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An overview on the Reliability of Modern Power Electronic Based Power Systems

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ABSTRACT Renewable energy resources are becoming the dominating element in power systems. Along with decarbonization, they transform power systems into a more distributed, autonomous, bottom-up style one. We speak of Smart Grid and Microgrid when distributed energy resources take over. While being a means to improve technical and financial efficiency, planning, operations, and carbon footprint, it is these new technologies that also introduce new challenges. Reliability is one of them, deserving a new way of describing and assessing system and component reliability. This paper introduces a new reliability framework that covers these new elements in modern power systems.

INDEX TERMS Adequacy, AC power system, Control, Cyber-security, DC power system, Grid modernization, Local reliability, Microgrids, Planning, Power electronics, Protection, Reliability, Security, Smart grids.

I. INTRODUCTION

Decarbonization has intensified the paradigm shift toward clean technologies in the society. Electrical energy as one of the common forms of energy carriers with increasingly use will play a paramount role in decarbonization, consequently in a sustainable development [1], [2]. Growing electricity demand enforces generation and transmission systems expansion, which introduces a huge amount of investment. Furthermore, the conventional, centralized structure of power systems is not efficient and clean enough due to power loss and reactive power flow in the transmission systems [1], [3]. Therefore, Distributed Generations (DGs) have been integrated into low/medium voltage distribution networks to enhance the overall system efficiency, availability and reduce operational costs. Moreover, renewable-based DGs facilitate the decarbonization process in electric energy sector.

Energizing distribution systems enables them also to operate in absence of the utility grid as a microgrid [1], [4]–[6]. A microgrid is an islanded distribution system which can supply its critical loads in the islanded mode employing local DGs and energy storage systems [4], [7]. Microgrid enabled distribution systems will bring some advantages including better efficiency, reliability, availability, and power quality [6]. However, optimal and reliable operation of different DGs and energy storage systems in microgrids requires Information and Communication Technologies (ICTs). Hence, the smart grid concept has been presented in order to optimally and reliably operate the modern distribution systems. Besides integrating DGs into distribution networks, large scale renewable power plants such as Photovoltaic (PV) and wind energy systems have been widely installed in power systems and today, the power grids are moving toward more/full renewable energy systems. Operation and planning of such systems with intermittent output and uncertain

power sources require availability of ICTs at generation and transmission levels as well [8]. Merging ICTs to the power systems introduces cyber-physical power systems, which could also be called smart grids, which facilitates power systems to cope with their costumer demands by smartly monitoring, decision making and control of modern power systems.

Besides the advantages introduced by the smart grid technologies in terms of efficiency, flexibility and operability, they pose new challenges to planning and operation of modern power systems. These challenges can be induced by restructuring the power grids by inclusion of renewable energies, microgrid technologies, ICTs, and power electronics. They may introduce a wide range of issues affecting the short-term and long-term performance of power systems, which is generally measured by power system reliability.

Due to restructuring in power systems, the traditional reliability concepts may not guarantee an appropriate performance of power systems. The conventional power system reliability is assessed by adequacy and security indices measuring its ability to supply its demand [9], [10]. These concepts are based on a centralized structure of power systems with the aim of fulfilling end-consumers requirements. However, moving to distributed structures requires a proper reliability assessment framework. Impact of grid modernization in modern power systems has been addressed by the Cigre C1.27 working group [11]. This working group has introduced new definition for reliability considering the inclusion of renewable energies, DGs, storage systems. According to this redefinition, power systems must not only be able to supply end-consumers but they should be also reliable enough for the suppliers including private DGs. Despite modification of reliability concepts in [11], reliability evaluation approaches as well as reliability metrics have not been introduced for modern power systems considering ICTs and

microgrids. Meanwhile, reliability of cyber-physical systems has been explored in [8] introducing a framework to include the ICT layer into the power system reliability analysis. This paper however does not address the local reliability requirements for distribution systems in microgrid mode operation. Furthermore, the local reliability of microgrids with new reliability indices have already been introduced in [12], while the impact of ICTs and dynamic structure of microgrids have not been addressed in [12].

