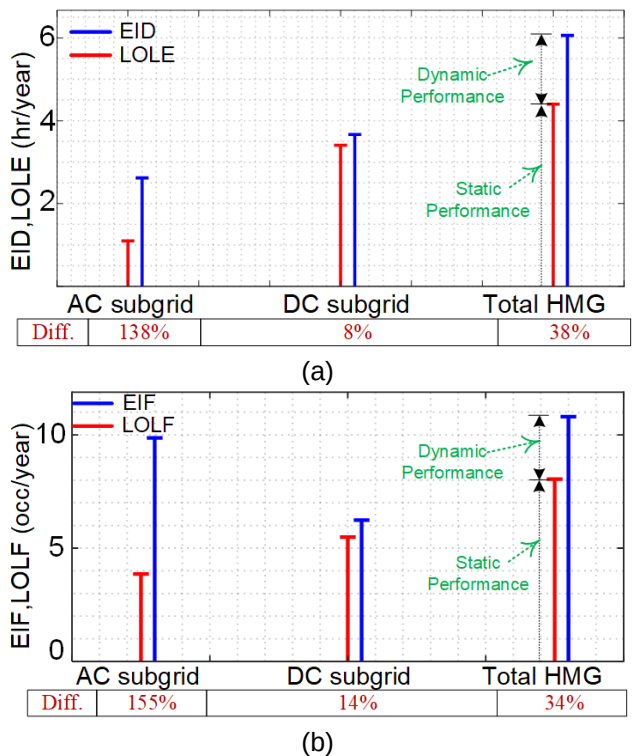


Figure 5-23. Subgrids and HMG (See Figure 5-9) System-level risk indices considering the impact of frequency stability. (a) EID and LOLE, (b) EIF and LOLF.

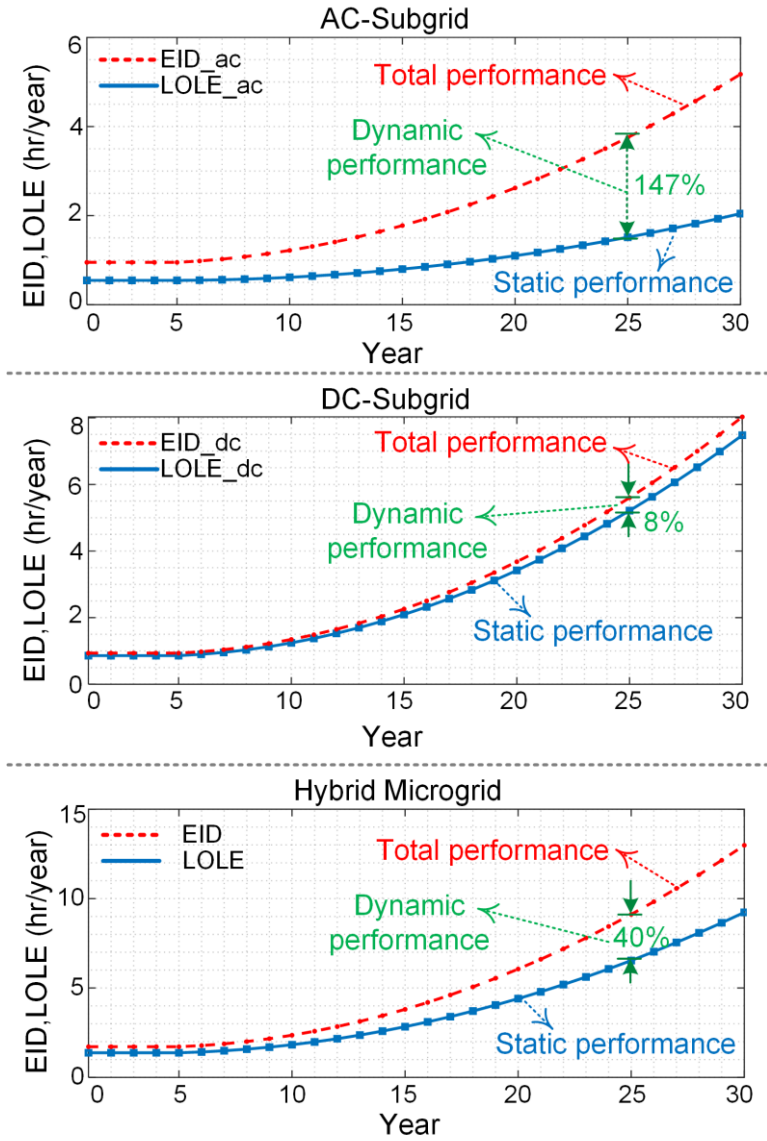


Figure 5-24. System-level duration risk indices for ac subgrid, dc subgrid, and overall HMG (See Figure 5-1) incorporating the wear-out failure of power converters.

Additionally, the consideration of power converter wear-out failures provides interesting insights into how frequency stability criteria influence dynamic risk over time. Illustrated in Figure 5-24 are the EID and LOLE risk indices for the ac subgrid, dc subgrid, and overall HMG. As depicted in Figure 5-24 (a), the aging of power converters increases risk levels over time, with a notable impact on dynamic

performance. For instance, by the 25th year, the disparity between EID and LOLE increases to 147%, highlighting the interplay between power converter wear-out failures and dynamic instabilities. As previously discussed, the effect on dynamic performance in the dc subgrid is comparatively modest compared to the ac subgrid, evidenced by an 8% difference according to Figure 5-24 (b). The overall risk in the HMG demonstrates increments in both static and dynamic performance, reaching 12.5 hr/year for EID and 9.82 hr/year for LOLE at the culmination of the 30-year lifespan, as shown in Figure 5-24 (c). Similarly, the scenario extends to the loss of load frequency, as illustrated in Figure 5-25. In the ac subgrid, the difference between EIF and LOLF stands at 153% by the 25th year, indicating a substantial impact of power converter wear-out on dynamic performance. Conversely, the disparity in the dc subgrid is relatively minor, at 14%, as shown in Figure 5-25 (b). At the overall HMG level, the discrepancy reaches 26%, underscoring the combined influence of power converter aging and dynamic instabilities on system-wide risk.

In conclusion, this study thoroughly examined the impact of frequency stability issues, which are particularly relevant for microgrids lacking secondary control mechanisms, on risk indices. The analysis concentrated only on this aspect, highlighting how the frequency stability criteria affect the risk of microgrids without secondary control. The subsequent sections of the thesis and proposed design solutions focused on mitigating the impact of IC DC-link voltage stability and transient angle stability, without considering the influence of frequency stability, assuming the HMG is equipped with secondary control.

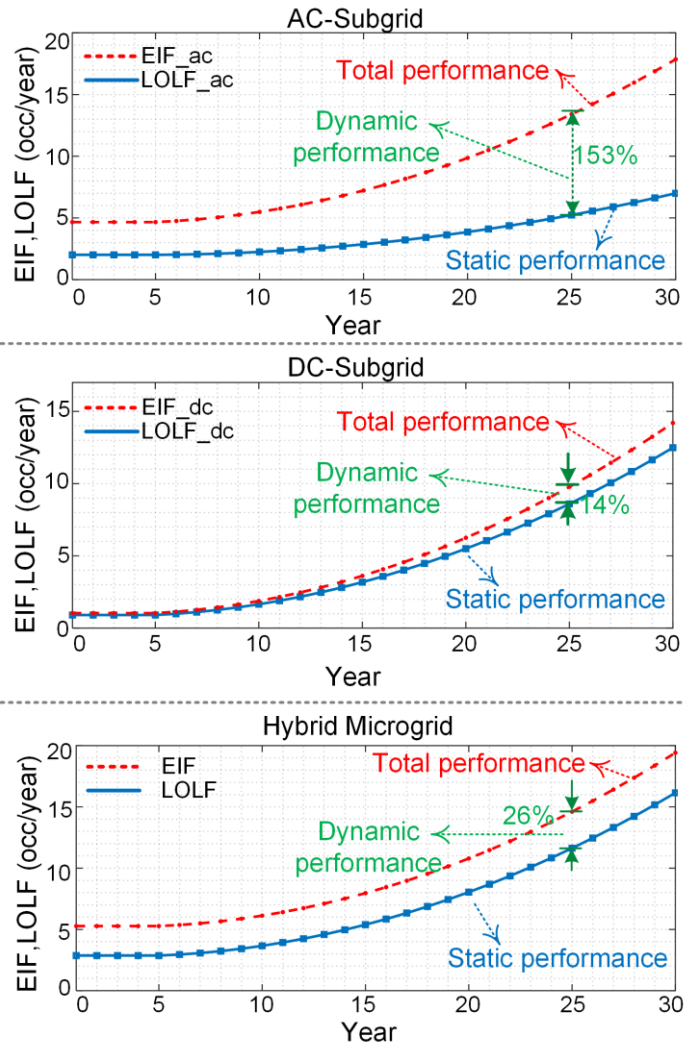


Figure 5-25. System-level frequency risk indices for ac subgrid, dc subgrid, and overall HMG (See Figure 5-1) incorporating the wear-out failure of power converters.

Chapter 6. Enhancing HMG

Performance: Design Solutions

6.1. Introduction

The substantial influences that stability issues have on the risk related to hybrid microgrids were demonstrated in Chapter 5. In particular, risk factors in the dc subgrid are significantly influenced by the stability margin of the Interlinking Converter, whereas risk factors in the ac subgrid get worse by the transient angle stability criteria. The purpose of this Chapter is to examine how the suggested multi-domain methodology offers a framework for successfully redesigning systems when risk levels are higher than predetermined thresholds. It tries to provide an overview of tactics for reducing the overall risk and the frequency of dynamic failures.

The suggested methodology provides a systematic approach to maximize efforts on system redesign when risk levels are higher than predetermined thresholds. It offers a structure for mitigating disparities in dynamic failure occurrences and lowering overall risk. Several studies have been carried out within this framework, such as sensitivity analyses to determine pivotal converters, studies into reconfiguration strategies for ICs, and evaluations of alternative energy source options during the design stage. To clarify each of these studies' unique contributions to risk reduction and system optimization, they will be looked at and expanded upon separately.

6.2. Sensitivity Analysis to Redesign the Dominant Converter at Component-Level

In modern power systems, power converters emerge as particularly fragile components, given their continuous energy conversion, exposure to thermal loading, and ability to withstand rapid power fluctuations. Moreover, the geographical placement of power converters further influences their operational efficacy because of operating under different mission profiles. These variables significantly contribute to system risk. Therefore, it is paramount to identify converters with the greatest potential to intensify both static and dynamic risks. Hence, identifying the dominant converter allows for strengthening its components such as power switches and capacitor banks, enhancing these converters at the component level. As an initial step in the HMG redesign process aimed at improving the overall risk, this investigation undertakes a sensitivity analysis to determine the most influential converter, redesign its components to prolong its lifespan, and assess the impact of the redesigned converter on system risk.

To conduct the sensitivity analysis, a constant failure rate assumption is made for all power converters except one, which is subjected to wear-out failure based on the data provided in Table 5-1. Under these varying failure conditions, the risk indices of the HMG are calculated for each scenario, iterating through all power converters. This study specifically focuses on four power converters: the fuel cell, PV system,

Microturbine, and Interlinking Converter. By comparing the extracted reliability indices under both static and dynamic failures, it is important to pinpoint the converter that exerts the most significant influence on overall system risk. Identifying this dominant converter serves as an important step for the subsequent redesign process. The sensitivity analysis results are presented in Figure 6-1, indicating that the Fuel Cell (FC) converter exhibits the most significant influence on the overall risk of the system. Both the EID and LOLE metrics demonstrate higher values compared to other scenarios. Several factors contribute to the elevated risk indices associated with the Fuel Cell converter, including the value of failure rates and repair times, the rate of wear-out accumulation, and its placement within the dc subgrid alongside the intermittent behavior of the PV system, necessitating additional power from alternate sources.

Furthermore, the Fuel Cell converter substantially impacts the dynamic performance of the HMG. Conversely, the PV system converter exhibits the least influence on the overall risk of the HMG, underscoring the pivotal role of the fuel cell within the dc subgrid. Additionally, the Interlinking Converter ranks as the second most impactful component in terms of risk, following closely behind the Fuel Cell.

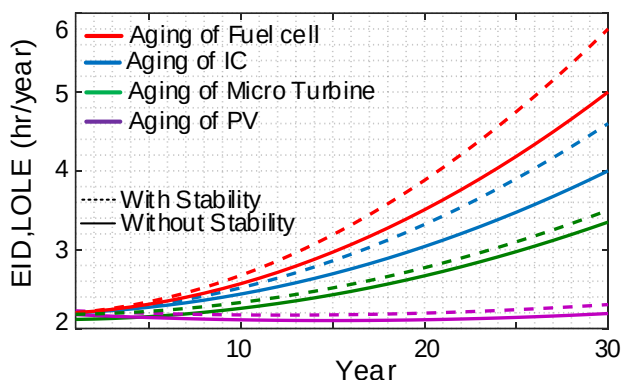


Figure 6-1. Findings from the sensitivity analysis: Assessing the effects of each converter's wear-out failure on the overall risk of the HMG.

To facilitate the redesign of the Fuel Cell converter and the selection of more robust components, various methods are available to estimate and evaluate the lifespan of delicate components such as power switches and capacitors. [156], [156]. The lifetime of these components relies largely on a multitude of factors, including operational parameters, load characteristics, thermal regulation, switching frequency, voltage levels, and component quality. These factors interact to determine the level of stress that switches and capacitors experience, which has a direct effect on their reliability and lifetime. Moreover, the design complexity and manufacturing standards of these components significantly contribute to their overall lifespan. In this study, particular emphasis has been placed on analyzing the lifespan of power switches, predominantly influenced by their junction temperature.

Variations in high-loading currents may put stress on die-attach solder and wire bonding, possibly resulting in failures. The Coffin Manson equation in (6.1) and the stress-strength analysis method are used in this study to estimate the lifespan. Chapter 2 section 4.1 defines the parameters.

$$N_f = A. \Delta T_j^\alpha . \exp \left(\frac{E_a}{k_b . T_{jm}} \right) \quad (6.1)$$

Two IGBTs are carefully chosen using the lifetime modeling approach shown in Figure 2-5, and the resulting Weibull distribution data, presented in Table 6-1, is obtained from the lifetime model forecast. Choosing the strongest switch among the available options lowers the failure rate and increases the converter's overall lifetime. This decision has a significant impact on the total risk associated with the HMG. Figure 6-2 illustrates the lifetime behavior of these two IGBTs, in which the second selected IGBT shows longer lifetime compared to the first IGBT (10N60T).

Table 6-1. Data regarding wear-out failure of IGBT types in the Fuel Cell converter.

IGBT type	α	β
10N60T	19	3.42
SGP15N60	21	3.5

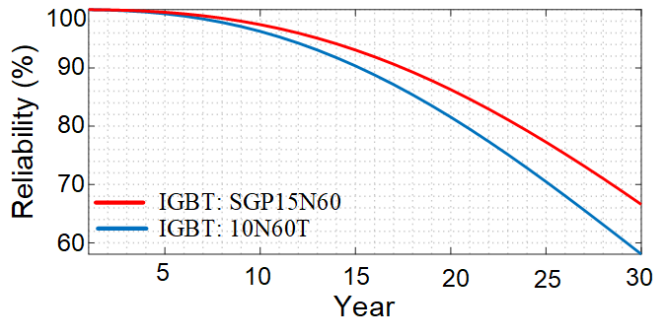
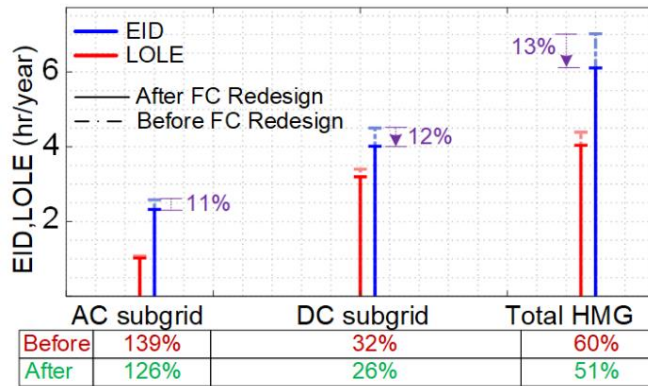
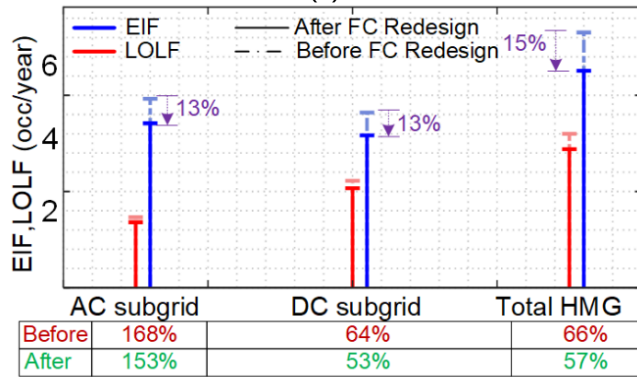


Figure 6-2. Lifetime modeling of two IGBTs under study in the Fuel Cell converter.

Figure 6-3 displays the comparison of reliability metrics with the Fuel Cell's updated failure data in Table 6-1. In general, the risk is decreasing for the ac and dc subgrids as well as the entire HMG, both with and without stability concerns. As an illustration, Figure 6-3 (a) displays a decrease of roughly 13% in the EID and a reduction of about 15% in the EIF for all subgrids. Additionally, for EID versus LOLE and EIF versus LOLE, the difference in dynamic failures for the overall HMG drops from 60% to 51% and from 66% to 57%, respectively. This solution works well for some HMG configurations that are getting close to the standard risk thresholds because it provides a small amount of risk mitigation.



(a)



(b)

Figure 6-3. Effect of Fuel Cell redesign on risk indices (a) EID and LOLE, (b) EIF and LOLF [J2].

In conclusion, the sensitivity study has provided valuable insights into the dominant factors influencing the risk profile of the HMG. By identifying the Fuel Cell converter as the most influential component, it has been possible to pinpoint areas for targeted intervention to reduce the overall risk. The redesign of the Fuel Cell converter, based on the sensitivity analysis results and lifetime modeling, offers a promising solution to enhance the system's reliability. The application of this solution involves implementing robust components and enhancing the lifetime of the Fuel Cell converter. By selecting more durable power switches and optimizing operating conditions, it is aimed to reduce failure rates and extend the lifespan of the converter. This, in turn, contributes to a decrease in system-level risk and enhances the overall performance and resilience of the HMG.

Furthermore, the comparative analysis of reliability indices before and after the redesign underscores the effectiveness of this approach in mitigating risks. The reduction in both static and dynamic failure indices across the ac/dc subgrids and the total HMG demonstrates the positive impact of the redesign strategy. Overall, the

sensitivity study and the subsequent application of the redesign solution pave the way for improved reliability and performance of HMGs. By addressing the vulnerabilities identified through sensitivity analysis, the risk of microgrid systems can be enhanced and ensures a continued operation under various operating conditions.

6.2.1. Reconfiguration of Interlinking Converter: Quantities and Size

An essential part of HMGs, the interlinking converter affects both static and dynamic failures throughout the dc and ac subgrids. In order to improve system performance, this research focuses on redesigning the IC and investigating ideal capacities and quantities. The effects of increasing the IC capacity from 10 kVA to 15 kVA on reliability measures are shown in Figure 6-4. A 20% capacity boost virtually eliminates dynamic failures at an IC capacity of about 13 kVA, as illustrated in Figure 6-4 (b). Increases beyond this threshold result in decreasing returns on risk mitigation. Although increasing the IC increases the reliability of the ac subgrid (Figure 6-4 (b)), its effects differ in the dc subgrid. Furthermore, Figure 6-4 (c) shows a significant reduction in the overall HMG risk, reducing the difference between EID and LOLE from 50% to 39% with only a 10% IC oversizing. Larger IC capacities also result in a noticeable reduction in dynamic risk, which eventually stabilizes the system.

Predetermined reliability standards are one of the many factors that determine the optimal amount of IC oversizing. As a result, although a 10% increase might be sufficient for certain HMG configurations, a 25% boost might be required for others to function at their best. Another useful tactic is to increase the quantity of ICs while keeping the overall capacity constant. The impact of increasing the number of ICs on reducing overall system risk is seen in Figure 6-5. For clarity, only the EID is depicted, although other reliability indices follow similar trends. As shown in Figure 6-5, the EID decreases from 6.2 hours per year to 5.4 hours per year when two 5 kVA ICs ($n=2$) are substituted with one 10 kVA IC ($n=1$).

This risk mitigation arises from operational variations in the event of an IC failure. When relying on a single 10 kVA IC, a failure leads to complete disconnection between the ac and dc subgrids. Conversely, employing multiple ICs in parallel ensures continuous operation even if one IC malfunctions, facilitating ongoing load supply. For instance, if the TAS criterion demands an additional 2 kVA in the ac subgrid for stability, a single IC failure mandates load shedding. In contrast, with two ICs, the operational IC can potentially sustain the load, partially or fully, drawing power from the dc subgrid as needed. Scaling up the number of ICs while maintaining capacity further enhances reliability. However, beyond a certain threshold, the risk reduction plateaus, with minimal differences between configurations. This study presents a compelling strategy for IC selection, balancing optimal capacity and numbers while considering cost factors, thus ensuring a more dependable and resilient system.