Notably, the reliability of modern power electronic systems have been reviewed in [13]–[16] where the reliability of power converters from component points of view is reviewed. Moreover, they provide statistical data to higgling the reliability and lifetime of power converters. In [16], also the effects of system architecture and converter topology design choices have been addressed. None of abovementioned papers are discussed on the reliability of power electronic based power systems considering different aspects of reliability at the system level.

The main goal of present paper is to explain the challenges induced by grid modernization and then to propose a new framework to evaluate the reliability of modern power systems. The induced challenges will deteriorate the reliability of the power systems; hence, the conventional framework may not appropriately evaluate the system reliability. Generally, the power system reliability is divided into "adequacy" associated with the long-term/operational planning activities and "security" related to the operation phase. This paper explains how the adequacy and security of power systems will be affected by the grid modernization, and how to modify to incorporate the impact of the modern technologies into the power system reliability. The main features the proposed framework will consider are as follows:

- Due to paradigm shift to decentralized/distributed generations and operating the distribution systems as microgrids, it is required to introduce local reliability.
- Smart operation of future power systems considering the distributed generations, microgrids and demand side management, employing ICTs over the physical system introduces cyber-physical power systems. The ICTs are exposed to hardware failure, data unavailability and cyberattack. Malfunctioning the ICTs will deteriorate the performance of the system and must be considered during planning of power system. Moreover, cybersecurity must be taken into account during operation of power systems, where cyberattacks may cause loss of power/energy due to malicious intrusion.
- Power electronics are becoming one of the major components of future power systems. They pose some challenges to power systems reliability. The main issue is the interaction with passive components making electro-magnetic interaction, with mechanical components making electro-mechanical interaction, and other converters causing control interactions. These kinds of interaction which may cause instability in the power systems should be considered during security assessment and contingency analysis. Moreover, the limited short circuit current capacity of converters compared to the conventional thermal facilities

may introduce some challenges for protection system especially in the microgrid operation mode.

This paper is structured as follows. First the concepts of reliability in conventional power systems is explained in Section II. Then, the development of the power system structure is presented in Section III. Afterwards, the induced challenges by grid modernization are highlighted in Section IV. Moreover, the proposed framework for reliability evaluation in modern smart power systems is presented in Section V. Section VI will explain strategies can enhance the power electronic systems reliability. Furthermore, a case study is presented in Section VII to illustrate the applicability of the proposed framework for local adequacy assessment in modern power systems. Finally, Section VIII summarizes the paper.

II. CONCEPT OF RELIABILITY IN POWER SYSTEMS

Technically, reliability is the ability of a system to perform as intended without any failure and within the desired performance limits for a specified time, in its lifetime conditions [17]. A power system is a large system with huge number of sub-systems and components operating together in order to perform its functionality as supplying the costumers for a long period of time regardless of its components lifetime. Achieving such performance requires dividing the power system functionality to long-term and short-term performances. The long-term performance can be measured by the ability of the power system to supply its demand at all times, which requires existing sufficient generation and transmission facilities with a desired level of reserve. This ability is called power system adequacy [10], [11]. Moreover, the short-term performance can be measured by the ability of the power system to withstand sudden contingencies and outages which is called power system security. Therefore, a reliable power system must be adequate and secure enough to deliver energy to all of its points at all the time. The system adequacy can be guaranteed by "planning" for sufficient facilities in long-term and the security can be fulfilled by stable "operation" of the system.

Planning and operation of power systems are hierarchically carried out with respect to the time as shown in Fig. 1. Planning can be performed in three periods of long-term, short-term and operational planning [2], [18], [19]. The long- and short-term planning is called facility planning, which is associated with developing the power system infrastructures, including installing generations, expanding transmission systems, and extending distribution systems, in order to support the customers considering the energy consumption growth. Furthermore, the operational planning is to utilize the existing system facilities by seasonal and weekly generation scheduling and day-ahead unit commitment with seasonal maintenance planning. The important objectives of the operational planning are to optimize the system operation subject to the generation costs, emissions and reliability. In the conventional power systems with a top-down structure, the system adequacy is hierarchically assessed in three levels as shown in Fig. 1. In the Hierarchical Level I (HL I) the generation capacity adequacy is evaluated, in the Hierarchical Level II (HL II), the composite generation-transmission system adequacy is explored, and Hierarchical Level III (HL III)
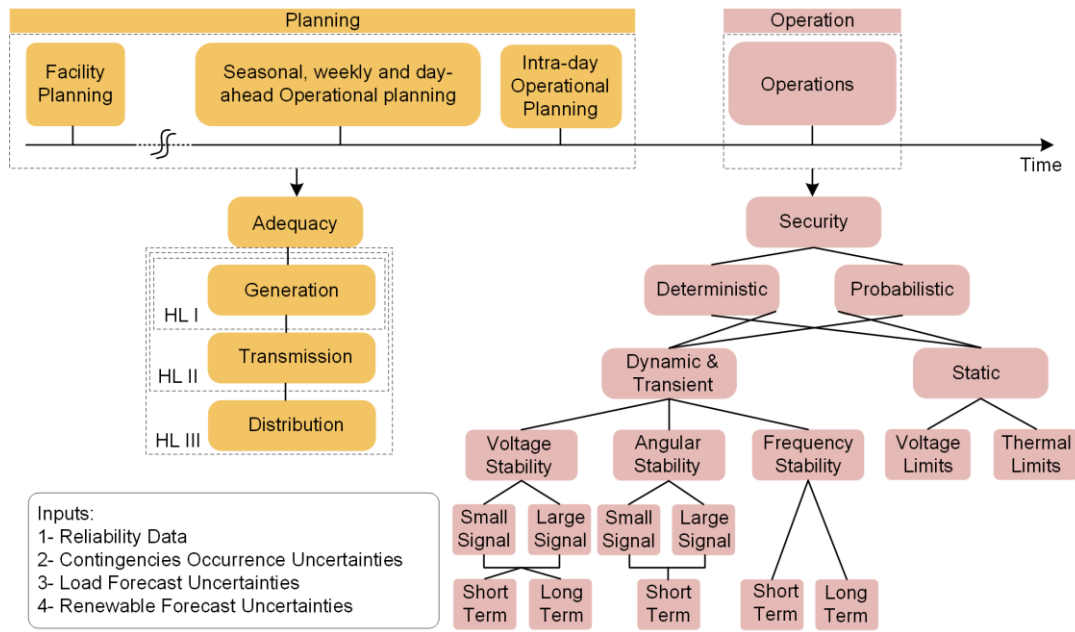
Fig. 1. Reliability evaluation framework in conventional power systems. HL x: Hierarchical Level x.

adequacy is associated with the distribution system reliability [10].

The operational planning output as scheduled power setpoints are assigned to the generation units under operation. The operation of power systems is subjected to various uncertainties including load forecast uncertainty, unplanned outages, short-circuit faults. The scheduled and actual load mismatches are compensated by the kinetic energy of rotating mass inertia of synchronous machines, which is called primary reserve, and/or frequency-responsive spinning reserve, which is called secondary reserve. However, the contingencies occurrence such as loss of generation, line, and transformer may introduce serious issues to reliable operation of the system. A contingency occurrence can cause equipment overloading, voltage violation and stability issues. The power system must be able to withstand any contingencies, which is attributed to its security level [20], [21].

As shown in Fig. 1, the security could be guaranteed by deterministic methods such as N-X criterion or probabilistic approaches considering the probability of contingencies and their consequences. The system security is classified into two categories including static and transient/dynamic security [20]. Static security is in charge of assuring the system voltage and equipment thermal limits violations to remain in an acceptable region within a steady state condition. However, before entering to a steady state, the system stability should be assured. Following the causes of instabilities, the power system stability is divided into voltage, angular and frequency stabilities [21], [22].