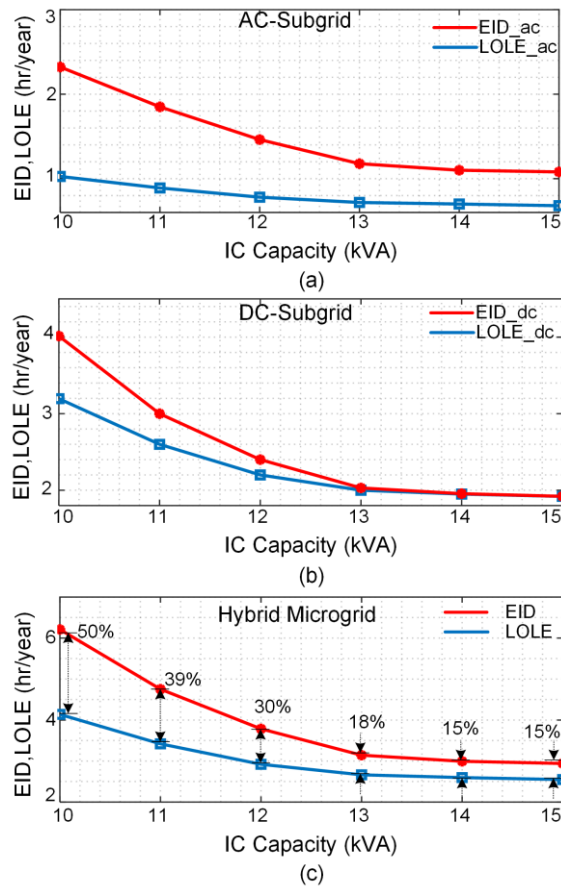


Figure 6-4. Impact of IC oversizing on the dynamic and static performance of HMG (See Figure 5-1). (a) AC subgrid, (b) DC subgrid, (c) Total HMG [J2].

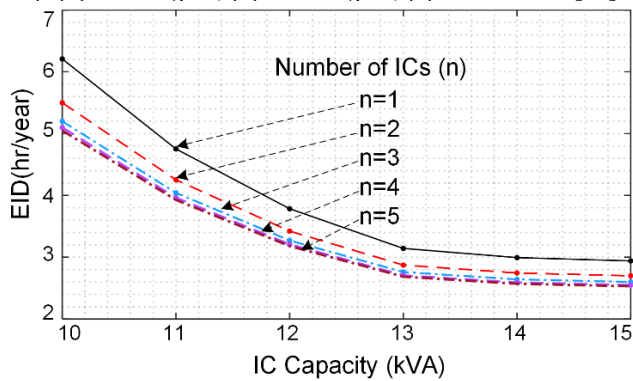


Figure 6-5. The effect of increasing the quantity of ICs on the overall risk of the HMG (See Figure 5-1) [J2].

Figure 6-6 provides a visual representation of how restructuring the interlinking converter configuration affects the overall risk mitigation within the hybrid microgrid. By comparing a restructured system equipped with two 6 kVA ICs to one with a single 10 kVA IC, considering both transient angle stability and IC stability issues, the effectiveness of this approach can be observed. The figure illustrates a significant reduction in both EID and LOLE and EIF/LOLF indices, indicating enhanced system reliability. Following the redesign of the interlinking converter concerning both its quantity and capacity, significant reductions can be observed in both EID and LOLE indices, amounting to 51% and 36% reductions, respectively. Specifically, LOLE decreases from 4.39 hr/year to 2.82 hr/year, while EID decreases from 7.02 hr/year to 3.42 hr/year. Similarly, there is improvements in the loss of load frequency, with reductions of 56% and 36% observed in EIF and LOLE, respectively, post-redesign. Moreover, the disparities in dynamic failures between the two configurations have notably diminished. Specifically, the difference between EID and LOLE has reduced from 60% to 21%, while the gap between EIF and LOLE decreased from 66% to 16%. This substantial reduction suggests a remarkable improvement in maintaining the HMG's operation within acceptable risk thresholds.

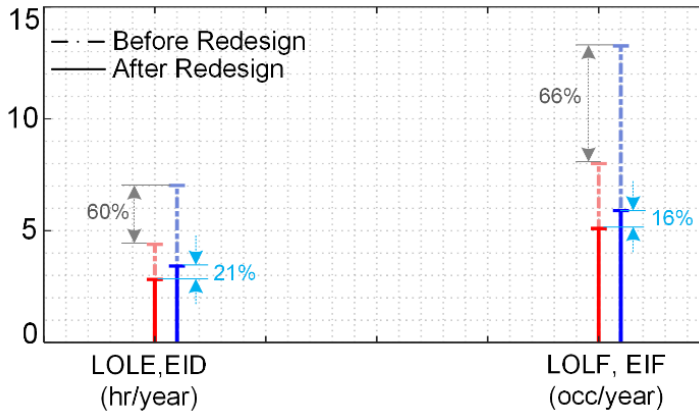


Figure 6-6. System-level risk indices considering reconfiguration of IC (Capacity: 12 kVA, Number:2 (2x6 kVA)) and FC redesign [J2].

The reconfiguration of the interlinking converter, focusing on both quantity and size, yields promising outcomes in mitigating risk within the different microgrids. As evidenced by the data, the adjustments result in substantial reductions across various risk indices. Notably, both the energy interruption duration and loss of load frequency indices experience notable decreases, indicating enhanced system reliability and stability. These improvements underscore the effectiveness of the IC reconfiguration strategy in supporting the HMG's resilience to potential failures and disturbances. Moreover, the observed reductions in dynamic failure indices, such as EIF and LOLE, further validate the effectiveness of this approach in minimizing operational uncertainties and ensuring consistent power supply within the microgrid. Overall, the

reconfiguration of the IC represents a crucial step towards optimizing the HMG's performance and strengthening its capability to operate within predefined risk boundaries.

6.2.2. Optimizing Renewable Energy Sources in System Redesign

Microgrids encompass diverse renewable energy sources, many of which, like wind plants and PV systems, are non-dispatchable, introducing uncertainties due to their intermittent power generation. The energy output from these sources is dependent on factors such as geographical location, wind speed, and solar irradiance profiles, directly influencing load supply and microgrid risk. This study aims to assess the impact of utilizing different energy sources in both ac and dc subgrids. Three scenarios are examined: Scenario 0 represents the existing energy sources in the studied HMG in Figure 5-1, comprising PV and FC in the dc subgrid and two Micro Turbines in the ac subgrid. Scenario 1 investigates the effects of replacing the 10 kW PV system in the dc side with a 10 kW wind turbine, while Scenario 2 explores the implications of substituting a 10 kW PV system for one 10 kW Microturbine (MT1) in the ac subgrid. The solar irradiance profile and the wind speed profile are depicted in Figure 6-7 (a) and (b), respectively. The solar irradiance profile aligns with the one presented in Figure 5-11.

Table 6-2 Various Scenarios for HMG sources (See Figure 5-1) [J2].

Sources				
	AC subgrid		DC subgrid	
Capacity	10 kW	15 kW	10 kW	10 kW
Scenario 0	MT1	MT2	PV	FC
Scenario 1	MT1	MT2	Wind	FC
Scenario 2	PV	MT2	PV	FC

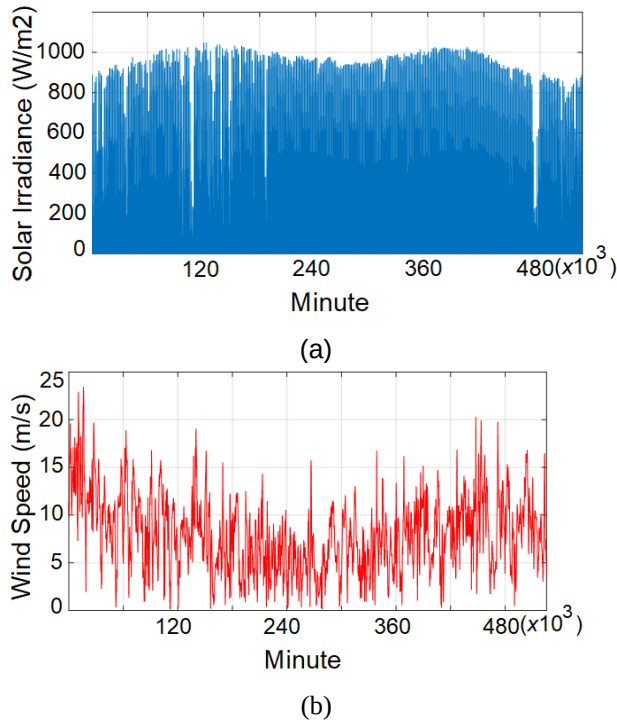


Figure 6-7. Non-dispatchable sources mission profiles. (a) Solar Irradiance for PV, (b) Wind Speed for Wind Turbine [J2].

As mentioned earlier, Scenario 0 replicates the results of the section that came before it (5.3.2), keeping the HMG's original configuration while taking the best ICs and FC converter redesign into account. The system-level reliability indices for each of the three scenarios are shown in Figure 6-8. In Scenario 1, the dynamic failures are significantly reduced when PV is replaced with a wind turbine. EID compared to LOLE dropped from 21% to 10%, and EIF compared to LOLF dropped from 16% to 6%, demonstrating this reduction. This highlights how crucial it is to choose the right energy source early on in the design process, as doing so greatly increases overall system risk. Moreover, this methodology can be implemented in operational phases to support additional sources in response to load growth or to enable stability improvements.

On the other hand, Scenario 2, which involves installing a PV system in place of MT1, makes the risk profile worse. The reconfiguration causes a significant increase in risk, as seen in Figure 6-8, as the expanded difference between EID and LOLE increases from 21% to 38%.

The findings show how important it is to select energy sources carefully in HMGs, as they have a significant impact on the system risk and reliability. Significantly, the suggested methodology offers a way for the systematic growth of the system in addition to enhancing the system stability and reliability during the original design

stage. This method addresses a crucial need in the development of energy ecosystems by ensuring a more stable and resilient configuration for hybrid microgrids through thoughtful selection and integration of renewable energy sources.

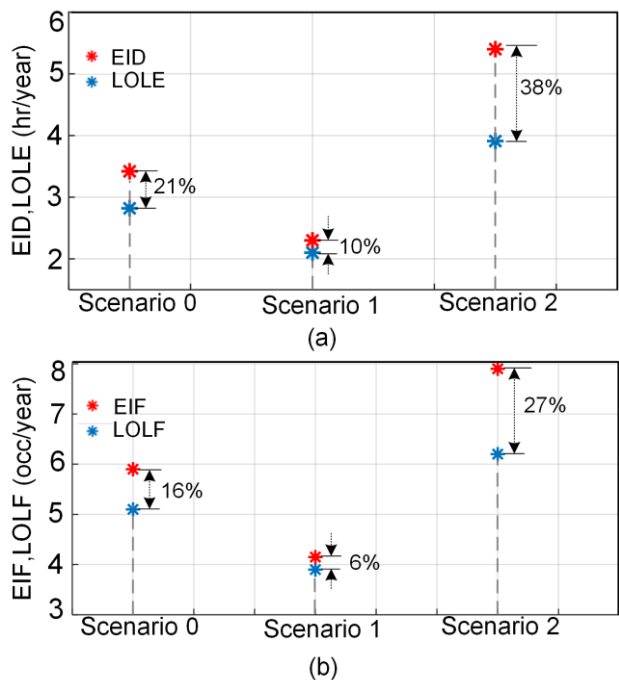


Figure 6-8. The impact of altering the types of sources in both ac and dc subgrids on the risk indices at the system level. (a) EID and LOLE, (b) EIF and LOLF

6.3. Summary

The results of the risk assessment for a particular microgrid design showed what happens when reliability is neglected during the design stage, which could lead to the microgrid being more reliable than intended. When accounting for dynamic failures and stability problems, the situation is made worse. Additionally, as component failure rates from wear-out increase, the microgrid's overall risk increases remarkably. The study found that some conditions, like the loss of generating units or abrupt changes in load, can cause transient angle stability problems, leading to reliability metrics that are higher than expected. Moreover, these metrics are made worse by the addition of Interlinking Converter DC-link voltage stability.

This study introduced a number of design guidelines that can be used at both the planning and operating stages of a hybrid microgrid (HMG) to better mitigate the effects of dynamic failures and increase overall reliability. The plan starts with a thorough component-level sensitivity analysis that leads to the redesign of the

dominating converter. The goal was to find stronger switches to replace the Fuel Cell, which functions as a dominant converter. The results showed that prolonging the dominating converter's life considerably reduces system-level risks in the HMG. The study then explored the reorganization of the Interlinking Converter, emphasizing its size and quantity. The study explored significant reductions in risk overall and in dynamic failures, especially in the dc subgrid, by analyzing IC capacity optimization. It does note, however, that risk reduction benefits diminish as IC capacity is increased beyond a certain point. Likewise, increasing the quantity of ICs reduces the overall system risk, but only up to a certain amount. Thus, in order to guarantee a system that is stable, dependable, and affordable, the study highlights the significance of attaining a balanced combination of optimal IC number and capacity. The system-level risk analysis highlights how IC reconfiguration significantly reduces the risk. The study concludes by recommending that renewable energy sources be optimized during system redesign in order to create a dependable and well-balanced hybrid microgrid. It emphasizes how replacing PV sources with wind results in notable drops in overall risk as well as dynamic failures. On the other hand, the research points out that substituting a PV system for MT1 makes matters worse and raises the risk significantly.

Chapter 7. Conclusion

This chapter serves as a culmination of the findings and conclusions drawn from this PhD project. It aims to provide a brief summary of the key outcomes and contributions of the study while also exploring potential possibilities for future research.

7.1. Summary

As previously discussed, the primary aim of this PhD thesis was to integrate dynamic failures stemming from stability issues into risk assessment models, ultimately developing a multi-domain design guideline for hybrid microgrids. The proposed model facilitates the simultaneous evaluation of both static and dynamic system performance, providing enhanced solutions for design and planning phases. The outcomes of these risk-based designs aim to enhance system reliability and stability. The research gaps identified include the need for comprehensive design guidelines that integrate both reliability and stability considerations, the lack of methodologies to evaluate dynamic failures in HMGs, and the limited understanding of the impact of renewable energy source integration on system risk. These gaps highlight the complexity and multidimensional nature of HMGs and underscore the need for innovative approaches to address them.

Thus, in Chapter 1, these research gaps were analyzed and explained in detail. The shortcomings of existing design methodologies and evaluation techniques were discussed, emphasizing the limitations in accurately assessing system reliability and stability. Motivated by these challenges, several research tasks were determined to tackle existing gaps, including the development of a multi-domain stability-oriented risk assessment model, investigation of the impact of dynamic failures on system risk, and exploration of microgrid redesign strategies for risk mitigation. Based on these research tasks, the project objectives were formulated to guide the study towards addressing the identified gaps and challenges effectively. These objectives include:

- Developing comprehensive design guidelines that integrate reliability and stability considerations.
- Investigating the impact of dynamic failures on overall system risk and reliability.
- Exploring microgrid redesign strategies to mitigate system risk and enhance stability.
- Proposing innovative methodologies for evaluating renewable energy source integration in HMGs.

However, it is essential to acknowledge the limitations and assumptions of this project. The complexity of HMGs and the inherent uncertainties associated with renewable energy sources pose challenges in developing accurate and robust evaluation techniques. Additionally, the scope of this study may be constrained by resource limitations and the availability of data. Despite these limitations, the project

aimed to make significant contributions to the advancement of HMG design and operation methodologies.

In Chapter 2, various aspects of designing power electronic-based power systems were analyzed. Initially, the design and planning processes of microgrids were investigated, covering challenges from control perspectives and optimization techniques. The design of microgrids based on the IEEE 2030 model was discussed, along with related standards in microgrid characteristics such as test systems, element modeling, control systems, and communication layers. Additionally, planning aspects of microgrids were examined, dividing them into long-term and short-term planning phases. Long-term planning strategies for strategic decision-making regarding microgrid deployment were explored, while short-term planning focused on operational considerations for day-to-day management. Finally, the latest efforts in the design for reliability concept in microgrids were discussed, including hierarchical levels of reliability assessments, such as device-level, component-level, and system-level assessments, as well as methods for estimating component lifetimes.

In Chapter 3, the focus shifted to power system dynamic failures, particularly stability issues within microgrids. The chapter explored understanding the concept of stability and its classification in microgrids. Various stability issues, including dynamic risks induced by Interlinking Converter (IC) DC link voltage stability, Transient Angle Stability (TAS), and frequency stability, were thoroughly examined.

Root cause analysis and time-domain simulations were conducted to investigate IC DC-link voltage stability. It was demonstrated that in the rectifying mode of operation, the IC DC-link voltage becomes unstable when transferring nominal power from the ac side to the dc side. The non-minimum phase behavior of the ac filter inductance was identified as the reason for this instability. Accurate modeling revealed the appearance of a zero in the transfer function, contributing to the instability.

Similarly, for TAS, the results highlighted how sudden load changes or the loss of one generating unit under specific circumstances could lead to the remaining sources in the ac subgrid reaching unstable operating conditions. These concepts were defined and explained using swing equations and equal area criteria. Time-domain simulations further illustrated these stability issues. Frequency stability was also examined, showing how load changes and absence of secondary control led to frequency instability in certain situations. The outcomes of Chapter 3 were instrumental in defining the stability margins and constraints that directly impact the loss of load in microgrids. By identifying and analyzing stability issues such as IC DC-link voltage stability, Transient Angle Stability (TAS), and frequency stability, the chapter shed light on the intricate dynamics within microgrid systems. These findings underscored the critical need to address dynamic failures in risk assessment models and the design of microgrids.

Chapter 4 explored the development of a multi-domain design framework for hybrid microgrids that integrates reliability and stability considerations simultaneously. It began by exploring conventional risk assessment methodologies such as state enumeration, capacity outage probability table (COPT), Monte Carlo simulation, Markov chain method, and semi-Markov method. Building upon these

methodologies, the chapter introduced a novel stability-oriented risk assessment methodology. This proposed approach extended beyond conventional methods by integrating stability considerations into the risk assessment process. The conventional and proposed methods were compared and contrasted, highlighting the advancements and benefits of the new approach. Overall, Chapter 4 laid the foundation for a comprehensive risk assessment framework that addresses both static and dynamic failures in HMGs, thereby enhancing the reliability and stability of these systems.

Chapter 5 of the thesis presented the application of the proposed framework in risk-based microgrid design, focusing on various aspects of risk analysis and design solutions to enhance microgrid performance. The chapter began by illustrating the practical application of the proposed framework in large-scale power plants, providing a practical example to show the importance of risk assessment in modern power systems. In the practical application of the proposed framework in large-scale power plants (150 MW wind power plant), several key findings emerged. Firstly, the analysis revealed a significant drop in full-time availability at the point of interconnection (PoI) to the grid, reducing to 52%. In addition, the time availability reached at approximately 99.42%, implying that the power plant is offline for approximately 50 hours within the span of a year.

Further investigation into production availability revealed that it stands at 96.78%. This suggests that a portion of energy production, equivalent to approximately 30.6 GWh, is lost due to system failures. This loss represents around 3.31% of the total energy produced. Furthermore, comparing the power losses attributable to components like cables and power transformers, which typically range from 2-3%, with the loss of energy due to failures underscores the critical importance of integrating reliability considerations into both power plant design and economic analyses. Overall, these findings underscored the importance of reliability in large-scale power plants and emphasize the need for comprehensive risk assessment methodologies to address potential failures and their associated impacts.

This chapter proceeded to explore the integration of dynamic stability considerations into risk analysis within the context of an HMG. The HMG configuration under study comprised two 10 kW and 15 kW microturbines in the ac subgrid, along with a 10 kW PV system and a 10 kW Fuel cell in the dc subgrid. Connecting these subgrids was a 10 kVA IC.

First, the chapter meticulously investigated the dynamic failure related to the IC DC-link voltage stability issue and its integration into the risk assessment framework utilizing the proposed stability-oriented risk model. With a stability margin of 0.93 for the IC in the rectifying mode of operation, the study revealed the intricate interplay between dynamic and static failures, illustrating how converter aging can instigate system instability and elevate the risk of load loss. Results showcased a significant 24% contrast between EID and LOLE, along with a substantial 43% difference between EIF and LOLF, with the wear-out failure impact worsening these ratios. Furthermore, the findings underscored the substantial influence of load profiles on system risk. Certain load profiles could maintain risk indices within acceptable thresholds, particularly when considering stability margins. However, in contrasting

scenarios, load characteristics could lead to heightened overall risk and compromised dynamic performance. Numerical analysis revealed that utilizing a load profile with higher demand in the dc subgrid escalated the 24% difference between EID and LOLE to 63%, and the 43% difference between EIF and LOLF to 105%. Hence, load profiles emerged as critical determinants in the design of highly resilient microgrids. Similarly, the study explored the examination of solar irradiance profiles, highlighting their pivotal role in system risk assessment. Variations in solar irradiance profiles were found to significantly influence system reliability and dynamic performance. Consequently, the incorporation of these factors into the design and evaluation of microgrid systems was evaluated imperative to ensure robust and resilient operation under diverse operating conditions. Moreover, the outcomes demonstrated that the highest impact of IC DC link voltage stability was observed in the dc subgrid, resulting in significantly elevated risk indices compared to static performance.

Next, the influence of Transient Angle Stability on HMG risk was assessed. As discussed previously, vulnerability to TAS arises from significant load variations or the sudden loss of generating units, which can destabilize the remaining units. The findings revealed that the TAS criterion significantly contributed to notable differences in the EID and LOLE reliability indices observed in the ac subgrid, with a 168% difference between EIF and LOLF and 140% for EID and LOLE. Conversely, in the dc subgrid, these variations were negligible, at 7% and 14%, respectively, indicating that the TAS criterion showed a greater influence on the ac subgrid. With a 38% difference for EID compared to LOLE and a 34% difference for EIF compared to LOLF for the overall HMG, these differences underscored the substantial impact of dynamic failures resulting from stability problems across the entire microgrid system.

Further analysis evaluated the concurrent impact of TAS and IC stability on HMG risk, emphasizing the need to consider multiple stability issues simultaneously to obtain a comprehensive understanding of system reliability. The results showed that the difference increased to 60% for EID compared to LOLE and 66% for EIF compared to LOLF for the total HMG. The proposed model provides the opportunity to initially quantify the risk within the system and then determine whether redesigning the system is necessary based on predefined risk thresholds. If a redesign is considered necessary, the proposed model offers solutions to mitigate or alleviate the impact of both static and dynamic failures.

The latest stability issue addressed in this study pertained to frequency stability. The analysis focused on examining the impact of frequency stability issues, especially relevant for microgrids lacking secondary control mechanisms, on risk indices. Specifically, the study concentrated on how frequency stability criteria affect the risk of microgrids without secondary control.

Finally, Chapter 6 explored design solutions to enhance HMG performance. Sensitivity analysis was conducted to redesign the dominant converter at the component level, aiming to improve system reliability. By identifying the Fuel Cell converter as the pivotal component applying the most influence, it is possible to pinpoint specific areas for targeted intervention to reduce overall risk. The redesign

of the Fuel Cell converter, informed by sensitivity analysis outcomes and lifetime modeling, offered a potential means of improving system reliability. Implementing this solution involved the integration of robust components and enhancing the lifespan of the Fuel Cell converter. Through the selection of strengthen power switches and optimization of operational conditions, the aim was to decrease failure rates and prolong the converter's longevity. Moreover, the comparative examination of reliability indices pre- and post-redesign underscored the effectiveness of this approach in risk mitigation. Following the redesign of the FC, the disparity in dynamic failures for the overall HMG, as indicated by EID versus LOLE and EIF versus LOLF, diminished from 60% to 51% and from 66% to 57%, respectively. This reduction in both static and dynamic failure indices across the ac/dc subgrids and the total HMG illustrated the favorable impact of the redesign strategy.

Reconfiguration of the Interlinking Converter in terms of quantity and size was also investigated as a second solution, highlighting its impact on reducing system risk. The reconfiguration of the interlinking converter, addressing both its quantity and size, was yielded promising results in mitigating risk across various microgrids. The outcomes illustrated substantial reductions in several risk indices, particularly noticeable in the duration of energy interruptions and the frequency of load loss occurrences. The effectiveness of this strategy in enhancing the microgrid's resilience to potential failures and disturbances was evident. Furthermore, the observed declined in dynamic failure indices, such as EIF and LOLF, affirmed the effectiveness of this approach in reducing operational uncertainties and ensuring consistent power provision. Specifically, the redesign of the interlinking converter in terms of quantity and size has narrowed the gap between EID and LOLE from 60% to 21% and reduced the difference between EIF and LOLF from 66% to 16%.

Finally, the study suggested optimizing renewable energy sources during system redesign to establish a reliable and well-balanced hybrid microgrid. It highlighted the significant risk reduction and decrease in dynamic failures achieved by replacing PV source with wind. Specifically, the difference between EID and LOLE decreased from 21% to 10%, and the difference between EIF and LOLF decreased from 16% to 6%. Conversely, substituting a PV system for MT1 worsen the situation, resulting in an increase in the difference between EID and LOLE from 21% to 38%, and between EIF and LOLF from 16% to 27%.

Overall, Chapters 5 and 6 showcased the practical application of the proposed framework and provided valuable insights into mitigating risk and enhancing performance in hybrid microgrid systems.

7.2. Main Contributions of the Thesis

The novelties of this PhD thesis are as follows:

Comprehensive understanding of reliability principles in microgrids: This thesis explored the fundamental principles of reliability within microgrids, encompassing design frameworks and relevant design standards. Chapter 2 provided a detailed

exploration of these concepts, including investigating the latest risk-based design guidelines. This discussion laid a solid foundation for subsequent chapters focusing on reliability assessment and system optimization.

Comprehensive understanding of the principles of stability and stability issues in microgrids: This thesis rigorously investigated the stability concept and classification in microgrids, focusing on dynamic risk induced by stability issues such as IC DC-link voltage stability, transient angle stability (TAS), and frequency stability. Chapter 3 extensively covered these principles, providing insights into the dynamic behavior of microgrids and their implications on system reliability and risk. The project emphasizes the need to consider dynamic failures in the design and operation of microgrids. Dynamic failures triggered by stability issues can have a significant impact on the overall system risk. The motivation here is to develop a design guideline that not only addresses static risks but also mitigates dynamic risks to ensure a more reliable microgrid.

Development of a multi-domain stability-oriented risk assessment model and design guideline: This project introduced a comprehensive multi-domain design guideline that integrates reliability and stability considerations. The motivation behind this endeavor is to address the existing gap between these crucial aspects of microgrid design, which have traditionally been treated independently. By bridging reliability and stability analyses, the aim is to enhance both static and dynamic performance, thereby providing a more holistic approach to microgrid design. Chapter 4 explored the development and implementation of this stability-oriented risk assessment model, presenting a novel methodology for evaluating HMG reliability while considering both static and dynamic failures. Here are some of the main advantages of the proposed multi-domain stability-oriented risk assessment model:

- The model integrates both reliability and stability considerations, providing a comprehensive framework for assessing the performance of hybrid microgrids. This holistic approach ensures that the design guidelines account for both static and dynamic failures, leading to more robust and resilient microgrid designs.
- By considering a wide range of potential failure scenarios, including both static and dynamic failures, the proposed model helps identify vulnerabilities in HMGs and provides insights into how to mitigate them. This leads to improved system reliability and reduced risk of disruptions.
- The model enables designers to make informed decisions about the design and operation of HMGs by quantifying the potential risks associated with different design choices.
- The proposed model can be customized to specific HMG configurations and operating conditions, making it suitable for a wide range of applications. It can accommodate changes in system components, operating conditions, and

environmental factors, ensuring its relevance and applicability in diverse scenarios.

- By conducting risk assessments during the design phase, the model helps identify potential issues before they appear in the operational phase. This proactive approach allows designers to address vulnerabilities early on, reducing the likelihood of costly downtime and disruptions later.
- The model provides valuable insights into the trade-offs between reliability, stability, and cost, empowering decision-makers to make informed choices that align with their priorities and objectives. This ensures that design decisions are aligned with overall system goals and requirements.

Investigating the Impact of Dynamic Failures on HMG overall risk: The study investigated the significant impact of dynamic failures on the overall risk of hybrid microgrids. By considering scenarios involving stability issues such as interlinking converter DC-link voltage stability, transient angle stability, and frequency stability, the research highlights the importance of addressing dynamic risks alongside static risks. This contributes to a deeper understanding of the complex interactions between stability issues and system reliability, laying the basic for more effective risk mitigation strategies. These investigations have been included in Chapter 5.

Microgrid Risk-Based Redesign and Configuration: The study explores the necessity of system redesign to mitigate overall risk and minimize dynamic failures in existing microgrids. By conducting sensitivity analysis to identify critical components and evaluating reconfiguration strategies, the research aims to provide practical solutions for enhancing the reliability and stability of microgrid systems. Additionally, the optimization of renewable energy sources is investigated to employ their potential in improving system performance. This comprehensive approach to microgrid redesign and configuration offers valuable insights for practitioners seeking to enhance the resilience and efficiency of their energy systems. These investigations have been included in Chapter 6.

7.3. Future Works and Research Perspectives

In this section, potential directions for future research and development are outlined based on the findings and contributions of this thesis. While this project has endeavored to address several research gaps, it is acknowledged that numerous interesting challenges remain to be studied. The results of the current research will be improved even more by addressing these issues in subsequent studies.

Some of the areas that can be considered for future studies include:

- *Enhanced Stability-Oriented Design Guidelines:* Future research could focus on refining and expanding the stability-oriented design guidelines proposed in this thesis. This could involve incorporating additional stability metrics, such as voltage stability and transient stability, into the design framework and risk assessment model. By integrating these additional stability issues into the risk assessment model, microgrid designers can gain a more

comprehensive understanding of the system's stability characteristics and identify potential vulnerabilities. This holistic approach to microgrid design ensures that stability considerations are adequately addressed, leading to more robust and reliable microgrid systems capable of withstanding various disturbances and contingencies.

- *Integration of Advanced Control Strategies:* Investigating the integration of advanced control strategies, such as predictive control and model predictive control (MPC), into microgrid design and operation could be a valuable avenue for future research. These control strategies have the potential to improve system stability and reliability by providing real-time optimization and coordination of distributed energy resources. By exploring the implementation of advanced control techniques, researchers can contribute to the development of more intelligent and adaptive microgrid control systems.
- *Exploration of Novel Energy Storage Technologies:* Future studies could focus on exploring the potential of novel energy storage technologies, such as flow batteries, supercapacitors, and thermal energy storage, for enhancing microgrid performance. These emerging technologies offer unique advantages, such as higher energy density, faster response times, and improved cycle life, which could address some of the limitations of traditional battery-based energy storage systems. By investigating the integration of novel energy storage technologies into microgrid design, researchers can contribute to the advancement of more efficient and sustainable microgrid solutions.
- *Real-World Validation and Case Studies:* To validate the effectiveness and applicability of proposed design guidelines and strategies, future research could involve real-world validation studies and case studies in collaboration with industry partners and microgrid operators. By deploying experimental microgrid systems and conducting field trials in diverse environments, researchers can gather valuable data and insights to assess the performance of microgrid designs under real operating conditions. Additionally, case studies of successful microgrid deployments and modifications can provide valuable lessons learned and best practices for future microgrid projects.
- *Incorporating Wear-Out Models for Additional Components:* In this study, the failure and wear-out mechanisms of power converters were thoroughly examined. Extending this analysis to include wear-out models for other critical components, would offer a precise understanding of system reliability over its operational lifespan.
- *Developing Complicated Energy Management Strategies:* Implementing the proposed model for larger scale microgrids requires the development of sophisticated energy management strategies. These strategies must account for the dynamic interactions between various components and optimize the operation of the microgrid under different operating conditions and uncertainties.

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Part II

Publications in the thesis

[J1]

A New Risk Assessment Approach for Design of Hybrid Microgrids Considering Stability Issues

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A New Risk Assessment Approach for Design of Hybrid Microgrids Considering Stability Issues

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Abstract: Stability issues can significantly increase the risk of hybrid microgrids (HMGs), particularly during island mode operation. The dynamic performance of the system can induce constraints and stability margins that may elevate the loss of load probability. This paper presents a new stability-oriented risk assessment model that bridges the conventional reliability models, stability, and system risk. The proposed model ensures the risk of the system by considering the redesign or reconfiguration of HMGs to address stability issues. Firstly, the interlinking converters (ICs) DC-link voltage stability is analysed to determine the acceptable power flow margins in rectifying and inversion mode. Next, the new general risk assessment model is introduced. The results show that the stability margin significantly increases the risk of the HMG, particularly when considering the aging of converters. The study also examines the impact of various load characteristics and ICs with different numbers but the same total size. In some cases, the risk is acceptable for the desired loads, or it can be reduced to an admissible level by reconfiguring the ICs. Finally, the paper demonstrates the effectiveness of the proposed model in the optimal design of HMGs, aiming to guarantee the system's risk.

1. Introduction

Hybrid microgrids (HMGs) have emerged as a crucial component in power electronic-based systems, capable of functioning in both grid-connected and off-grid modes [1]. However, their small scale, high integration of renewables, and lower inertia present distinctive challenges, particularly when operating in island mode [2]. Key concerns encompass reliability, stability, power quality, and resiliency [3]. Maintaining a delicate balance between generation and load is imperative for microgrid operation, necessitating a system that is both reliable and stable, ensuring an uninterrupted power supply within an acceptable risk threshold. Stability and reliability, affecting both dynamic and static performance, are of paramount significance.

In contrast to conventional power systems, microgrids employ power electronics for energy conversion. With the increasing utilization of power electronics, susceptibility to load loss becomes a potential risk [4]. Load loss can stem from two primary factors: static and dynamic performance. While static performance pertains to component failures and is integrated into traditional reliability assessment models [5], dynamic performance directly influences system stability [6]. Nevertheless, transients and stability issues related to voltage/frequency in microgrids can escalate system risk without causing component failure [7, 8]. In these scenarios, microgrid components may face limitations due to over/under voltage/frequency issues or DC-link voltage instability of power converters. Thus, considering the intertwined nature of reliability and stability and their collective impact on overall system risk is essential for robust risk assessment methods.

Reliability concerns can also exert an influence on HMG stability. For instance, the aging of power converter components like switches and capacitors can induce voltage

fluctuations potentially leading to system instability [9]. Furthermore, power converter aging can trigger various instability issues, such as thermal instability [10], frequency instability [11], and harmonic distortion [12]. These intricate connections between reliability and stability, coupled with heightened system risk, may substantially shape power converter design.

Current risk assessment methodologies predominantly concentrate on identifying static failures originating from components [13]. These models ascertain potential failure modes, evaluating the probability and consequences of each. Typically, risk assessment in power electronic-based systems operates at three levels [14]. At the component level, the reliability of individual components such as capacitors and switches are analyzed [15, 16]. Factors like mission profiles [18], temperature [19], humidity [20], and vibration [21] significantly impact component reliability and, consequently, system risk. System-level evaluation scrutinizes the overall system reliability using various risk techniques like failure modes and effects analysis [22], fault tree analysis [23], and event tree analysis [24]. Components are modeled in series or parallel configurations with respect to reliability, aiming to meet the desired standard of reliability [4]. At the operational level, the system's reliability throughout its lifespan is assessed, encompassing maintenance, repair, and replacement [25]. At this stage, the system's availability is monitored, and if it falls below the minimum risk threshold, redesigning may be necessary from the component level up [14]. However, these models solely consider component failure, and system reliability is predicated on static performance. In microgrids, where components are highly interdependent, susceptibility to stability issues that may destabilize the entire system and result in greater load loss is elevated. Consequently, this form of dynamic failure elevates

the overall system risk.

The stability challenges and classification in microgrids can be bifurcated into two primary categories: (1) control system stability and (2) power supply and balance stability [26]. The transients and dynamics resulting from this classification may have distinct impacts on system risk. For example, in the HMG structure depicted in Fig. 1, interlinking converters (ICs) play a pivotal role in ensuring system stability. As demonstrated in [27-29], the DC-link voltage of the ICs may operate in an unstable state during rectifying mode. This instability stems from the non-minimum phase characteristic, a consequence of the ac-filter inductance, which restricts power flow during rectification, heightening the likelihood of load loss in HMGs. Additionally, inappropriate control strategies, particularly in island mode, may induce frequency stability challenges [30, 31]. The impact of imprecise tuning of droop gains in microgrids with droop control has been explored in [32], revealing that excessive gains lead to significant frequency fluctuations even with minor load changes. Conversely, reducing gains diminishes the system's responsiveness to load alterations. Consequently, in hybrid microgrids, minor disturbances can upset the balance between load and frequency, increasing risk.

The conventional approach has separately addressed stability and reliability issues in modern power electronic-based systems, without considering the interplay between static and dynamic failures in risk assessment models. However, this interplay is indispensable for designing systems that are both stable and reliable. Enhancing risk assessment models necessitates accounting for how static and dynamic failures interact and their potential influence on overall system reliability. This will lead to a more comprehensive understanding of potential risks and more effective measures to prevent failures, ensuring the secure and reliable operation of power systems.

To tackle these challenges, this paper proposes a novel stability-oriented approach for risk assessment in power electronic-based power systems. This approach aims to model both static and dynamic system performance, establishing a direct link between system risk, stability, and reliability for HMGs. By doing so, it becomes possible to optimize the converter design to ensure the stability and reliability of the power grid. This new approach holds the potential to enhance the accuracy of risk assessment models and enable more effective management of potential risks associated with modern power systems.

The subsequent sections of this paper are organized as follows: Section 2 delves into the analysis of interlinking converter DC-link voltage stability to derive stability constraints for use in the ensuing sections. Section 3 introduces the proposed stability-oriented risk assessment model for hybrid microgrids, elucidating how it bridges stability and reliability. Section 4 presents various simulations and case studies demonstrating the capability of the proposed model in designing HMGs for stable and reliable operation. Finally, Section 5 provides important insights and a summary of the paper's outcomes.

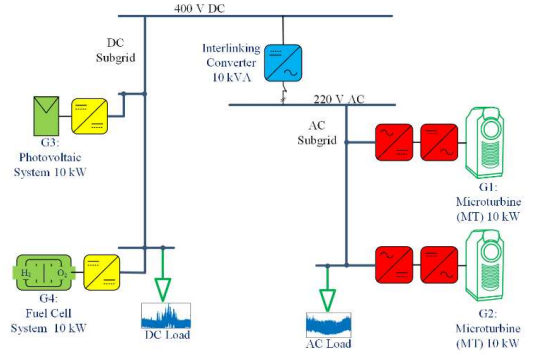


Fig. 1. Single line diagram of a hybrid microgrid with one interlinking converter between ac and dc subgrids

2. DC-link Voltage Stability of Interlinking Converters

Stability issues in microgrids are distinct from those found in conventional power systems due to their small size, strong coupling between system variables, low inertia, among other factors [33]. Based on the PES TR66 classification, stability challenges in microgrids arise from control system, power supply, and balancing issues [26]. Thus, there are numerous stability concerns that can impact the risk of microgrids. As it is not feasible to examine all of these issues in a single study, this paper focuses on analyzing DC-link voltage stability to validate the proposed model.

Fig. 2 presents a comprehensive depiction of the IC's architecture and control mechanism, which links the dc sub-grid to the ac sub-grid. Depending on the power status of distributed generators (DGs) and loads, the IC can transfer power in both inversion and rectifying modes, requiring the IC to be stable in both operating modes. A precise nonlinear model of the IC has been investigated in prior studies [30, 31]. The following section describes the mathematical model of the IC to determine the minimum required stability margin to ensure a stable IC operation. The power balance equation of the IC can be derived using (1) [30].

$$\frac{1}{2} C_{dc} \frac{d}{dt} (V_{dc}^2) = P_{dc} - P_{ac} \quad (1)$$

The first term of (1) represents the energy stored in the dc-link capacitor (C_{dc}) with V_{dc} denoting the voltage across the capacitor. P_{dc} and P_{ac} are the exchanged dc and ac powers, respectively, as shown in Fig. 2. Due to the nonlinearity of the power balance equation with respect to V_{dc} , the energy stored in the capacitor (W) can be used as a state space variable, as shown in (2).

$$\frac{dW}{dt} = P_{dc} - P_{ac} \quad (2)$$

Conventional models usually overlook the stored energy (W_L) in the ac-side filter (L_f) as it has a small value compared to the other variables and is zero in steady-state operation. These models express the ac-side power as given in (3).

according to the mode of operation and the value of P_{dc} . In the inversion mode, where P_{dc} is positive, the "zero" appears on the left-hand side, resulting in a stable condition. On the contrary, in the rectifying mode, where P_{dc} is negative, the system will have a Right Half-Plane Zero (RHPZ). In such case, the system dynamics will be derived as nonminimum phase, and consequently the phase margin will be reduced if the value of P_{dc} is close to the IC rated capacity.

To demonstrate the impact of AC-filter dynamics and the resulting "zero" in the transfer function, an eigenvalue analysis was conducted. The IC and control system parameters are provided in Table 2 in the appendices. Fig. 3 illustrates the movement of the root locus of the dominant eigenvalues by varying P_{dc} . According to Fig. 3, when P_{dc} is increased in the inversion mode (dc to ac power flow), the dominant modes move towards the left-side of the S-plane. Therefore, the system will be stable due to higher damping.

Conversely, in the rectifying mode of operation, an increase in P_{dc} leads to movement of dominant modes towards the right half-plane and puts the system into an unstable condition. For instance, when the transferred power reaches to $P_{dc} = -0.93 \text{ pu}$, the dominant modes become very close to the origin, and the system becomes unstable thereafter. Hence, it is crucial to operate the IC within a limited boundary in terms of stability to avoid instability. The stability margin affects the risk of the HMG and increases the loss of load. Therefore, it is necessary to consider the impact of such stability issues in the risk assessment models.