Angular stability is associated with the ability of power system to retain the synchronism of synchronous generators after a disturbance. In steady state, there is an equilibrium between electromagnetic and mechanical torques of generators, and all the generators are synchronized with each other. Any disturbance such as large load change, generator trip, line/transformer outage, and short circuit fault, causes acceleration or deceleration of rotors. The relative rotor angles will be changed and based on the operating state before disturbance and the disturbance severity,

the rotor angles may reach an equilibrium state or lose synchronism. The electromagnetic torque variation can be decomposed into two components including synchronizing torque and damping torque. The rotor angle instability occurs due to the lack of either sufficient damping torque leading to oscillatory instability, or sufficient synchronizing torque causing non-oscillatory (aperiodic) instability. Following the disturbance severity, the angular stability may occur subjected to the small disturbances causing small signal (dynamic) instability or large disturbances causing transient instability with aperiodic rotor angle oscillations. The angular stability may occur within a few seconds.

Frequency stability refers to the power system ability to retain the frequency under a severe contingency causing imbalance between generation and load. Frequency instability may occur in the form of frequency oscillations causing generator or load trip. Sever disturbances may cause large excursions in the system voltage, frequency and power flow. These severe conditions can be maintained by control and protection systems with a fast response, such as generator control and under-frequency load shading, by prime mover reaction with a slow response. The system frequency stability can be assured by an appropriate coordination of controls and protection systems, sufficient equipment responses and appropriate primary and secondary reserve.

Voltage stability refers to the ability of a power system to retain/restore the voltage of system after any disturbance. Voltage instability occurs once the system controllers cannot prevent progressive voltage rise or fall within a contingency. The voltage stability is categorized as small and large signal stability. The small signal stability refers to the system ability in maintaining the voltages under small disturbances depending on the load characteristics, and continuous/ discontinues control systems. Furthermore, the large signal stability is associated with the system ability to retain the voltages due to large disturbances depending on the system and load characteristics,

continuous/discontinues controls and protection systems. The voltage instability may start in a few seconds associated to the fast dynamics of loads, converter fed unit, and extend to several minutes associated with the slow dynamics of such as transformer tap changers, and generator current limiters.

A secure operation of the power system requires assuring both static and dynamic performance of the system subjected to any planned and unplanned contingency. Therefore, the conventional power systems reliability can be guaranteed by adequate planning and secure operation in different time frames as shown in Fig. 1. However, this framework may not be proper enough for modern power systems due to the inclusion of new technologies. In order to address the required modifications on this framework, first, the structure of modern power systems will be presented in the next section.

III. STRUCTURE OF MODERN POWER SYSTEMS

In conventional power systems, electric power has been generated by large-scale thermal power plants, and delivered to the consumers by transmission and distribution systems in a centralized, top-down structure. Also, the control and monitoring of the conventional power systems was centralized. The power flows from power plants to the consumers through high voltage transmission and medium /low voltage distribution systems. Planning activities of the conventional power systems including marketing, energy management, unit commitment and power flow, monitoring and protection are centrally carried out. Therefore, strong and adequate transmission facilities are required in order to support the system demand with a desired level of reliability.

Global warming together with fossil fuel depletion has intensified the paradigm shift from thermal power plants to clean energy resources in the electric power generation. Thereby, small-scale renewable resources such as PV and wind systems have been integrated into the distribution systems [3]. Increasing use of renewable energies for electricity generation has changed the power and energy market players finally leading to deregulation in the power systems. Thereafter, the concept of DG has gained an increasing interest for developing the structure of power systems. Moreover, the large-scale renewable plants such as PV parks and wind farms have been integrated into the transmission and medium voltage distribution systems. Integrating DGs in the distribution systems has formed active networks, and hence, changing the power flow direction. This fact initiated the electric network deregulation.

Furthermore, increasing use of renewable energies with intermittent output power requires employing energy storages for smoothening the power and voltage fluctuations as well as coping with the generation-consumption mismatches. Moreover, employing utility-scale energy storages is necessary in the case of mowing toward one hundred percent renewable energies. Besides the renewable resources, the new technologies such as DC transmission systems and Electric Vehicles (EVs) are also key components of the future modern power systems. The EV technology is a growing industry, which will affect the planning and operation of the power systems. Installing fast charging stations may require proper infrastructures supplying the batteries in a desired time. Moreover, bidirectional power flow may be

required for grid supporting purposes by the EVs. For public transportation such as electric busses, wireless charging stations can facilitate the transportation services. Moreover, intelligent control strategies should be used for optimal operation of the power grids with high penetration of EVs.