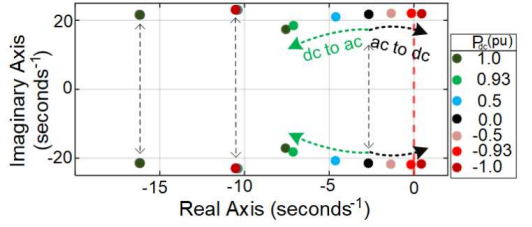


Fig. 3. Impact of P_{dc} variation on loci of dominant modes

frequency, duration, and amount of unsupplied loads [14]. In this study, regarding to the size of the HMG, two significant indices, namely, Loss of Load Expectation (LOLE) and Loss of Load Frequency (LOLF) are selected as the risk metrics. The mathematical representations of these indices are given in (17) [38].

$$\begin{aligned} LOLE &= \frac{1}{N} \sum_{i=1}^N LLD_i \left(\frac{\text{hr}}{\text{year}} \right) \\ LOLF &= \frac{1}{N} \sum_{i=1}^N LLO_i \left(\frac{\text{occ}}{\text{year}} \right) \end{aligned} \quad (17)$$

Where N represents the number of sampling years, LLD_i represents the duration of load loss, and LLO_i is the loss of load occurrence.

Typically, these indices assess the system's overall risk, taking into account the components' static failure.

3.2. Proposed Method

To integrate the impact of dynamic performance into the overall system risk, the effect of stability can be represented as illustrated in Fig. 4. The IEEE PES technical report 66 provides guidance on incorporating various stability issues in HMGs. Once the stability issues in the HMG have been identified, the causes of instability can be determined using Root Cause Analysis (RCA) techniques such as eigenvalue analysis, root locus analysis, and time-domain simulations. Thus, for each stability issue, several stability margins and constraints are derived.

In the subsequent phase, the availability status of the relevant components affected by the identified instability issue is adjusted. This is achieved by combining the stability margins/constraints with the availability state generator models. For instance, in this study, as explained in section 2, the IC stability margin ($Sm=0.93$) is integrated with the IC availability state. As a result, the margins of the IC availability state shift from $[-10, 10] \text{ kVA}$ to $[-9.3, 10] \text{ kVA}$. This implies that to ensure stable IC operation, the IC transferred power in rectifying mode should not exceed -9.3 kVA .

After modifying the availability states of the components, the updated availability states can be incorporated into the power unit's convolution and/or conventional energy management approach. Subsequently, new risk indices are generated that encompass both the dynamic and static failures of the HMG.

Thus, the proposed model bridges the stability and reliability, enabling a precise assessment of the system's overall risk, considering both static and dynamic failures.

3. Proposed Stability-Oriented Risk Assessment Approach

In this section, a new risk assessment method considering the stability issues for HMGs is proposed. This method simultaneously analyses the static and dynamic performance of the system, as illustrated in Fig. 4. The green frame represents the conventional risk assessment method, which focuses on the system's static performance. The blue frame indicates the proposed risk model, which bridges the dynamic performance stemming from stability issues and the conventional static performance. In the following, both methods are discussed.

3.1. Conventional Method

In conventional risk assessment methods for power systems, as depicted in Fig. 4, the availability state is generated based on the failure data of each component using various risk assessment techniques, such as Monte Carlo simulations [35], Markov chain [36], and also AI approaches [37]. Subsequently, the power availability of power generations (e.g., PV, Wind, Fuel Cell) is determined by convolving the availability states with the power mission profiles. These mission profiles may exhibit substantial fluctuations, as seen in PV and Wind units, or vary around a constant value.

In the next step, the power flow in HMGs is performed, adhering to the predetermined energy and power management strategies. The specific energy management method employed in this paper is discussed in section 4.3. Ultimately, the total risk of the system will be determined based on load losses. Various risk indices can be utilized to evaluate the

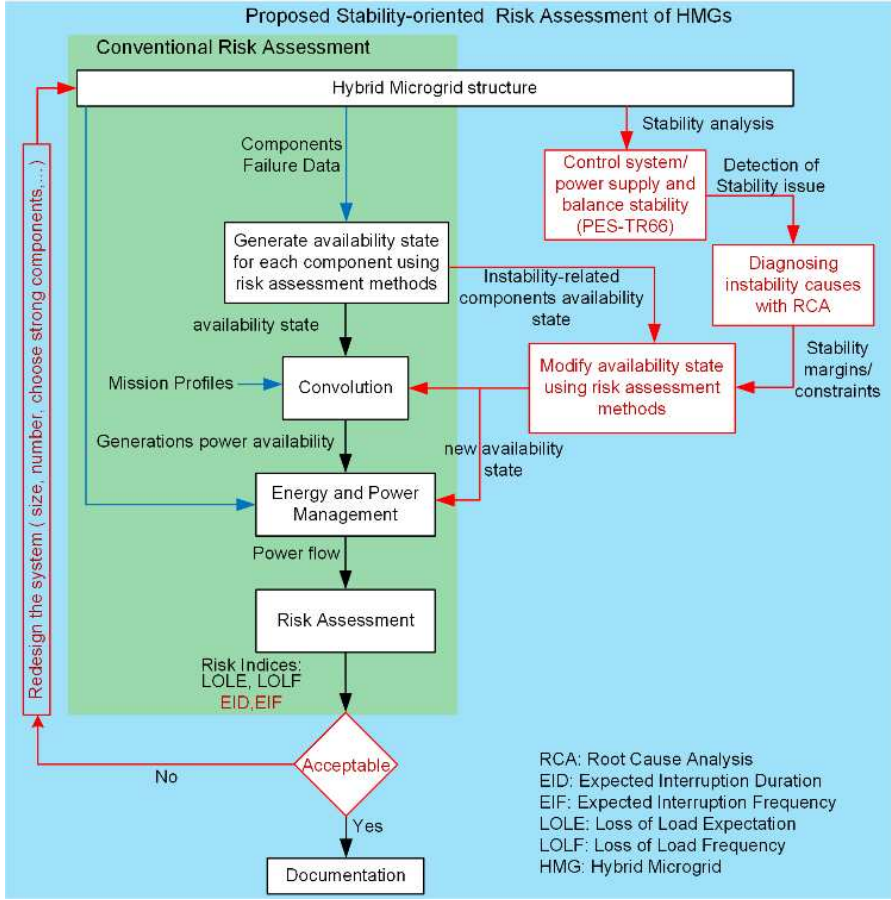


Fig. 4. The proposed stability-oriented risk assessment model for HMGs

Therefore, the impact of component failures on both system risk and stability can be modeled accurately. Since the proposed method considers both static and dynamic failures of the system, two new reliability indices are introduced in this study as follows:

- (1) Expected Interruption Duration (EID)
- (2) Expected Interruption Frequency (EIF)

The mathematical models of EID and EIF are defined in equations (18) and (19), respectively:

$$EID = LOLE + (\text{dynamic performance}) \text{ hr/year}$$

$$= \frac{1}{N} \cdot \sum_{i=1}^N LLD_i + \frac{1}{N} \cdot \sum_{j=1}^k \sum_{i=1}^N ULD_i(S_m^j) \quad (18)$$

$$EIF = LOLF + (\text{dynamic performance}) \text{ occ/year}$$

$$= \frac{1}{N} \cdot \sum_{i=1}^N LLO_i + \frac{1}{N} \cdot \sum_{j=1}^k \sum_{i=1}^N ULO_i(S_m^j) \quad (19)$$

In the above equations, k is the number of components leading to stability issues in the system, ULD_i is the

unsupplied load duration resulting from stability margin (S_m), and ULO_i is the unsupplied load occurrence resulting from stability margin (S_m).

After evaluating the overall system risk, if the risk indices fall within the acceptable desired level, the design process will be completed without any further changes to the system. Otherwise, the system must be redesigned with regard to factors such as size, number of components, and selection of stronger devices.

This method provides an optimal design guideline for HMGs to comply with the acceptable desired level of system risk, taking into account both dynamic and static failures. In the next section, the proposed model will be implemented on the HMG depicted in Fig. 1, and the impact of dynamic failures, various load profiles, and IC redesign on the overall system risk will be investigated.

4. Numerical Analysis

To illustrate the impact of stability issues and the resulting dynamic failures on the overall system risk, the AC/DC hybrid microgrid shown in Fig. 1 has been considered as a test system. The DC sub-grid of the microgrid is supplied by

a 10 kW Photovoltaic (PV) system and a 10 kW Fuel Cell (FC) system, while the AC sub-grid is fed by two 10 kW Microturbines (MT). In case of any power shortages, a 10 kVA Interlinking Converter (IC) connected between the AC and DC sub-grids transfers the excess power to either side as needed.

As per the proposed model, the first step towards evaluating the system risk using the new approach is to determine the stability margin for the system. Therefore, the next section will focus on performing time domain simulations to verify the small signal results obtained in Section 2 and demonstrate the impact of the IC rectifying mode of operation on the instability of DC-link voltage. Subsequently, the implications of this stability issue on the overall system risk will be discussed.

4.1. Time Domain Simulation Results

The Root locus analysis has revealed that existing a zero in the transfer function of $W(s)/I_{gd}(s)$ as shown in equation (15), leading to instability in the DC voltage of the IC when it operates in rectifying mode. To further demonstrate this instability, two case studies have been conducted in the time domain simulations, showcasing both inversion and rectifying modes of operation for the IC. The relevant parameters for the IC can be found in Table 2 of the appendices [34].

4.1.1 The IC Inversion Mode of Operation

In this case study, it is assumed that the ac sub-grid load is overloaded and there is sufficient power to transfer from dc to ac sub-grid. The load characteristics in per unit for 4-seconds timespan are shown in Table 1, considering the IC capacity as a base power ($S_b = 10 \text{ kVA}$). The dynamic responses of power and the DC-Link voltage are depicted in Fig. 5. As shown in Table 1, the dc sub-grid load is considered a constant value at 1 pu. From time $t=0$ to 2 s, the ac load increases from 1 to 2 pu and the ac sub-grid is capable to supply the load. At $t=2$ s, the ac load is overloaded to 2.5 pu. Therefore, as shown in Fig. 5 (a), the IC transfers 0.5 pu power from dc to ac side, and the DC-link voltage is stable according to the Fig. 5 (b). The ac load is also increased at $t=3$ and 4 s to 2.93 and 3 pu, respectively. Under these conditions, the IC successfully transfers the required power in the inversion mode without any instability in the DC-link voltage. Thus, the IC can transfer its rated capacity (10 kVA or 1 pu) and ensure the stability of the DC-link voltage while operating in the inversion mode.

4.1.2 The IC Rectifying Mode of Operation

In this case study, the impact of power transfer from ac to dc sub-grid on the stability of the DC-link voltage has been analyzed. The load in the ac sub-grid is constant at 1 pu, while the dc load varies from 1 pu to 3 pu, as shown in Table 1 for rectifying mode. The dynamic response of the generation unit, IC power flow and the DC-link voltage are shown in Fig. 6. In this case, the IC operates in rectifying mode with power flowing from the ac to dc side. As Fig. 6 (a) illustrates, for the time period from $t=0$ to 2 s, the dc sub-grid supplies its load up to 2 pu. At $t=2$ s, the dc load is increased to 2.5 pu and the IC transfers -0.5 pu excess power from the ac to the dc side.

The dc load further increases to 2.93 pu at $t=3$ s and the IC continues to supply the required excess power from the ac side. In this condition, the DC-link voltage remains stable as depicted in Fig. 6 (b). However, when the dc load increases to 3 pu at $t=4$ s, the DC-link voltage becomes unstable, resulting in the HMG operating in an unstable condition.

Thus, based on the RCA demonstrated and time domain simulations, a proper stability margin needs to be defined in order to ensure the stable operation of the IC in rectifying mode. The time domain results indicate that by setting the stability margin (S_m) to 0.93, the HMG can operate in a stable condition.

Therefore, this criterion will be utilized in the risk assessment model. The next sections will describe the applied power management and energy flow strategy for the HMG illustrated in Fig. 1. Then, the risk assessment, considering various scenarios, will be modelled.

4.2. Power Management and Energy Flow

The power flow management is carried out based on the HMG's topology and generation/load limitations, as shown in Fig. 4, before executing the risk assessment and obtaining the risk indices. Following the HMG structure in Fig. 1 and the control system of the IC in Fig. 2, the power management is performed as follows:

In the dc sub-grid, the PV (G3) and Fuel Cell (G4) supply power to the dc load, while the ac load in the ac sub-grid is powered by two microturbines (G1, G2). The IC is not authorized to transfer power as long as both sub-grids can meet their respective load demands. To achieve this, the total generation (P_G) and consumption (P_L) of each side are monitored, and when P_G is equal or greater than P_L , the value of K_c in control system is set to "zero". However, in the event of power shortage ($P_G < P_L$), the IC can transfer the required power to both sides by setting an appropriate value for K_c . In accordance with equation (9). The direction of power transfer is determined by the changes in V_{pu}/f_{pu} .

4.3. Impact of stability on HMG Risk

In this scenario, we investigate the impact of bridging the stability and reliability on the overall system risk. The failure data of the converters are presented in Table 3 of the appendices, where the aging of the converters is modeled using the Weibull distribution function (α and β are scale and shape factors, respectively). Additionally, the hourly load profile of Fig. 8 (a) and solar irradiance profile of Fig. 9 (a) are considered for this analysis. Fig. 7 shows the system-level risk indices for both conventional and proposed methods. Incorporating stability and dynamic failure into the system increases the overall risk of the system. For example, the risk results in Fig. 7 (a) reveal a 4.6% difference between EID and

Table 1 Load characteristics in pu during the specified time

	Load	Time (s)				
		0	1	2	3	4
Inversion mode	AC load (pu)	1	2	2.5	2.93	3
	DC load (pu)	constant= 1				
Rectifying mode	AC load (pu)	constant= 1				
	DC load (pu)	1	2	2.5	2.93	3

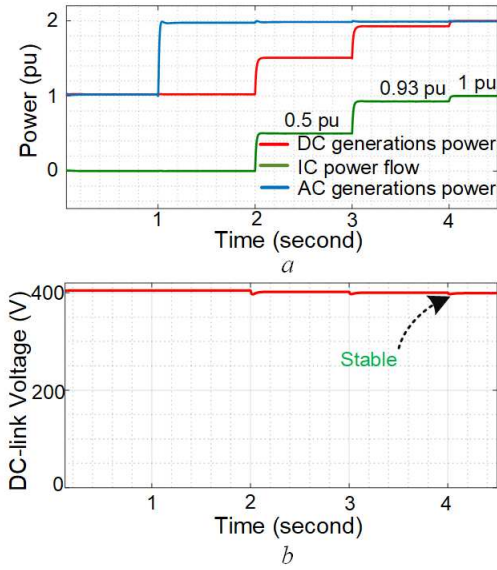


Fig. 5. Dynamic response of DC-link voltage, power flows of dc and ac subgrids and interlinking converter power flow in inversion mode of operation, (a) Power, (b) DC voltage

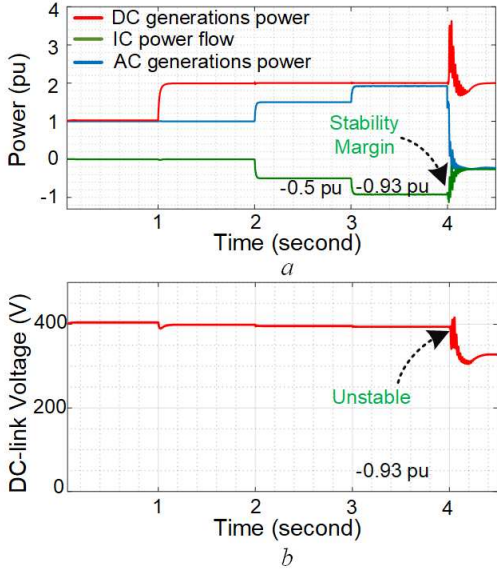


Fig. 6. Dynamic response of DC-link voltage, power flows of dc and ac subgrids and interlinking converter power flow in rectifying mode of operation, (a) Power, (b) DC voltage

LOLE in the first year, which grows to 18% in the 27th year. This is significant because it suggests that dynamic performance has a considerable impact on the overall system risk. These results also emphasize the strong coupling between static and dynamic failures in the system, meaning that the aging of the converters increases the risk of instability in the grid and, consequently, the risk of loss of load.

The inclusion of dynamic failure in the analysis also

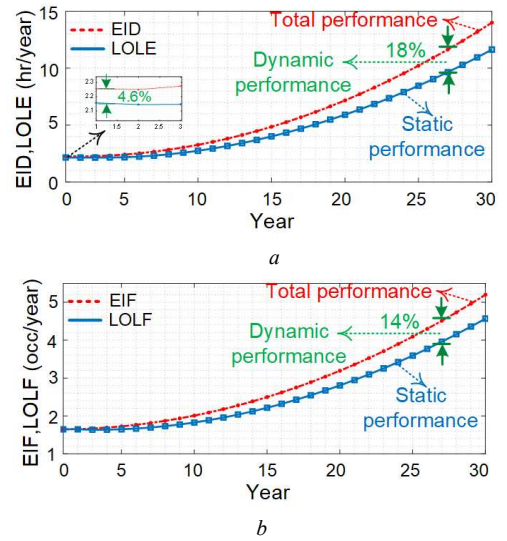


Fig. 7. System-level risk indices for hybrid microgrid shown in Fig. 1 with/without stability margin. (a) EID and LOLE, (b) EIF and LOLF

impacts the frequency of failures in the HMGs. Fig. 7 (b) reveals that the overall risk (EIF), which considers both static and dynamic performance, is consistently higher than the LOLF throughout the 30-year lifespan, resulting in a 14% difference in the 27th year. These findings demonstrate that the proposed model provides a more precise risk assessment when stability issues are included. However, it also highlights that the overall risk may surpass the acceptable and standard desired level of reliability for the system, necessitating the optimal redesign of the system to maintain risk within acceptable limits.

4.4. Impact of Different Load/Solar Irradiance Profiles

The risk indices are derived by combining generation and load profiles. Therefore, different load profiles will result in various risk indices, and this will be paramount in presence of stability. To illustrate the impact of different load profiles on system risk, two load profiles have been considered as Fig. 8 (a) and (b). As it can be seen, the load characteristics differ in terms of MWh and load peak distribution. For example, Fig. 8 (c) compares the cumulative distribution function (CDF) of dc loads. In 50% of the time, dc load profile 1 is higher than 11.9 kW, whereas it is 6.5 kW for dc load profile 2. This means that using dc load profile 1 will require more power flow from the IC in rectifying mode.

By employing load profiles and considering the solar irradiance profile of Fig. 9 (a), the overall risk indices are as shown in Fig. 10. As the results indicate, the overall risk related to load profile 1 for both dynamic and static performance is higher than load profile 2. Fig. 10 also shows that for some load profiles, the risk indices may vary within an acceptable level for both dynamic and static performance, and there is no need to redesign the system. For instance, considering Fig. 10 (a), even though the EID is 24% higher

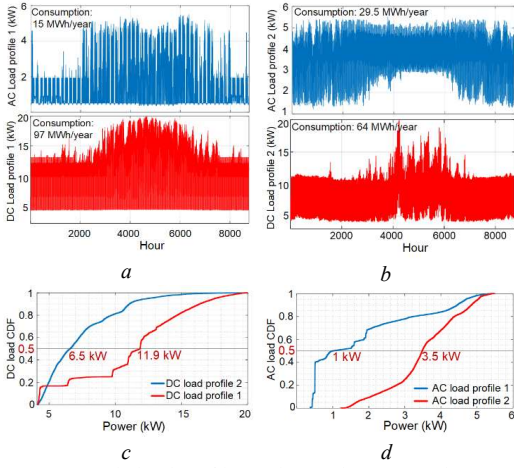


Fig. 8. Hourly load profiles and Cumulative Distribution Function (CDF) of loads: (a) Load profile 1, (b) Load profile 2, (c) CDF of DC loads, (d) CDF of AC loads

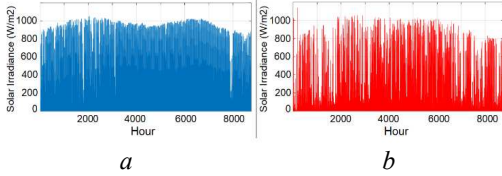


Fig. 9. Annual solar irradiance profiles for PV system. (a) Irradiance profile 1, (b) Irradiance profile 2

than LOLE for load profile 2 in the 27th year, the overall risk at the end of system's lifetime is significantly lower than the risks associated with load profile 1. There is around 55% reduction in EID, indicating that the risk results of load profile 2 may vary within standard margins, and for the HMG with this type of load, there is no need for further optimal design.

Another important point to consider is that dynamic failure may have worst impact on system risk, even if the total risk has decreased. According to Fig. 10 (b), the EIF is 27% higher than LOLF for load profile 2, while this value is only 14% for load profile 1 which has higher overall risk. This is mainly due to the existence of more peak loads on the dc side for load profile 2, requiring the IC to transfer more power in rectifying mode. However, the stability margin confines the flow of power, leading to an increase in the loss of load due to the dynamic performance and ultimately resulting in a higher risk in the system.