The DC transmission systems are also aiding to the grid modernization. Mowing towards one hundred percent renewables has imposed interconnection of power networks, which can economically be carried out by HVDC transmission systems. Moreover, the future distribution systems will be energized to locally support the demand. Reliable operation of such systems may be feasible by interconnecting the medium voltage distribution systems. Medium Voltage DC (MVDC) transmission systems can facilitate this integration [23] since the DC systems are more economical efficient and reliable compared to the AC systems. This is due to the fact that the DC systems are free of reactive power flow, frequency and synchronization issues.

Optimal operation of new the new power system technologies such as renewable resources, energy storage systems, microgrids and EVs need real-time monitoring and control systems for appropriate decision making which, can be performed in a distributed or a decentralized manner. Therefore, a general structure of future power systems as cyber-physical power systems can be made up of three layers of (1) physical, (2) communication and coupling, and (3) decision layers as shown in Fig. 2 [8]. Considering the incorporation of new technologies into the power systems, the future physical layer will be hybrid AC-DC grids as shown in Fig. 3. Compared to the conventional power systems, the large-scale renewable power plants and utility-scale energy storage systems are connected into the transmission system. Moreover, MVDC transmission systems are employed for interconnecting medium voltage distribution systems as well as interconnecting HVDC and distribution systems.
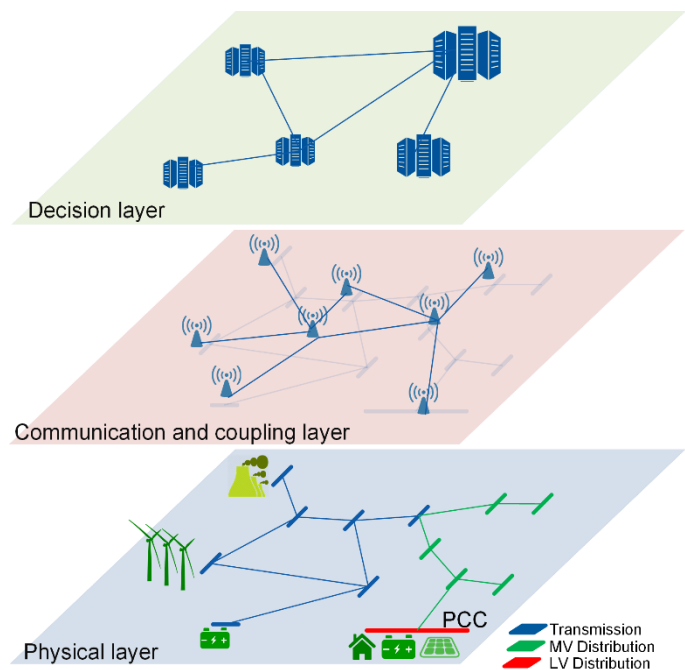