These results confirm that load characteristics have a significant impact on the overall system risk, especially when it comes to dynamic failures. However, in some cases, they may guarantee the desired standard level of risk, and there is no need to redesign the system.

Additionally, the non-dispatchable sources and their various mission profiles play a critical role in the total performance and reliability of a system. As depicted in Fig. 11, a comparison of the HMG risk for the solar irradiance profiles shown in Fig. 9 (a) and (b) reveals crucial insights.

According to Fig. 11 (a), reduced solar energy availability during periods of low irradiance (e.g., irradiance profile 2) leads to a higher risk for the system. For example, the EID and LOLE increase by 19% and 17%, respectively. Notably, the impact of changing the solar irradiance profile on EIF/LOLF, as illustrated in Fig. 11 (b), is even more significant, resulting in an approximately 50% higher risk compared to the results obtained from irradiance profile 1. This emphasizes the importance of considering uncertainties coming from different solar irradiance profiles as distinct generation sources in the design and evaluation of the system risk.

4.5. Impact of Different ICs Structure

As outlined in the proposed model, after obtaining the new risk indices, which takes into account both static and dynamic failures, the system risk indices may not be in an acceptable level. If this occurs, different scenarios can be considered to redesign the system while consider stability and reliability perspectives based on the structure of the HMG. The key advantage of the proposed model is that the redesign process is carried out with a holistic approach that considers both perspectives. In this case study, the 10 kVA IC was replaced with two 5 kVA ICs using the same failure data. Fig. 12 illustrates the configuration of the ICs, which are connected between ac and dc sub-grid. Fig. 13 compares the system-level risk indices for the aforementioned structures. According to Fig. 13 (a), using two ICs with the same total capacity results in an 18% reduction in EID and 21% in LOLE compared to using a single 10 kVA IC.

This reconfiguration also affects the number of failures, as shown in Fig. 13 (b). The reduction in EIF is 7%, and for LOLF, it is 9% compared to the single IC connection.

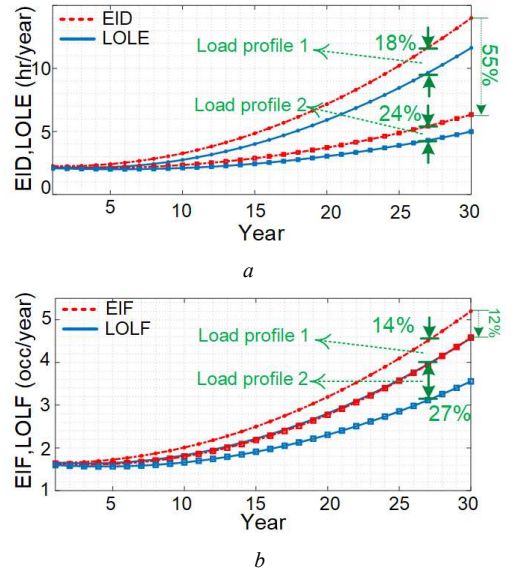


Fig. 10. System-level risk indices for load profile 1 (dot marker) and load profile 2 (square marker) considering the solar irradiance profile 1 shown in Fig. 9 (a). (a) EID and LOLE, (b) EIF and LOLF

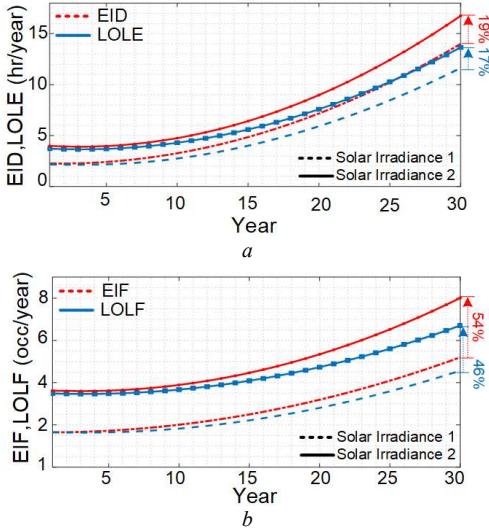


Fig. 11. System-level risk indices for solar irradiance 1 (dash lines) and solar irradiance 2 (solid lines) considering load profile 1 characteristics. (a) EID and LOLE, (b) EIF and LOLE

In fact, increasing the number of ICs provides the system with the opportunity to avoid losing all the power flow in case of IC failure. When only one IC is present in the system, failure results in the loss of the entire 10 kVA capacity. However, with two ICs, if one fails, the other can still transfer power up to 5 kVA.

Although this approach shows promising results, there is still a significant difference between dynamic and static performance. Therefore, it is recommended for systems where the overall risk is not excessively high (e.g., load profile 2) and we need to reduce the risk by 10-20% to ensure acceptable system performance.

To manage and reduce the impact of dynamic performance, other approaches can be used, such as redesigning the converter that has the dominant impact on dynamic performance, optimal oversizing of IC, changing the number of ICs with different capacities, and adding more renewable sources to the DC side. However, all these approaches require an exact sensitivity analysis, which will be conducted in future works.

5. Conclusion

This paper presents a modelling approach that connects stability and reliability to ensure overall risk in HMGs. The proposed method highlights the significant impact of dynamic failures on overall system risk, in addition to the static failures that comes from component failures. Furthermore, the results underscore the interplay between dynamic and static failures, as the aging of converters can lead to system instability and an increased risk of load loss.

The results also indicate that the AC/DC load profiles have a significant impact on the system risk. For certain load profiles, the risk indices, considering the stability margins, may fall within acceptable levels. However, in some cases,

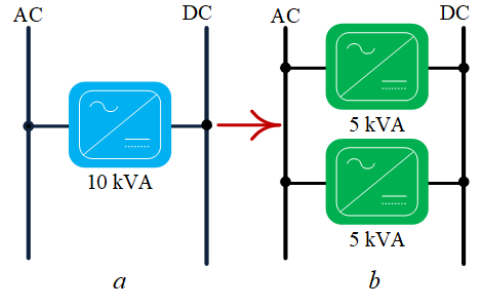


Fig. 12. A hybrid microgrid with (a) a single 10 kVA IC, and (b) two 5 kVA ICs

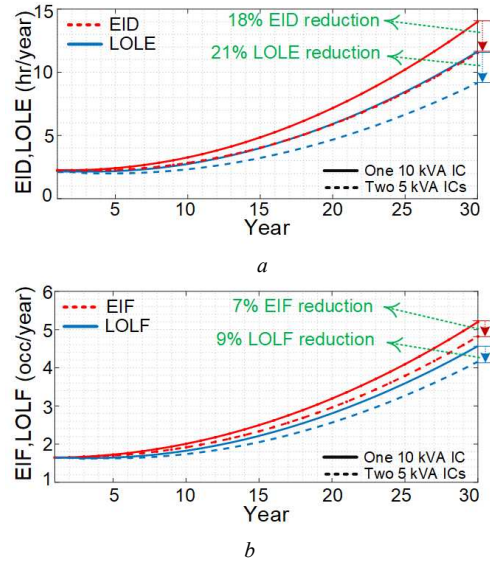


Fig. 13. System-level risk indices for different IC structures: one 10 kVA IC (solid) and two 5 kVA ICs (dashed) (a) EID and LOLE, (b) EIF and LOLE

the load characteristics may lead to an increase in overall risk and a deterioration of dynamic performance. Thus, load profiles are a crucial factor in HMG design.

In addition to its ability to provide an optimal and comprehensive guideline for system redesign or reconfiguration, the proposed method demonstrated that increasing the number of interlinking converters with the same total capacity can significantly reduce the risk of the system, despite the persistence of dynamic failures, which contribute to increased total risk. This reconfiguration method is suitable for systems requiring only a small reduction in risk to ensure a stable and reliable operation.

This model simplifies the coupling of system risk with the stability and reliability of the HMG. Therefore, optimized design and sizing of the components can be achieved to ensure an acceptable system performance.

The future investigation will focus on optimal design and operation of HMGs considering multiple generation sources and interlinking converters in terms of number and capacity.

6. Appendices

Table 2 The characteristics and settings of the interlinking converter and its control system

Symbol	Simulation
V_{dc} (V)	400
f_0 (Hz)	50
$V_{dc}^{min}, V_{dc}^{max}$ (V)	390,410
K_c	8000
f^{min}, f^{max} (Hz)	49,51
L_f (mH)	4.5
k_p, k_I	8,120
$k_{p,PLL}, k_{I,PLL}$	40,1000

Table 3 Failure data of hybrid microgrid converters

Definition	Failure rate λ (10^{-6} /hr)	Repair rate μ (r/hr)	Weibull distribution factors	
			α (yr)	β
Interlinking Converter	2.2	0.007	20	3.8
PV	2.9	0.01	22	4
Microturbine	1.2	0.0125	22	3.5
Fuel Cell	2.1	0.0083	19	3.42

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The Impact of Sun Tracking on the Reliability of Solar Inverters

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The Impact of Sun Tracking on the Reliability of Solar Inverters

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Abstract- This paper explores the impact of sun-tracking systems on the reliability of PV inverters from a wear-out perspective. Besides reliability analysis, the Levelized Cost of Energy (LCOE) for different sun-tracking systems is calculated considering the replacement of PV inverters subjected to wear-out failures. The outcomes are beneficial for design for reliability, system-level planning, and economical design optimization in PV systems considering the trade-off between the obtained energy and the reliability. Simulations on a residential PV system show that even though the obtained energy is increased by sun-tracking systems, the inverter reliability and lifetime is limited compared to the fixed panels. Furthermore, the LCOE under different tracking systems depends on the replacement time and the project lifespan. Numerical analysis on a residential PV inverter illustrates the impact of different factors on the selection of a sun-tracking system for PV applications.

Keywords— Cost Efficiency, Levelized Cost of Energy, Sun Tracking, Reliability.

I. INTRODUCTION

In recent years, ecological and environmental issues caused by the use of fossil fuels have intensified the global paradigm shift to clean and renewable energies. Among renewable energy resources, photovoltaic systems (PVSs) are rapidly growing [1]. PVSs can be integrated into power systems at distribution or transmission levels. To standardize the connection of PVSs, different requirements and codes are developed by national and international committees. However, various challenges and issues are remaining to enhance the performance of such systems including control [2]–[4], protection, operation, reliability, and planning [5]. This paper exclusively focuses on the reliability assessment of PV systems with an emphasis on the impact of sun-tracking systems on PV inverters.

Different factors affecting the reliability of PVSs are addressed in the literature. Such studies can be divided into component-level studies [6]–[9], converter-level studies [10]–[12], and system-level studies [13], [14]. In the component level studies, the reliability enhancement of capacitors and switches are studied in various works. In the converter level studies, a redesign of the power converter control structure is presented. Furthermore, the mutual impact of other converters in a multiple converter system on the reliability of the entire converter-based system is

discussed in [15]. The impact of different converter topologies on the PVS reliability is illustrated in [16].

The reliability of PV converters is analyzed considering the impact of mission profiles in [16]. In the mission profile studies, it is shown that the various solar irradiance profiles can affect the reliability of power electronic devices in a different way. Furthermore, the impact of PV array sizing on the reliability and lifetime of PV systems has been presented in [17]. Although oversizing of PV panels increases the obtained energy, it intensifies the loading of PV inverters and may adversely affect the reliability of PVSs. In other words, the oversizing of PV panels increases the inverter thermal loading, which consequently reduces the total reliability and lifetime of the system. Furthermore, the reliability assessment of PV Battery systems for DC and AC-coupled configurations is studied in [18]. As shown in this study, the point of connection of the battery unit affects the loading of PVS and consequently its reliability. Also, it is concluded that the DC-coupled configuration has higher reliability.

Besides the above-mentioned factors, the impact of sun-tracking systems on the reliability of PV inverters and the overall performance of the PVSs has not been addressed. Even in commercial inverters, there is no recommendation for use of inverters for fixed panels or panels with tracking systems. However, sun-trackers are employed as an effective solution for improving the energy obtained by PVSs. Therefore, they change the loading of the inverter, and consequently, affect the electro-thermal stress of the converter devices. As a result, the converter failure rate, especially those failures associated with the wear-out of components impacts both the converter design and the economic analysis of PVS generation.

The well-known economic measure for renewable generations is the Levelized Cost of Energy (LCOE). It is attributed to the project costs including initial cost, operation, maintenance cost, fuel cost, etc. as well as the produced energy within the planned lifespan [19]–[21]. So far, the replacement of the inverter is considered identical for fixed panels and trackers for LCOE calculation. However, the converter reliability is not the same for different tracking schemes. This will impact the LCOE of the PVS and consequently the planning and design decision-making. Therefore, it is required to analyze the impact of sun-tracking systems on the reliability of PV inverters and overall PVS performance.

This paper explores the impact of sun-tracking systems on the reliability of PVS converters and the associated components. The achievements of this paper can be used

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for the optimal design of the converter and the tracking system. The remainder of this paper is organized as follows. In Section II, the sun-tracking strategies are described. Section III presents the reliability of converters and provides the lifetime model for different components such as IGBT, diodes, and capacitors. The proposed cost-efficiency analysis to find the optimal replacement time of inverters, and LCOE estimation is presented in section IV. The numerical analysis and related discussion, and conclusions of the manuscript are given in sections V and VI, respectively.

II. SUN TRACKING SYSTEMS

A typical structure of a PV system is shown in Fig. 1, which consists of PV arrays, a solar inverter, a connector, and a transformer. In this system, several factors affect the inverter reliability such as solar irradiance, ambient temperature, active and reactive power, etc. [22]. The PV array structure determines the value of active power obtained from solar panels. To extract the maximum possible power, sun-trackers are used, which adjust the PV array orientation at an optimal angle [23]. Depending on the location of installation, the sun-trackers increase the obtained energy by 10-100% compared to the fixed panels [24].

Different sun-tracking systems are illustrated in Fig. 2, which consists of (i) fixed installation, (ii) single-axis tracker, and (iii) dual-axis tracker. In a single-axis tracker, the tracking axis only rotates in one of a horizontal, a vertical, a polar or a tilted direction. For the dual-axis tracking, the two rotating axes of elevation-azimuth, tip-tilt, or tilt-roll tracking are available, which provides a reduced incidence angle to improve overall energy yield.

Fig. 3 shows a one-day solar irradiance for fixed, single-axis, and dual-axis panels, which clearly demonstrates the impact of using a sun-tracking system on the extraction of more energy from PV panels. Dual-axis and fixed panels have the highest and lowest value of obtained energy, respectively. The higher the value of the generated power, the more is the loading of PV converters; and consequently, the rate of aging of inverter components is increased. To show this fact, the reliability of converters is discussed in the next section. Accordingly, the numerical analysis is presented to illustrate the impact of the sun-tracking system on the reliability of PV inverters.

III. RELIABILITY OF CONVERTERS

For reliability assessment of the PV converter, different failure mechanisms of vulnerable devices can be considered. Among them, capacitors and power switches are the most vulnerable devices against failure, which are presented in the following.

The lifetime model of an electrolytic capacitor (L_t) is obtained by using (1).

$$L_t = L_0 \cdot 2^{\frac{T_0 - T_t}{n_1}} \cdot \left(\frac{V_t}{V_0}\right)^{-n_2} \quad (1)$$

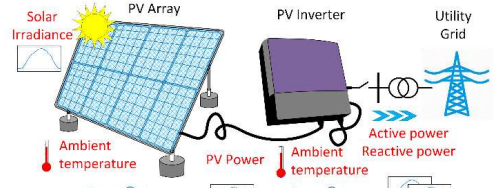


Fig. 1. Typical PV system with different converter lifetime stressors including solar irradiance, ambient temperature, active and reactive power.

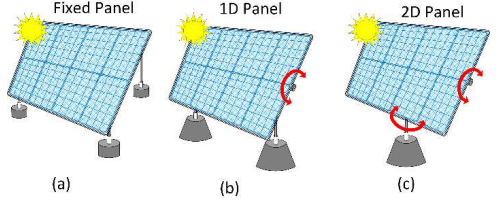


Fig. 2. Different PV array installation (a) fixed panel, (b) horizontal single-axis tracking panel (1D), and (c) dual-axis panel (2D).

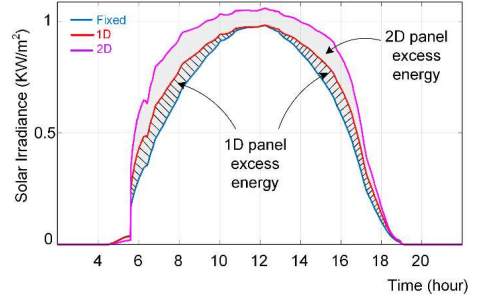


Fig. 3. Solar irradiance on the solar panels with fixed, single-axis, and dual-axis installed panels.

where, L_0 is the nominal lifetime under nominal voltage V_0 and nominal capacitor temperature T_0 , and L_t is the capacitor lifetime under voltage V_t and the capacitor temperature T_t . The constant values of n_1 and n_2 are provided in [25].

Furthermore, the lifetime of power switches mainly depends on the junction temperature and the temperature swing. Number of cycles to failure (N_f) for power switch is related to the minimum junction temperature (T_{jm}) and temperature swing (ΔT_j) as given by (2).

$$N_f = A \times \Delta T_j^\alpha \times e^{\left(\frac{\beta}{T_{jm}}\right)} \times \left(\frac{t_{on}}{1.5}\right)^{-\gamma} \quad (2)$$

where, t_{on} is the rise time of the temperature cycle. A , α , β and γ are lifetime model constants, which can be obtained from aging tests [26]. The values of lifetime constants are given in table I.

Depending on the applied mission profile, the critical devices experience different thermal damages. The damage gradually increases and finally causes a wear-out failure. The wear-out failure prediction procedure of power switches and capacitors are discussed in [27] and this method is adopted here for reliability prediction of PV converter.

IV. LCOE ANALYSIS IN PVS

As discussed in the previous section, working under the different mission profiles with specified sun-tracking schemes leads to different failure rates. Therefore, the reliability and the lifetime of the converter will not be identical for different sun-tracking systems. Hence, to retain the reliability of the converter at a desired level, the converter needs to be redesigned or replaced at a proper time. Since the converter reliability is affected by the sun-tracking scheme, its planned replacement time varies depending on the employed tracking method. On the other hand, the replacement time of the converter will affect the LCOE of the PVS. As already mentioned, the state-of-the-art LCOE analysis does not consider the planned replacement of the converter. However, this will impact the LCOE. Therefore, it is important to model the impact of the sun-tracking system on the inverter reliability and hence on the system LOLE. According to the obtained LCOE, an optimal tracking scheme can be selected for a given mission profile.

To obtain the converter replacement time, the cost-efficiency measure is utilized where the trade-off between planned and unplanned maintenance costs determine the optimal replacement time. Using this method, the converter should be replaced either when it fails or at a pre-specified year of t_0 , whichever comes first [28]. Mathematically, the mean time between failure (MTBF) can be obtained by using (3).

$$\begin{aligned} MTBF(t_0) &= \int_0^{t_0} t f(t) dt + t_0 \cdot \Pr(T \geq t_0) \\ &= \int_0^{t_0} (1 - F(t)) dt = \int_0^{t_0} R(t) dt \end{aligned} \quad (3)$$

where $f(t)$ is aging failure probability density function (PDF), $F(t)$ is the cumulative density function (CDF), and $R(t)$ is the reliability function. In this paper, the reliability function with the Weibull distribution function is used as given by (4).

$$R(t) = \exp\left(-\left(\frac{t}{\alpha}\right)^\beta\right) \quad (4)$$

where, α and β are the scale and shape factors, respectively.

By defining c as planned replacement cost if no failure happens until t_0 , and y as unplanned maintenance loss cost if failure occurs before t_0 , the total mean replacement cost $CT(t_0)$ is obtained by (5).

$$CT(t_0) = \frac{c + y \cdot F(t_0)}{MTBF(t_0)} \quad (5)$$

Furthermore, a Cost Efficiency measure $CE(t_0)$ is represented by (6), in which $r = y/c$ [29].

$$CE(t_0) = \frac{CT(t_0)}{CT(\infty)} = \frac{1 + r \cdot F(t_0) \cdot MTBF(\infty)}{1 + r} \quad (6)$$

High-cost efficiency is obtained in low value for $CE(t_0)$. Thus, the optimal planned maintenance period for converter is calculated by minimizing (6) for each mission profile.

As already mentioned, sun-tracker increases the absorbed energy, and leads to more energy production by PVS. The produced energy by dual-axis panel would

reaches up to 30-35% more than that of fixed panels [30]. However, in addition to more produced energy, the economic evaluation in terms of the additional initial installation and Operation and Maintenance (O&M) costs should be considered. Furthermore, the reliability assessment criteria for different configuration of PV systems (e.g., fixed, single and dual-axis panels) should be derived. To select suitable tracking systems, LCOE is adopted. LCOE is defined as a price at which electricity must be generated from a specific source to break even over the lifetime of the project [31]. The LCOE can be obtained by using (7).

$$LCOE = \frac{I_0 + \frac{F_m}{(1+r)^m} + \sum_{t=1}^n \frac{M_t \cdot (1+g)^t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t} (1 - \text{Degradation})^t} \quad (7)$$

where,

I_0 : initial investment (\$)

M_t : annual operation and maintenance costs (\$)

r : discount rate

F_t : annual fuel cost (which is 0 for PV system)

F_m : cost of inverter replacement in year m

E_t : annual energy production (kWh)

g : operation & maintenance growth rate.