Fig. 2. Cyber-physical structure of modern power systems with three layers of operation [8]
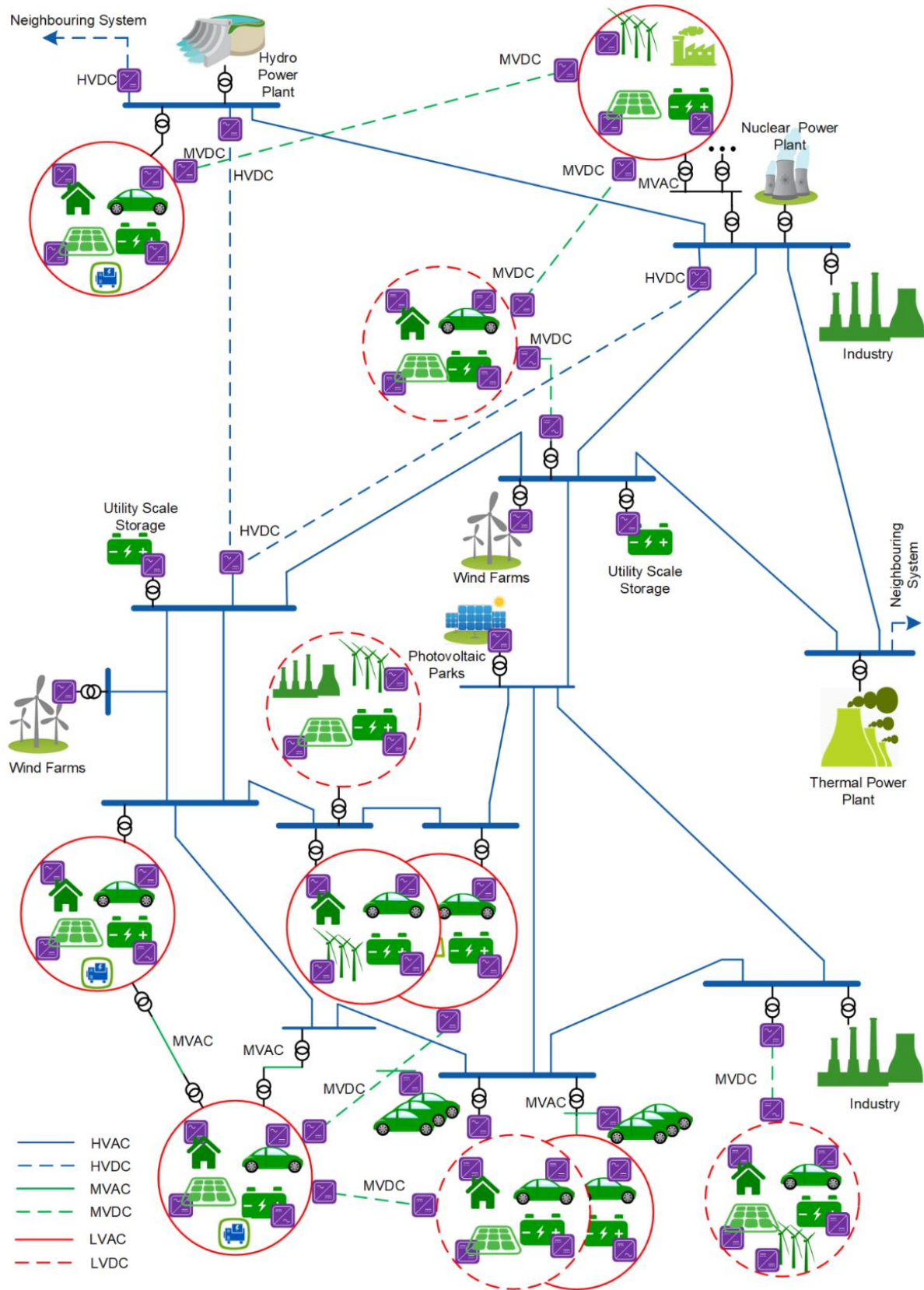
Fig. 3. Typical structure of modern power systems with hybrid AC and DC sub-grids. AC is solid lines and DC is dashed lines.
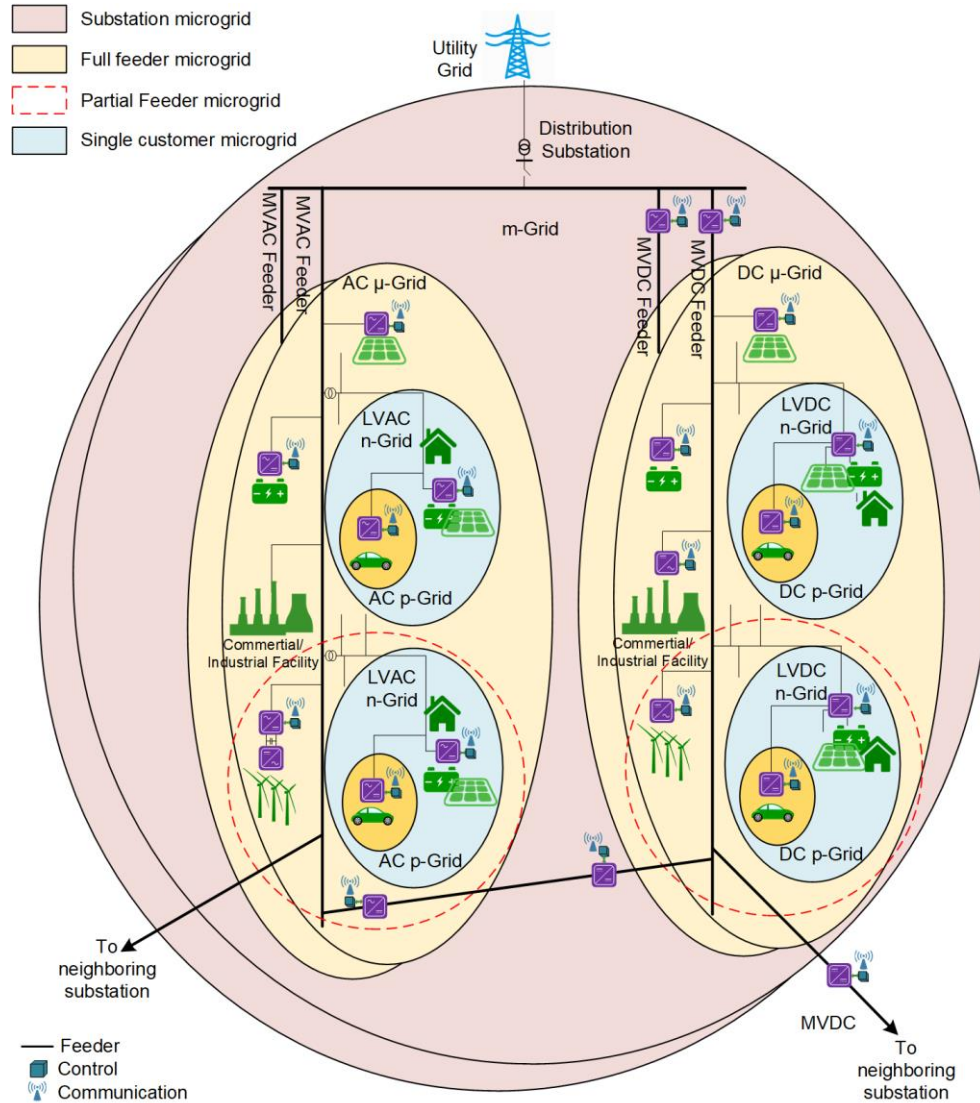
Fig. 4. Typical structure of future distribution systems with hybrid AC and DC sub-grids – p-Grid: Pico-grid, n-Grid: Nano-grid, μ-Grid: Microgrid, m-Grid: Milli-grid.