The annual produced energy within the project lifespan is usually considered constant. However, the failure rate of the converter is not constant and increases gradually year-by-year, which adversely affect the total obtained-energy from different structures. Therefore, the output energy should be obtained considering the reliability of the converter to get realistic results. To quantify the subject, a case study is provided in the following.

V. NUMERICAL ANALYSIS

In this section, to evaluate the impact of the sun-tracking system on the reliability of PV inverters, the reliability of a single-phase residential inverter is calculated considering a single-axis, a dual-axis sun-tracker, and a fixed panel. The structure of the PV inverter is shown in Fig. 4, which consists of a boost converter and an H-bridge inverter. The converter specifications including the power switches and capacitor lifetime parameters are summarized in TABLE I. Moreover, the cost of different parts of the system is summarized in TABLE II. The operation and maintenance costs for residential PV systems are given in TABLE III. Furthermore, the PV cost data is derived from the National Renewable Energy Laboratory (NREL) Q1 2021 report [32]. Based on the data represented in [30], the O&M costs for fixed, single, and dual-axis PV systems are around 1.0, 1.28, and 1.5 percent of their total installation prices, respectively.

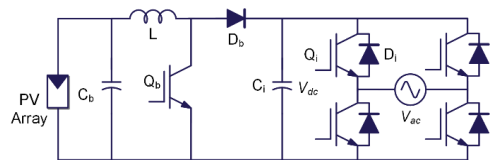


Fig. 4. Structure of the single-phase PV inverter.

TABLE I
INVERTER COMPONENTS SPECIFICATIONS.

Parameter	Value	Parameter	Value
L	2 mH	A	$9.34E14 \pm 5\%$
C_b	120 μF	α	$-4.416 \pm 5\%$
C_i	$3 \times 390 \mu F$	β	$1285 \pm 5\%$
Q_b	IGBT10N60T	γ	$0.3 \pm 5\%$
Q_i	IGBT15N60T	n_1	$10 \pm 5\%$
D_b	IDV20E65D1	n_2	$3 \pm 5\%$
D_i	IDV20E65D1	T_n	$105^\circ C$
f_{sw}	20 kHz	V_n	450 V
V_{dc}	400 V	V_{ac}	230 V, 50 Hz

TABLE II
5kW RESIDENTIAL BENCHMARK COSTS IN US (\$/WDC) [32]

Component	Cost (\$/WDC)
Module	0.33
Inverter	0.27
Structural BoS	0.13
Electrical BoS	0.29
Supply Chain Costs	0.26
Sales Tax	0.07
Install Labor	0.22
Permitting, Inspection, Interconnection	0.31
Profit	0.68
Sales & Marketing (Customer acquisition)	0.4
Overhead (General & Admin.)	0.32
Total Price	3.28

TABLE III
O&M COSTS FOR RESIDENTIAL PV SYSTEMS (\$/kWDC/YEAR) [32]

O&M Type	Cost (\$/kWDC/YEAR)
Module cleaning & vegetation management	1.36
System inspection & monitoring	3.69
Component parts replacement	9.02
Module replacement	1.6
Inverter replacement	7.07
Land lease	0
Property tax	1.9
Insurance, asset management, and security	0.9
Operations administration	3.4
Total O&M	28.94

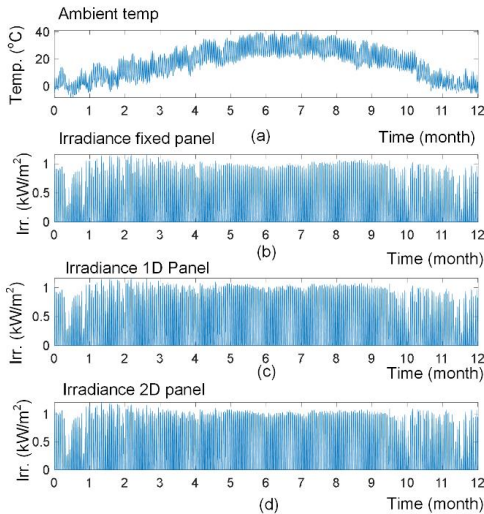


Fig. 5. (a) Annual ambient temperature and solar irradiance for (b) fixed panel, (c) 1D panel and (d) 2D panel.

Fig. 5 shows the annual ambient temperature (T_a) and solar irradiance for fixed, single-axis and dual-axis panels, respectively. For more details, an hourly solar irradiance (kW/m^2) for a cloudy day of a year is shown in Fig. 6 (blue graphs). As shown in Fig. 6, the sun-tracking system increases the loading of the inverter even under the cloudy conditions. In the graph representation form, the junction temperature of a power switch (Q_i) is shown in Fig. 6 (the orange graphs) for different PV array installations. As a conclusion, the junction temperature for a dual-axis panel takes the highest value, and the lowest value is obtained for the fixed panel.

The failure rate of different components under three mission profiles for different PV array installations is given in Fig. 7. As shown in Fig. 7, the H-bridge inverter switches (Q_i) have the main contribution in failure rate of the converter. Furthermore, using sun-trackers results in a higher failure rate of inverter switches. For instance, in 30 years of operation, the failure rate of switches in dual-axis and single-axis panels are respectively 18 and 9 times higher than that of fixed panels. The failure rate of other components for the given mission profiles is negligible.

To show the reason for higher failure rates of the switches under sun-tracking operation, the corresponding junction temperatures for a day of a year are illustrated in Fig. 6. As shown in Fig. 6, the different sun-tracking systems with the corresponding solar irradiance levels are the first reason for the difference in the junction temperature and consequently the failure rates. The higher the energy conversion is, the faster aging of the components occur. As it can be seen in Fig. 6 (orange curves), the mean junction temperature for single and dual tracking systems is higher than that for the fixed panel. Furthermore, the junction temperature swing (ΔT) is higher for single/dual tracking systems compared to the fixed panel due to the low frequency oscillations induced by climate conditions. For instance, in the given day of Fig. 6 and the given thermal cycle, ΔT is $26^\circ C$ for the dual-axis tracker and $18^\circ C$ for the single-axis tracker system, while it is very small for the fixed panel. As a result, according to (2), the higher junction temperature and temperature swing yield to a lower lifetime and faster aging of components as shown in Fig. 7.

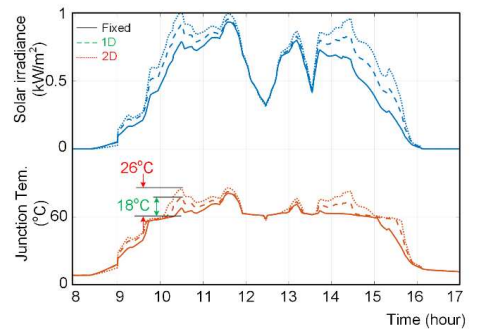


Fig. 6. Hourly results of solar irradiation and measured junction temperature of an IGBT for the fixed, single-axis and dual-axis panels.

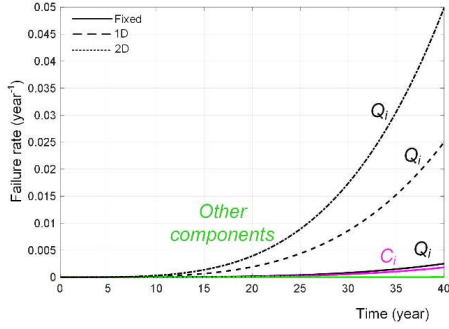


Fig. 7. The failure rate of different components under different mission profiles in Fig. 5.

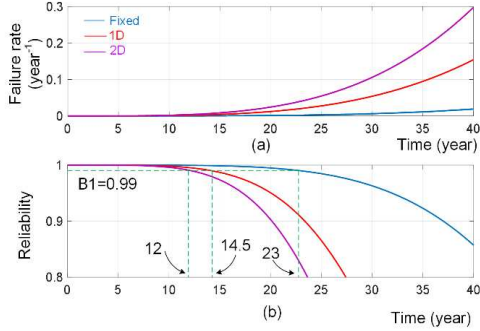


Fig. 8. Obtained (a) total failure rates and (b) reliability functions of PV inverter under fixed, single-axis and dual-axis panels mission profile.

The total failure rate and reliability functions of the PV inverter under a given mission profile with a fixed, single-axis and dual-axis panels are shown in Fig. 8 (a) and (b), respectively. The failure rate of components after around the 10-year operation is increased rapidly when using sun-tracking systems compared to fixed panels. For example, in the 20th year, dual-axis panels impose failure rates of two times higher than that of single-axis panels and three times higher than that of fixed panels. Fig.8 (b) also shows the total reliability of the converter for different mission profiles. According to Fig. 8 (b), employing a fixed panel results in a less stress on the converter, and consequently, a higher reliability for the PVS.

Using sun-trackers decrease the reliability of the converter, such that the reliability index for dual-axis sun-trackers is less than that of for single-axis and fixed panels. For instance, during the 20-year operation, the reliability of the converter is 99.5%, 95% and 90% for fixed, single-axis and dual-axis panels, respectively. Moreover, the converter B1 lifetime – at which the reliability is 99% – is 23, 14.5 and 12 years for the fixed, single-axis and dual-axis panels, respectively. As a result, the converter end-of-life is halved by using sun-trackers compared to the fixed PV arrays. Therefore, although sun-tracker increases the energy availability, it increases the failure rates and consequently the maintenance costs. Therefore, there would be a trade-off between the extracted energy and the converter reliability, which is important for system-level planning of large-scale PV power plants.

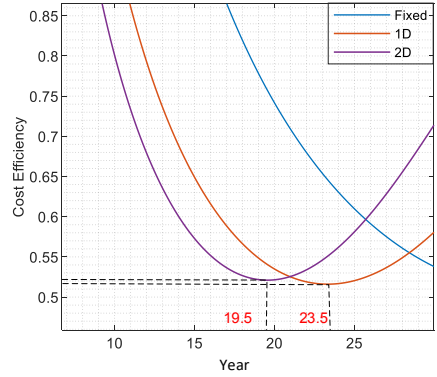


Fig. 9. Cost efficiency of the inverter under fixed, single, and dual-axis PVS used for preventive maintenance planning.

Item	Fixed	Single-axis	Dual-axis
Discount Rate (%)	7	7	7
Degradation (%)	0.7	0.7	0.7
m	0	23.5	19.5
I_0 (\$)	16350	18476	19620
O&M (\$/year)	163.5	236.48	294.3
O&M growth rate (%)	2.5	2.5	2.5

According to the Fig. 8 (b), the reliability behavior of the inverter varies for three tracking schemes. To keep the reliability within an acceptable level, proper preventive maintenance action needs to be taken into account. For instance, the cost efficiency analysis can be done to determine the optimal replacement periods under different tracking systems. The cost-efficiency of the inverter replacement for $r = 2.7$, by assuming 30 years of project lifetime is shown in Fig. 9. The optimal replacement time for dual-axis and single-axis PVS inverter are 19.5 and 23.5 years, respectively. For the fixed panel PVS, it is not required to plan for preventive replacement of the inverter during the 30 years of operation according to Fig. 9. However, in case of failure, corrective maintenance needs to be performed.

By specifying the replacement time and considering the installation and maintenance cost data given in TABLE IV, the LCOE value for different tracking schemes can be achieved. The LCOE of fixed, single-axis, and dual-axis for different operation times are shown in Fig.10. The total produced energy at the end of 30 years for fixed, single-axis, and dual-axis PVSs are 308.2, 372, and 393 MWh, respectively. It means that a 27.5% higher energy is achieved by dual-axis PVs compared to the fixed panels. Also, the increase of energy for single-axis PVS is 21% compared to the fixed panel. However, the LCOE of the dual-axis panel is relatively higher than the others which are 17.5 cents/kWh in the 30th year. Therefore, this scheme is not economical even with higher energy production. On the other hand, if the project lifetime is considered about 25-year, the single-axis topology will be the best choice. Assuming a 30-year operation, it is necessary to replace the inverter of the single-axis structure to keep the reliability of the system at an acceptable level. In this case, the fixed panel would be the proper choice according to Fig. 10.

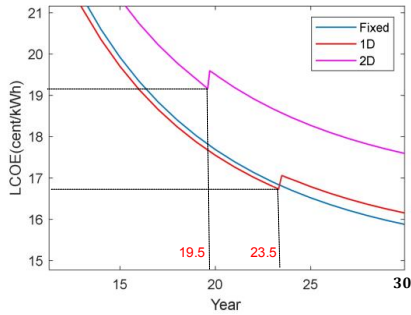


Fig. 10. LCOE estimation of fixed, single-axis, and dual-axis PVs.

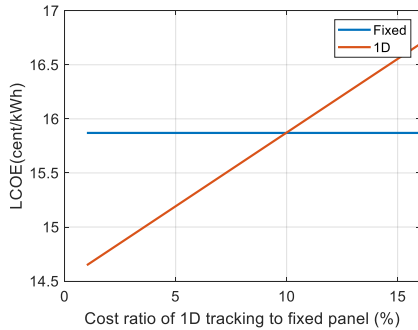


Fig. 11. LCOE PVS for different cost ratios of fixed and single-axis tracker systems.

The LCOE is significantly related to the initial cost of the projects. Therefore, the sensitivity analysis considering the variation of the single-axis tracker system cost to change from 5 to 20 % of the fixed installation has been done. The results of LCOE for different costs of the single-axis tracking system are shown in Fig. 11. According to Fig. 11, if the cost of single-axis PVs exceeds the 10% of fixed panels, the fixed installation is preferred for 30-year operation compared to another topology.

Notably, the obtained results are valid for the cost data given in TABLE IV to illustrate the impact of sun tracking system on PVS performance. The analysis can be performed for different values of discount rate and O&M costs.

VI. CONCLUSION

This paper has explored the impact of sun-trackers on the reliability and performance of solar photovoltaic systems with specific focus on power inverters. Three PV panel installation with fixed structure, single-axis and dual-axis tracking systems have been analyzed. This paper shows that despite of absorbing more energy by tracking systems, the inverter failure rate is remarkably increased; and thus, its end of life is considerably limited. Furthermore, the impact of sun-trackers on the failure rate of different components has been explored. For given mission profiles and selected converter components, it is shown that the inverter switches became the most failure-prone components.

According to the results of this study, for a reliable and

an optimal design of the PV inverter, the impact of tracking systems must be taken into account. Moreover, even though the excess energy will improve the availability of energy in the whole system, the converter lifetime limitations affect the long-term planning and maintenance decisions. Thus, by considering the reliability of converters, the economic decision may be changed. It has also been illustrated that the selection of a fixed or tracking system depends on the project timespan as well as economical parameters. The future work could be focused on the impact of PV systems equipped with different sun tracking strategies on the reliability of power systems. This may impact the energy availability of power systems and hence will give better insight to design of sun tracking systems and inverters in large scale PV power plants.

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Risk Evaluation of Hybrid Microgrids
Considering DC-Link Voltage Stability

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Abstract— This paper proposes a new risk assessment framework for hybrid microgrids design incorporating DC-link voltage stability issues of bidirectional voltage source converters. The dynamics of the ac side may lead to unstable operation of the dc-link voltage in rectifying mode. This problem will decrease the stability margin and limit the allowable power flow of converters in rectification mode. As a result, the overall reliability of the microgrid will be affected. Therefore, stability issues need to be taken into account within the planning and design of microgrids. Unlike the operation phase, where deterministic stability analyses are performed to ensure a secure operation of microgrids, in the design phase, the impact of stability on the overall system reliability needs to be modeled. The proposed method illustrates the impact of stability on the overall system risk thus facilitating stability-informed design optimization in microgrids. The effectiveness of the proposed method is verified through a hybrid microgrid (HMG) system considering a DC-link voltage instability issue. The risk assessment model is applicable for different stability challenges in future power electronic based power systems.

Keywords— DC-link Voltage Stability, Rectification mode, Reliability, Risk Assessment, Stability Margin

I. INTRODUCTION

Moving towards carbon-neutral technologies in power systems, while facilitating high sustainability, will compromise the system reliability. The induced uncertainties by variable and climate-dependent renewable generations and dynamic interactions of power electronics will remarkably impact the stability of power electronics-based power systems such as microgrids [1]. Besides deterministic stability analysis in such systems, for optimized design and operation, it is also required to incorporate the stability issues in the planning phase by proper risk assessment methods.

Risk assessment in the power system context is so far performed for static behavior of the system components considering the outage frequency and expected downtimes [2]. These methods thus provide a measure of system reliability based on the duration of a power outage, e.g., loss of load expectation (LOLE), expected energy not supplied (EENS), loss of load frequency (LOLF), etc., that are used for planning and design optimization in power grids. Recently, by increasing the volume of power converter-based units, the reliability of power converters needs to be incorporated into the system-level reliability assessment [3]. This method models the impact of both renewable uncertainties and converter outages that help model-based design and planning of power electronic-based power systems.

Despite of the conventional power systems, microgrids include a set of uncertain power sources combined with power electronics, which induce reliability issues in the system. The power electronic device's lifetime is related to operating conditions such as temperature, humidity, and power loading mission profiles. Several reliability models to enhance the risk and efficiency of the microgrids have been addressed in the planning and design phase [2]–[4]. Moreover, the impact of source's uncertainties like photovoltaic (PV) and wind energy systems on the reliability of the power system have been analyzed comprehensively in different kinds of literature [5], [6]. However, the reliability of the microgrids can be deteriorated by other issues such as stability.

The existing stability challenges in the microgrids and their classification are completely different from the conventional methods [7]. This is due to the small size of microgrids, fast dynamic changes, higher R/X relationship [8], strong coupling between system variables [9], etc. Therefore, the stability issues can be investigated from various perspectives such as control system stability, power supply and balance stability.

The energy conversion of microgrids is performed using power electronics, and among them, the voltage source converters (VSCs) are widely used for various applications [10]. The VSCs can pose many stability challenges and therefore affect the overall risk of the power system. In order to investigate the impact of the stability challenges and represent the new general risk assessment model, the focus of this paper is on the dc-link voltage stability of VSC in HMGs. The VSCs can transfer power in inversion and rectifying mode. However, a comprehensive analysis [11], [12] indicates that the VSC runs into an instable mode in rectifying mode during nominal operating conditions.

Some solutions are explored in [12], and [13] to guarantee the stable operation of VSCs in rectifying mode. Restricting the transferred power in rectifying mode or considering the non-minimum phase behavior of VSC in the design phase is some of the proposed solutions. But these approaches may limit the system dynamics and reduce the efficiency of the system. Therefore, it is important to address the impact of stability on the overall reliability of the system and then take into account in planning and design phase of HMGs.

So far, the stability analysis is performed to model the stability root causes and figure out mitigation methods to enhance the system stability. Furthermore, the impact of

uncertainties on the stability margin and stability indices are analyzed in a probabilistic way in [14]–[16]. However, the impact of stability issues at the system level has not been addressed in the literature, while this is of paramount importance for ensuring stable and secure operation when doing design optimization.

In order to address this issue, this paper proposes a risk assessment approach to incorporate stability issues into power system risks. This approach facilitates strengthening the system stability and managing the system risk within the design of power systems to guarantee the overall system reliability. The proposed approach is examined in a power electronics-based hybrid microgrid (HMG) considering the DC-link voltage stability using simulation studies.

The remainder of this paper is organized as follows. In the Section II, the mathematical linear model of the voltage source converter is described to find out the stability margin. Section III presents the proposed risk assessment model of the HMG considering the stability issues. To show the impact of the proposed model on risk of the system, some case studies are analyzed in Section IV. Finally, the outcomes are presented in Section V.

II. MATHEMATICAL MODEL OF VOLTAGE SOURCE CONVERTER

This section investigates the impact of ac side dynamics on the Interlinking Converter (IC) dc-link voltage stability in rectifying mode of operation. Fig. 1 shows a general schematic diagram of a voltage source interlinking converter that can operate either in inversion or rectification mode. The DC and AC sub-grids comprise various dispatchable and non-dispatchable sources along with loads. A mathematical model of the power flow of Fig. 1 is given in (1).

$$\frac{1}{2}C_{dc}\frac{d}{dt}(V_{dc}^2) = P_{dc} - P_{ac} \quad (1)$$

Where C_{dc} and V_{dc} are the DC-link capacitor and voltage, P_{dc} and P_{ac} are the exchanged dc and ac powers as shown in Fig. 1.