Furthermore, energizing the distribution systems as active distribution systems brings some advantages from the energy efficiency, stability, security, availability and resiliency standpoints [6]. The microgrid technology aids to active distribution networks to be operated in terms of any contingency occurrence, which may stop energy delivery. The microgrid is an active power grid with sufficient energy sources including power supply and energy storage to support its critical loads in the absence of utility [1], [4], [6], [7], [24]. Therefore, the modern power distribution systems structure will be cluster of microgrids forming multi-terminal hybrid AC-DC grids as shown in Fig. 4 [25], [26] in the future.

The microgrid structures can be classified following the location and size of the microgrid. Considering the location on a distribution feeder, it can be classified as a single-customer microgrid, partial feeder microgrid, full feeder microgrid and substation microgrid as it is shown in Fig. 4 [26]. Moreover, based on the size of microgrid, it can be classified as pico-, nano-, micro-, milli- and inter-grid [25]. Conceptually, both

classifications indicate a dynamic structure of future distribution networks, where an islanded zone/feeder can form a sub-grid operated individually. Therefore, the micro-grids are dynamically decoupled building blocks of the future power systems [25]. The microgrids can be Direct Current (DC) or Alternative Current (AC) as well as hybrid AC/DC microgrids [27] based on the nature of the prime energy source. Different structures of microgrids have been introduced in [1].