The left side of (1) is the energy variation of the dc-link capacitor. As this term is nonlinear based on V_{dc} , the term of $W = 0.5C_{dc}V_{dc}^2$ is considered as a space state variable instead of V_{dc} . Furthermore, the ac side power of the IC can be derived as:

$$P_{ac} = \frac{3}{2}(V_{gd} \cdot I_d + V_{gq} \cdot I_q) + P_{Lf} \quad (2)$$

Where (I_d, I_q) and (V_{gd}, V_{gq}) are dq -frame components of the ac-side currents (I_{abc}) and voltages (V_g). The term P_{Lf} is

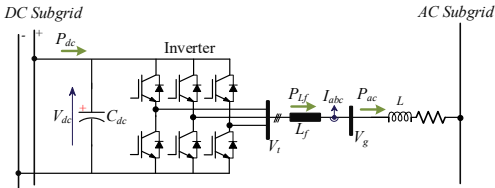


Fig. 1. Single Line Diagram of VSC for bidirectional power flow in HMGs.

the instantaneous power of the ac filter which can be obtained as (3) [12].

$$P_{Lf} = \frac{3}{2}L_f \left(I_d \cdot \frac{dI_d}{dt} + I_q \cdot \frac{dI_q}{dt} \right) \quad (3)$$

In the conventional control methods, the term of P_{Lf} is neglected due to its small value and zero value in the steady state. However, this term may cause unstable operation of the system in some operating points.

By considering the zero value for V_{gq} and substituting (3) and (2) into (1), it results in (4).

$$\frac{dW}{dt} = P_{dc} - \frac{3}{2}V_{gd}I_d - \frac{3}{2}L_f \left(I_d \cdot \frac{dI_d}{dt} + I_q \cdot \frac{dI_q}{dt} \right) \quad (4)$$

Linearizing (4) at the operating point, we obtain:

$$\frac{dW}{dt} = P_{dc} - \frac{3}{2}V_{gd}I_d - \frac{3}{2}L_f \left(I_d^0 \frac{dI_d}{dt} + I_q^0 \frac{dI_q}{dt} \right) \quad (5)$$

Where I_d^0 and I_q^0 are the ac filter currents at the operating point. Using (1) and considering that P_{Lf} is zero in steady state the I_d^0 is obtained as $I_d^0 = P_{dc}/1.5V_{gd}$.

Re-writing (5) in the Laplace domain and substituting I_d^0 results (6), where “ s ” is the Laplace operator.

$$W(s) = \frac{P_{dc}(s)}{s} - \frac{\left(\frac{3}{2}V_{gd} + \frac{L_f P_{dc}}{V_{gd}} s \right)}{s} I_d(s) - \frac{3}{2}L_f I_q^0 s I_q(s) \quad (6)$$

Equation (6) shows the impact of the ac filter energy, in which the transfer function of $W(s)/I_d(s)$ has a zero at $Z = -1.5V_{gd}^2/L_f P_{dc}$. Therefore, neglecting the P_{Lf} will remove this zero from the calculations.

The location of zero depends on the operating point of the system (P_{dc}) and can vary from $-\infty$ to $+\infty$. In inversion mode the P_{dc} is positive, and thus the zero is located at the left-hand side of the S-plane. In contrast, rectifying mode of operation yields negative P_{dc} , which moves the zero to the right-hand side. By operation of the IC in nominal power in rectifying mode, the zero shifts closer to the origin. Therefore, the dc-link voltage behavior will be as a non-minimum phase, which limits the phase margin and may cause system instability.

To find the maximum allowable transfer power of IC in rectifying mode and show the effect of non-minimum phase zero, the IC of Fig. 1 with the parameters given in TABLE I is investigated. The corresponding frequency response for different power flows (-1 p.u to +1 p.u) is depicted in Fig. 2. For positive P_{dc} , the stability margin increases by adding positive phase to the system. However, in rectifying mode of operation, in which P_{dc} is negative, the corresponding zero adds negative phase margin to the system. Thus, according to the TABLE II for P_{dc} more negative than -0.5 p.u the system

TABLE I
PARAMETERS OF THE INTERLINK CONVERTER (IC) UNDER STUDY

Parameters	Symbol	Value
Nominal Power	P_{nom}	12 kW
Line to Line Voltage	V_{LL}	380 V
DC link Voltage	V_{dc}	1100 V
Filter Inductor	L_f	3.5 mH
DC Link Capacitor	C_{dc}	4 mF

TABLE II
STABILITY MARGIN OF THE DC-LINK VOLTAGE CONTROL

$P_{dc}(p.u.)$	Phase Margin (°)	Gain Margin (dB)
1	142	-
0.5	113	-
0.1	95	-
0	74	-
-0.1	60	9
-0.5	46	6
-0.8	32	4
-0.85	26	3
-0.9	18	1
-0.93 -1	Unstable	

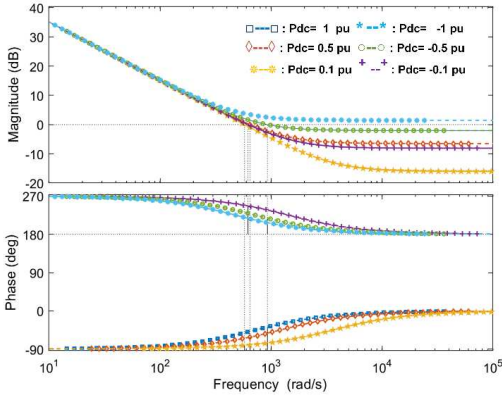


Fig. 2. Frequency response of the system for different P_{dc} . Operating both in rectifying and inversion mode.

will operate in undesirable performance, and for P_{dc} negative than -0.93 p.u the system will be unstable.

By determining the stability margin and consequently the maximum power flow for the IC in rectifying mode, this value will be taken into consideration in the risk assessment analysis in next sections.

III. PROPOSED RISK ASSESSMENT APPROACH

In this section, a new risk assessment method for HMG including the DC-link voltage stability margin is proposed. In this model, regarding to the allowable power transfer capacity of IC between ac and dc grids in rectifying mode which ensures the stable operation of DC-link voltage, the stability margin is obtained as discussed in Section II. Afterwards, the updated availability state of the IC is incorporated into the system risk assessment. More details pertaining to this stability issue is discussed in [17] and in this paper the results of that are employed. The flowchart of the proposed risk assessment model is illustrated in Fig. 3 which comprises the conventional risk assessment method and the proposed

model. In the following, both models are elaborated.

A. The conventional risk assessment method

In this model, at first, the availability states of the generation sources are obtained by using different methods like Monte Carlo simulation, Markov method, and etc. In this paper, the Monte Carlo simulation is used. After that, the generation's power availability is determined by the convolution of the generated states with existing mission profiles or the power of dispatchable units. Then, based on the HMG topology, the power flow and energy management are performed, and finally according to the loss of energy the risk of the system is obtained.

Different reliability indices can be calculated to evaluate the risk of the HMG. Here, two important indices are considered as (7) [18].

$$LOLE = \frac{1}{N} \sum_{i=1}^N LLD_i \left(\frac{hr}{year} \right) \quad (7)$$

$$LOLF = \frac{1}{N} \sum_{i=1}^N LLO_i \left(\frac{occ}{year} \right)$$

Where LOLE is the Loss of Load Expectation and it is defined as the total hours per year that the load cannot be supplied, N is the sampling years and LLD_i is the loss of load duration. Moreover, LOLF is the Loss of Load Frequency, which is the number of periods per year that the load is not supplied, and LLO_i is the loss of load occurrence.

B. Proposed risk assessment method considering the stability of the IC

In the conventional method, it is assumed that the interlink converter can transfer the power up to its nominal capacity (± 1 p.u) in both inversion and rectifying mode. But, as described in section II, the DC-link voltage is being unstable in rectifying mode when the converter operates close to -1 p.u. Therefore, this issue affects the risk of the HMG, and its impact must be taken into account in the total risk assessment of the system. Notably, in this paper, only the dc-link voltage stability is considered, however, without losing the generality of the method, other types of stabilities can be incorporated into the proposed risk assessment method. The conventional method can be modified as depicted in Fig. 3.

As shown in Fig. 3, the stability analysis of HMG is done to find the stable operation of IC dc -link voltage and consequently the limited transferred power in rectifying mode as described in the previous section. This analysis can be done using different methods like Eigenvalue analysis, Nyquist stability criterion, Lyapunov Method, etc.

Having the stability margin of the IC, the next step is to extract a new availability state for the converter. This is done in same way as the conventional method by employing the Monte Carlo or another method. Afterwards, the generation units availability and energy management of the HMG based on the new availability state of the IC are calculated. Finally, the risk of the system incorporating the stability is evaluated and compared with the conventional model.

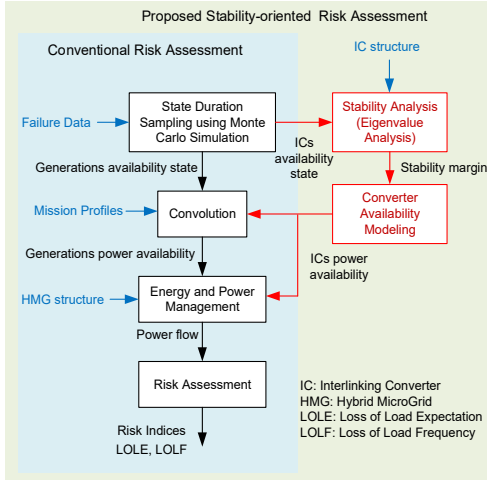


Fig. 3. The proposed risk assessment model considering the stability issues in the Interlinking Converter (IC).

IV. NUMERICAL ANALYSIS OF MICROGRID

In this section, to verify the effectiveness of the proposed risk assessment method, a hybrid microgrid with two different IC structures is analyzed as shown in Fig. 4. As shown in the figure, the ac sub-grid consists of two 7.5 kVA dispatchable generation units (G1, G2) and the dc sub-grid comprises a 10 kVA (G3) unit and a PV system with a maximum power of 10 kW. To show the impact of the system topology and its effect on the total risk of the system, the ac and dc sub-grids of Fig. 4(a) are connected through one 12 kVA converter, whereas in Fig. 4(b) two 6 kVA converters are used. Moreover, the solar irradiance of the PV system is shown in Fig. 5 as a mission profile. The time resolution of the mission profile is per hour.

A. Energy and Power Management system

In order to supply the ac and dc sub-grid loads, the power management system extracts the maximum power from the PV system and during uncertainties or energy shortages the remaining dispatchable generation units (e.g., G1, G2, and G3) supply the loads as follows:

The PV system operates in the MPPT mode for different mission profiles to support both the ac and dc loads. If the PV can not supply the loads, G3 has to supply the dc side excess load and the G1 and G2 have to supply the ac side load. When the dc side requires more energy, the ac sub-grid excess energy is transferred to the dc sub-grid through the IC. This hypothesis is the same for the dc side and whenever the ac sub-grid requires more energy, it will be supplied by the dc sub-grid.

During the insufficient supply of energy, the power transfer limits of the IC due to its confined capacity, and stability margin criteria in rectifying mode, the availability of the HMG will be deteriorated.

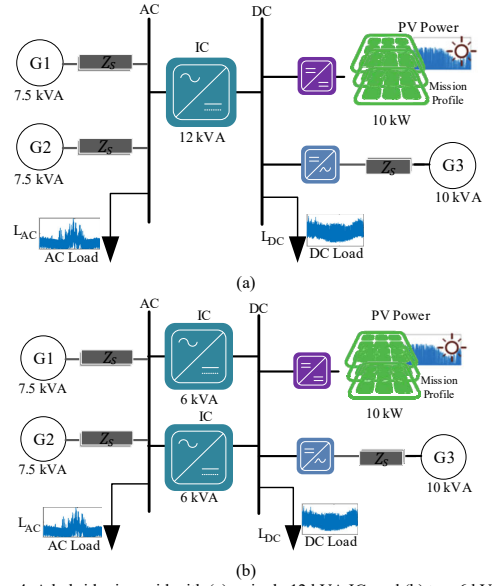


Fig. 4. A hybrid microgrid with (a) a single 12 kVA IC, and (b) two 6 kVA ICs.

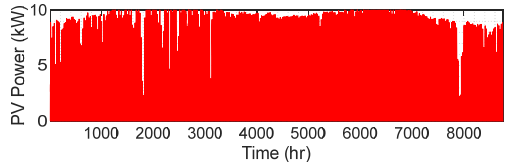


Fig. 5. A 10 kW PV system mission profile for one year operation

B. Impact of Load Profiles

The ac and dc load curve profiles directly affect the transferred power through the IC both in inversion and rectifying mode. Therefore, in order to investigate the impact of the load profile on the proposed method, two different load profiles for both ac and dc sub-grids have been considered as shown in Fig. 6 and Fig. 7. The hourly AC and DC load profile 1 is depicted in Fig. 6. (a) and (b) respectively. In addition, Fig. 7 (a) and (b) shows the load profile 2 characteristics.

In order to illustrate the load profile characteristics, the corresponding Cumulative Distribution Function (CDF) is shown in Fig. 8(a) and (b) for the AC and DC loads respectively. Fig. 8 shows the distribution of the loads, in which, e.g., 50% of load power is higher than 0.7 kW for ac load profile 1 and 1.65 kW for ac load profile 2. This will impact the power flow of the interlinking converter.

C. Case Studies

Based on aforementioned data and calculated stability margin for the converter in the Section II, two different scenarios have been investigated to show the impact of dc-link voltage stability on the risk assessment of the HMG. The maximum allowable transferred power of the IC in rectifying

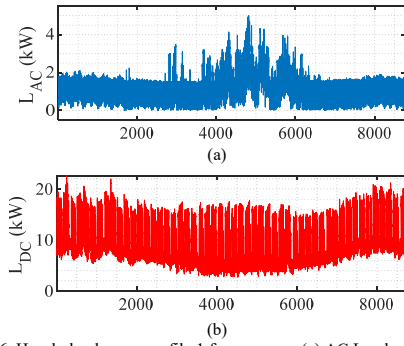


Fig. 6. Hourly load curve profile 1 for one year: (a) AC Load profile 1 (L_{AC}), and (b) DC load profile 1 (L_{DC}).

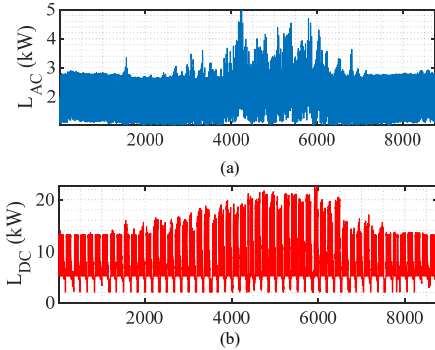


Fig. 7. Hourly load curve profile 2 for one year: (a) AC Load profile 2 (L_{AC}), and (b) DC load profile 2 (L_{DC}).

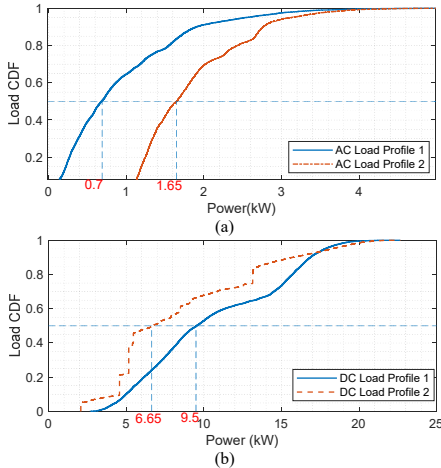


Fig. 8. The Cumulative Distribution Function (CDF) of (a) AC load profiles and (b) DC load profiles

mode is considered -0.935 p.u to maintain the system in stable operating mode. It is worth mentioning that to extract the stability margin, small-signal stability analysis is needed to be employed. Details of each scenario is as follows:

Scenario 1) In this case the HMG of Fig. 4(a) is analyzed

in which ac and dc sub-grids are connected via one 12 kVA IC. The risk assessment results for Load profile 1 and Load profile 2 are shown in TABLE III. For a better understanding, the conventional and the proposed risk assessment methods are compared in TABLE III.

In the conventional method, it is assumed that the IC can transfer the power of ± 1 p.u without any stability issues on the dc-link voltage. Therefore, the LOLE and LOLF of load profile 1 will be 2.73 hr/year and 0.63 occ/year respectively. However, in the proposed method by considering the stability margin of -0.935 p.u for IC in rectifying mode, the IC restricts the energy supply for some hours and consequently reduces the whole HMG availability.

Thus, as depicted in TABLE III the LOLE and LOLF will be increased to 2.99 hr/year and 0.67 occ/year respectively. The rate of changes for the LOLE will be 9.52% and for the LOLF will be 6.35% which shows a significant increment compared to the conventional method. Therefore, considering the stable operation of the HMG, which leads to specifying the stability margin for the IC, it deteriorates the risk of the system.

On the other hand, the load profile and its characteristics directly affect the risk of the system. As shown in TABLE III by employing Load profile 2, the LOLE and LOLF in conventional method will be 4.28 hr/year and 2.64 occ/year, which shows a drastic increase compared to Load profile 1. These results by considering the stability margin are increased by 30.24% for LOLE and 38.59% for LOLF. Thus, depending on the type of the loads, the stability margin can increase the risk of the system significantly. Therefore, this issue must be considered in the design phase to keep the risk of the system in a reasonable range.

Scenario 2) In this case two 6 kVA ICs are used in parallel according to Fig. 4(b) rather than just using one 12 kVA IC. The results of the risk assessment is shown in TABLE IV. The two main outcomes of this structure are as follows:

1) the overall reliability indices for either conventional or proposed method are reduced for both load profiles. For instance, the LOLE of Load profile 1 in the conventional method is decreased from 2.73 to 2.12, and for proposed method reaches to 2.45 from 2.99. This can be explained in a way that using two ICs structure rather than one IC with the

TABLE III
RELIABILITY INDICES OF HMG FOR SCENARIO 1 WITH ONE IC

	Load profile 1		Load profile 2	
	LOLE (hr/yr)	LOLF (occ/yr)	LOLE (hr/yr)	LOLF (occ/yr)
Conventional method	2.73	0.63	4.28	2.64
Proposed Method	2.99	0.67	5.58	3.65
Rate of Change (%)	9.52 %	6.35 %	30.24 %	38.59 %

TABLE IV
RELIABILITY INDICES OF HMG FOR SCENARIO 2 WITH 2 ICs

	Load profile 1		Load profile 2	
	LOLE (hr/yr)	LOLF (occ/yr)	LOLE (hr/yr)	LOLF (occ/yr)
Conventional method	2.12	0.55	4.16	2.57
Proposed Method	2.45	0.63	5.37	3.56
Rate of Change (%)	15.7 %	13.73 %	29.09 %	38.52 %

same capacity, prevent the whole power flow loss during the IC failure. It means that in some cases at least one of the ICs is available to transfer the power while the failure of a single IC structure will isolate the ac and dc sub-grids. Therefore, using parallel ICs with the same capacity of a single IC improves the overall risk of the HMG.

2) Considering the stability margin to be the same as the first scenario will deteriorate the risk of the HMG. As depicted in TABLE IV, for Load profile 1 the LOLE and LOLF are 15.76% and 13.73% higher than the conventional method respectively. This situation is being worst for Load profile 2 due to its load characteristics, such that, the LOLE and LOLF are increased by 29.09% and 38.52% respectively. It is worth mentioning that the rate of risk changes by considering the stability margin in two IC structures is more than in a single IC structure. It is because sometimes there is enough power to transfer through the converter, but due to failure in one of the ICs, a maximum of 6 kVA power can transfer while in a single IC structure the capacity is 12 kVA. Thus, in some cases, two IC HMG might lose more energy than in a single IC. In other words, in addition to stability margin criteria, the unavailability of one 6 kVA IC will cause more energy reduction for a while.

V. CONCLUSION

This paper has proposed a method for risk assessment in microgrids considering the impact of stability and load-generation uncertainties. The impact of DC-link voltage instability on the power transfer capability of interlinking converters and consequently its effect on the total risk of hybrid microgrids have been explored. The results showed that the stability margin is limited in rectifying mode of operation, which is because of the non-minimum phase behavior of the IC. This issue may cause instability of the system and it is required to consider the stability margin of the ICs in HMG.

In order to model and address this stability issue a general risk assessment model has been proposed in this paper. The numeric analysis for different load-generation profiles and IC structures indicated that considering the stability margin significantly increases the risk of the system. Even though increasing the number of ICs with the same rated power reduces the risk of HMG compared to the single IC, but still the stability margin affects the overall system reliability. Furthermore, the risk of the system may be deteriorated by changing the load characteristics and therefore, the rate of risk changes compared to the conventional method will be remarkable and needs to be included.

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A Perspective on Power Converters Design: Stability and Reliability Aspects

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A Perspective on Power Converters Design: Stability and Reliability Aspects

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Abstract— This paper proposes a new approach for design of power electronics converters considering reliability and stability issues from a system level perspective. Conventional design approaches rely only the reliability of the overall system. However, a converter failure can also introduce stability issues, which in turn increase the risk of loss of load in power electronics-based power systems. This may be severe considering increasing failure rate due to aging of converters. In this paper, a modeling approach is proposed to link the reliability of the converter, stability, and risk of the system in order to design a converter to guarantee acceptable performance of the overall system. Simulations on a hybrid micro grid (HMG) illustrate that even though the stability issues increase the total risk of the system, optimal oversizing and redesigning of the critical components can reduce the risk of system and minimize the adverse impacts of the system stability.

Index Terms—Dynamic performance, Reliability, Stability margin, Static performance

I. INTRODUCTION

Power electronics has become the backbone of modern society in various sectors such as transportation, Power to X, energy savings and smart microgrids [1]. This huge penetration of power electronics in the power systems has led to some major challenges such as low inertia, harmonics, stability, and reliability [2]. These challenges are prominent e.g., in Hybrid Microgrids (HMGs). Two major challenges the power converters are facing in HMGs are their stability and reliability. The reliability and efficiency remarkably depend on the performance of power electronics converters. Reliability is associated with the failure of converter components, which indicates the static performance of the converters [3]. Furthermore, stability is subjected to the dynamic performance of the converters [4]. By proliferation of power electronics converters in power systems, these two issues are no longer independent, and they are mutually interacting with each other. This will in turn affect the design of converter and the total performance of the power systems.

So far, design of the converter has been performed considering the aging of its components using physics of failure analysis under specified mission profiles [5]. By this, the converter components are designed in a way that the total reliability of the power converter fits the required level of probability of survival. The converters have been analyzed under different operating conditions to evaluate their useful lifetime and thereby extract the most fragile

components. Humidity can also strongly affect on power electronic switches and capacitors [6]. Humidity will deteriorate the degradation and lead to leakage current increment or voltage blocking capability reduction in switches. The temperature and temperature cycling also have a remarkable impact on converters lifetime [7]. It may affect some demanding areas in semiconductors like baseplate solder joints, chip solder joints, and wire bonds. Such issues gradually increase the probability of components failure and consequently push the static performance of the converters into a higher risk mode.

The component-level risk assessment later has recently been expanded to consider the power system performance [8], where the design of converters is performed to guarantee desired level of reliability in power system, which is measured by risk indices including loss of load expectation (LOLE) and loss of load frequency (LOLF) [9]. This system-level risk assessment method, models both components failure and renewable generations uncertainties, which will be beneficial to include in design, planning and operation phase.

However, by increasing the failure of the components, not only the LOLE will be increased, but also, the risk of instability in the power grid will also be challenged. Therefore, this needs to be taken into account during design of a converters for grid applications as well as in the system analysis. The stability challenges in HMGs are not restricted only to the frequency and voltage stability and they can be analyzed from different perspectives like converter and electric machine stability, power supply stability, and etc. [10].

The stability issues similar to the components failure can induce various restrictions in the power system and increase the risk of loss of load. For instance, the non-minimum phase characteristics of bidirectional voltage source converters, may put the DC-link voltage of converters in unstable mode in rectifying mode of operation [11]–[12]. As demonstrated in [11] and [12], the interlinking converters, which connect the ac and dc sub-grids to each other, have an important role on stability of HMGs. It is shown that when the transferred power of interlinking converter increases from ac to the dc sub-grid, the stability margin of the HMG might be reduced, and the DC-link voltage may become unstable.

The dynamics in the system lead to critical limitations in load supply and these types of challenges will increase the overall system risk. Therefore, it is important to

consider the impact of stability on risk assessment evaluation models.

So far, the stability and reliability issues have been analyzed independently and the interaction between static and dynamic failures have not been addressed in the risk assessment models, while this plays an important role on stable and reliable design of the modern power electronic based power systems.

In order to address above-mentioned issues, this paper proposes a new approach for risk assessment in power electronic based power system that can model both static and dynamic performance of the system. This will bridge the interlinking system risk to stability and reliability of the converters. As a result, optimal design of converters can be performed in order to ensure both reliability and stability of the power grid.

The remainder of this paper is organized as follows. In section II, the proposed stability-oriented risk assessment approach for HMGs is presented. Section III gives some study cases and simulation results to illustrate the effectiveness of the proposed approach on the optimal design of converters and to guarantee stable and reliable operation of the HMGs. Finally, the conclusions of the results are given in section IV.

II. PROPOSED SYSTEM PERFORMANCE MODELING

In conventional risk assessment methods for power systems, at first, the availability of the generation sources is obtained by using different methods like Monte Carlo simulations, and Markov chain approach. In this paper, the Monte Carlo simulations method is employed. Afterward, the availability of the generation's power is determined by the convolution of the generation's available states with the mission profiles of load and generations. Then, the power flow and energy management among energy sources are performed, and finally according to the loss of load the risk of the system is obtained.

There are different risk indices to measure the loss of load in power systems. The popular ones are the amount of time per year that the load cannot be supplied – measured by Loss of Load Expectation (LOLE) and the number of times per year that the load cannot be supplied – known as Loss of Load Frequency (LOLF). This procedure is shown in Fig. 1. The mathematical definition of the mentioned indices is described at (1) [13]:

$$\begin{aligned} LOLE &= \sum_{i=1}^n P_i(C_i - L_i) \left(\frac{hr}{year} \right) \\ LOLF &= \sum_{i=1}^n f_i \left(\frac{occ}{year} \right) \end{aligned} \quad (1)$$

Where C_i is available capacity on hour i , L_i is forecast peak load on hour i , and $P_i(C_i - L_i)$ is the probability of loss of load on hour i . f_i is the loss of load occurrence.

Conventionally, these indices consider the static failure of components. In order to incorporate the impact of dynamic performance on the system risk, the impact of stability can be modeled as shown in Fig. 1. As an example

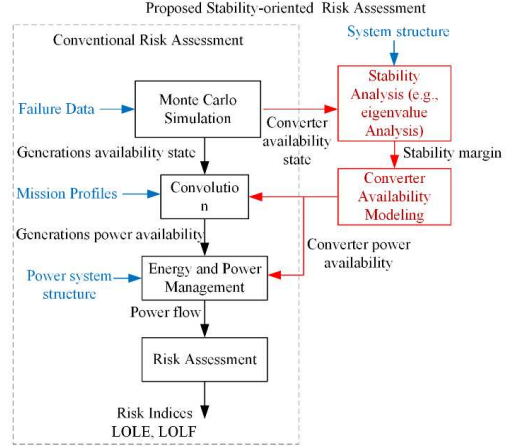


Fig. 1. The proposed system level risk assessment with inclusion of dynamic and static performance of power converters.

of stability which is used in this paper – without losing generality – the DC link voltage stability in rectifying mode of bi-directional three-phase AC-DC converters have been considered. According to the non-minimum phase characteristics of these converters in rectifying mode, the stability margin is decreased where at higher power flow from AC to DC, the system becomes unstable [11]. This can be used as a stability indicator, where the loading of converter considering generation and demand profiles approaches the stability margin, either the system becomes unstable, or load shedding needs to be applied. In either cases, the load is not supplied and the LOLE and LOLF will be affected. This is also the case for other stability issues, where not only static failures, but also dynamic failures impact the system risk. The procedure of risk assessment with stability consideration is shown in Fig. 1.

In this method, the Interlinking Converter (IC) DC-link voltage stability is selected as a stability issue. The details of this study will be explained in the next section. Then, the stability analysis is performed using root cause analysis methods such as eigenvalue analysis, root locus, Lyapunov Method, etc. After determining appropriate stability margin/constraint, which can guarantee the stable operation of the IC, the availability states of the IC are modified. Then, the new availability states are used in energy management and generating power availability of the system. Finally, the updated risk assessment indices are derived considering the impact of dynamic performances.

Therefore, by evaluating the risk of the system with respect to the dynamic and static failures, the impact of converter failure on both system stability and system risk can be modeled. This will facilitate new design guidelines for power converters to fulfill the desired level of system risk. In the next section, the impact of converter failure and its redesign on the system risk, both dynamic and static, will be illustrated in a power electronics-based power system.

III. NUMERICAL ANALYSIS

To illustrate the impact of the dynamic performance on the overall system risk and converter design, a hybrid AC/DC microgrid is considered as shown in Fig. 2. The system consists of two AC and DC feeders connected to each other with a 10 kVA interlinking converter. In addition, two 10 kW Microturbines (MT) are connected to the AC side using power-electronic converters. In the DC subgrid one 10 kW photovoltaic (PV) system and one 10 kW Fuel Cell (FC) supply the DC loads. The cumulative AC and DC load profiles are shown in Fig. 4 per hour for one year. Moreover, the failure rate of converters under given mission profiles are shown in Fig. 3. As it can be seen from Fig. 3, the PV converter is aged faster than other converters and MTs, FC and IC are located in the next steps, respectively.

The main stability issue is identified in this analysis to be the DC link voltage stability of the interlinking converter. The mathematical model of this issue has been described in [11] and [14]. According to the non-minimum phase characteristics of this converter, the DC link voltage becomes unstable under power flow from AC to DC side at power levels close to rated power. The DC link voltage under different operating conditions is shown in Fig. 5.

According to the power management strategy, while the ac and dc subgrids are capable to supply their loads, the IC is not allowed to transfer power. In case of power shortages in each side, the IC will transfer the excess power to supply the loads. The power flow through the IC can be either inversion mode or rectifying mode. As Fig. 5 (a) depicts, when the load of DC side increases to 2.5 pu ($S_{base}=10$ kVA) at $t=2$ seconds, the IC transfers -0.5 pu power from the AC side to the DC side. It is assumed that the load of AC side is constant and 10 kVA. By increasing the DC load to 2.93 pu at $t=3$ seconds, the IC is able to transfer the power -0.93 pu without voltage instability.

However, once the DC load at $t=4$ seconds increases again, due to this stability issue, the system becomes unstable when the rectifying power becomes more than 0.93 pu. The dynamic performance of the DC-link voltage is shown in Fig. 5 (b). Alternatively, to keep the system operating, the load shedding must be applied, which means inadequate power to supply the grid demand. Therefore, in this case the stability margin of 0.93 pu is defined as a constraint in the risk assessment method to guarantee the stable operation of the HMG.

In order to analyze the risk of the HMG using the proposed method, three different scenarios have been considered as follows:

Scenario 1) Determine the impact of dc-link voltage stability on the overall risk of the system.

Scenario 2) Redesign the converter which has the dominant impact on the system risk using sensitivity analysis.

Scenario 3) Investigate the impact of IC oversizing on the system risk.

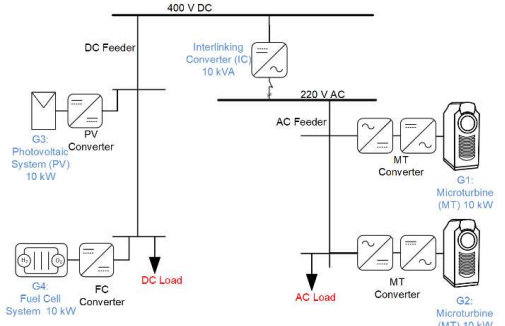


Fig. 2. A hybrid AC/DC power electronics-based power system (hybrid microgrids) selected for risk analysis.

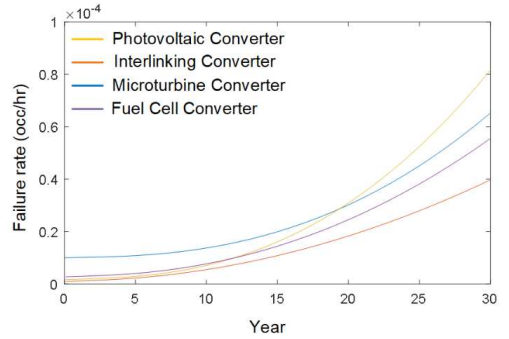


Fig. 3. Failure rates of converters shown in Fig. 2.

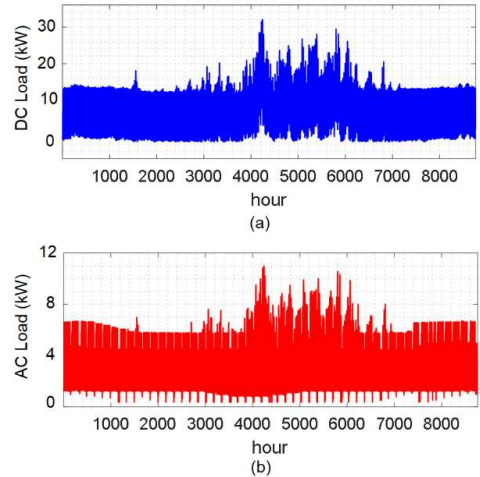


Fig. 4. Hourly mission profiles of AC and DC loads in Fig. 2.

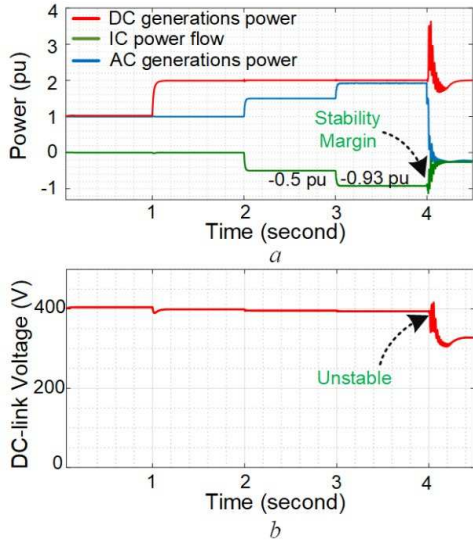


Fig. 5. The dynamic performance of DC-link voltage controlled by IC under different load flow conditions in rectifying mode of operation.

A. Scenario 1: Impact of instability on system risk

In this scenario, the risk assessment of the HMG has been performed to show the impact of dynamics (which are derived from the DC-link voltage stability) on the system risk. The risk indicators including LOLE and LOLF are shown in Fig. 6. This figure shows static risk that is due to the failure of components and dynamic risk that is due to the instability in the overall systems. As shown in Fig. 6, by increasing the failure rate of the converters due to aging, the risk of the system including LOLE and LOLF is increased for both the static and dynamic part. This is of paramount importance as it shows that the dynamic part has significant impact on the system risk. According to Fig. 6 (a), in the beginning, the LOLE of the system is 4.8 % higher compared to the conventional method, which is due to the dynamic performance, and it reaches to 36% in the 25th year.

The dynamics also affect the number of failures in the system. As Fig. 6 (b) shows, the LOLF of the system considering the stability is high and the dynamic performance leads to 24% difference in LOLF in the 25th year. Therefore, the results show that considering the stability issues will significantly affect the system risk and may exceed from the acceptable performance.

This analysis also highlights the interaction between static failure and dynamic failure in the power electronics-based power systems. Higher failure of converters increases the risk of instability in the grid and consequently the risk of loss of load. Therefore, by proper design of converter and reducing its aging failure rate, both static and dynamic system risks will be reduced.

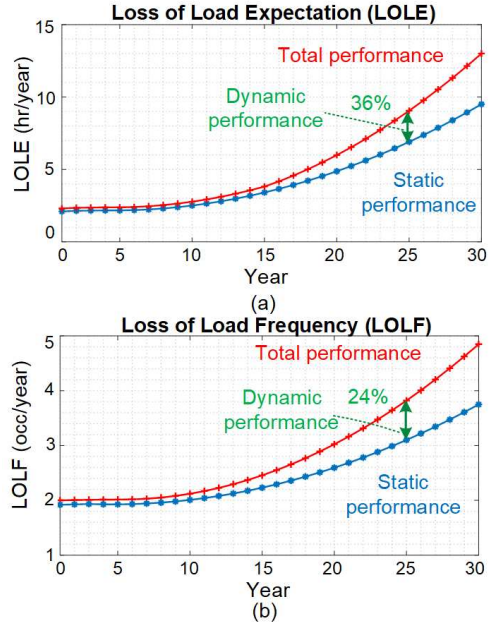


Fig. 6. System level risk indices of HMG shown in Fig. 2.

B. Scenario 2: Redesigning of dominant converter

As described in the previous scenario, the aging of the converters increases the risk of the instability in the system. But, based on the failure characteristics and the location of the power converters in the system, each of them has different impact on the overall risk. Some of them have the highest impact on increasing the static and dynamic risk of the system compared to the others.

By doing some sensitivity analysis revealed that the fuel cell (FC) converter has a dominant impact on the system risk. Therefore, the converter components are redesigned to shift up its aging process. In order to determine the dominant converter, it is assumed that one converter has the aging characteristics same as Fig. 3 and the remaining converters failure are constant. This process is performed for all converters. Finally, the risk results are compared which each other and the converter that has the major impact on the system risk and dynamic performance is determined as a dominant converter.

The risk of the system is then calculated as shown in Fig. 7, where the re-designed converter is improving the overall system risk. For instance, the LOLE is reduced from 9.2 hr/year to 7 hr/year in the 25th year according to Fig. 7 (a), which shows 25% improvement in system risk. Moreover, the dynamic risk is also remarkably decreased by improving the converter reliability. Comparing LOLE, the dynamic risk is decreased from 36% to 19%, following Fig. 6 (a) and Fig. 7(a).

Redesigning the FC beside of improving the loss of load duration, reduces the number of failures. As Fig. 7 (b) shows, the dynamic risk of the LOLF is reduced from 24%

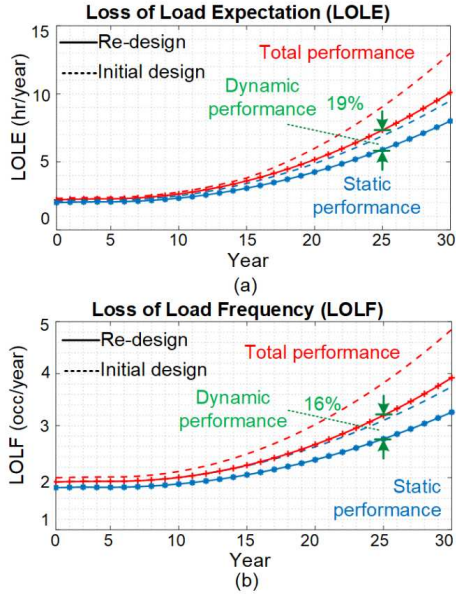


Fig. 7. System level risk indices in Fig. 2 considering a re-design of fuel cell converter.

to 16%. In addition, the overall risk of the system both for static and dynamic failures is improved and, in some cases, it can be in an acceptable level of the risk performance.

Therefore, the results show that redesigning the dominant converter can be a suitable solution to decrease the overall risk of the system in the presence of stability issues and the consequent dynamics.

C. Scenario 3: Impact of IC oversizing

Redesigning of the converters is an alternative approach in order to reduce the risk in the system as well as the dynamic performance. However, as illustrated in the previous study, there are still significant difference between static and dynamic risk. Since the dynamic risk is derived from the IC confined capacity in rectifying mode of operation, oversizing the IC can improve the overall risk of the system and reduce the dynamic risk.

To demonstrate the impact of the IC oversizing, it is assumed that the IC capacity has been oversized by 15% (e.g., 11.5 kVA). In addition, the redesigned characteristics of the FC has been considered in this study. The risk of the system is shown in Fig. 8, where the oversizing of the IC besides of FC redesigning is reducing the risk of the system significantly. For instance, the LOLE is reduced from the 9.2 hr/year to 5 hr/year at the year of 25 according to Fig. 8 (a), which shows 46% improvement in the system risk. This risk improvement is much higher than the single redesign of the FC. Additionally, the dynamic risk is significantly reduced in the 30 years lifetime and the 36% differences reaches to 12.5% in the

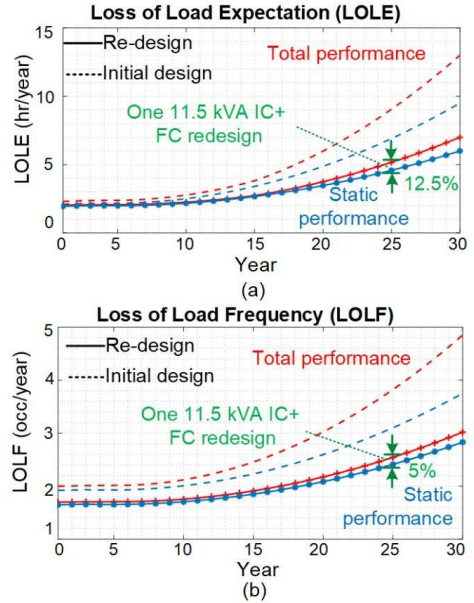


Fig. 8. System level risk indices in Fig. 2 considering a re-design of fuel cell converter and IC oversizing (15%).

25th year. The overall system risk also, goes to the lowest level and depending on the system allowable risk boundaries, it can operate at acceptable levels.

These results show how converters reliability and IC oversizing can impact the system risk both in dynamic and static failures. As a result, the converter design, not only must be performed with the static requirements, but also with respect to their impact on the system stability.

IV. CONCLUSIONS

This paper has proposed a more comprehensive approach for design of power converters considering stability and reliability issues to ensure an overall reliability of power electronic-based power systems. Unlike the conventional design approaches which rely on static performance of the power system, this paper showed that the dynamic performance has noticeable impact on the system reliability. The main reason is that the aging of converters can increase the risk of instability in system, which in turn will increase the risk of loss of load. On the other hand, the stability issues induce new constraints into the system, which confine the performance of some components and lead to an increase of the overall system risk.

The results showed that by a proper design of converters which have dominant impact on the system risk, the overall performance of the system will be guaranteed. In addition, the dynamic risk can be decreased remarkably.

The proposed method is enabling to determine the optimal oversizing of the interlinking converter aiming to

decrease both the overall system risk and the dynamic risk for given mission profiles. As a result, the method facilitates bridging system risk to stability and reliability of the converters. So, improved design of converters can be obtained in order to ensure both reliability and stability of the power grid.

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