Basically, each microgrid is a small grid connected to the neighboring feeders/grids, and hence, it must assure for adequate and secure operation. In practice, the utility or neighboring grid is a back-up for each microgrid. Therefore, a suitable monitoring and control of any contingency and failure occurrence, can properly separate the microgrids to be operated in the islanded mode. Recent advances in ICTs facilitate the monitoring and control of power systems. Adding communication systems to the active distribution networks introduces smart grid technology.

Operation of such a complex grid with active networks and communication systems employing a top-down control strategy –
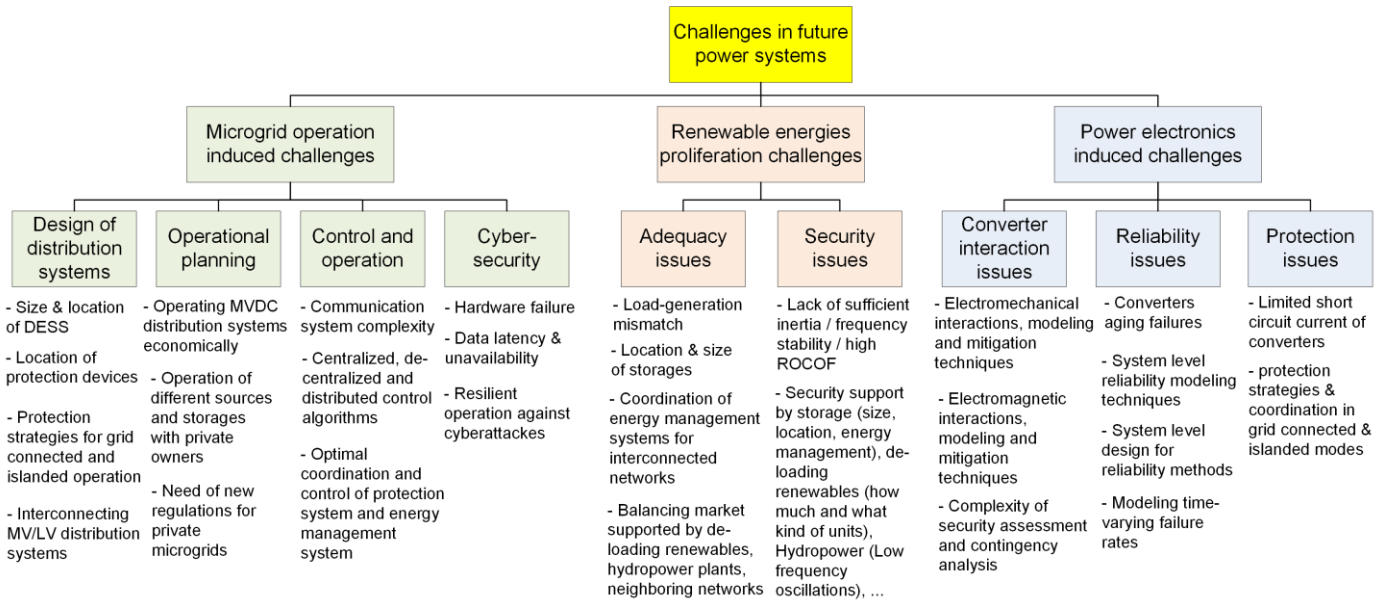
Fig. 5. Challenges in future power electronic based power systems.

like the conventional power systems – requires strong communication infrastructures and central control, decision making system, which is not an efficient, economical and reliable approach. Therefore, distributed power and energy management strategies with local communication networks can help for reliable operation of modern power systems [28], [29]. Thus, the future power systems will be as distributed as possible both in structure and control levels [30]. As much as the structure becomes distributed, the overall efficiency and stability will be enhanced and as much as the control system becomes distributed, the system will be more resilient against uncertainties and cyber-attacks.

IV. Challenges in Future Power Systems

The grid modernization in both structure and operation will introduce new challenges to reliable, resilient and efficient operation of future power systems. The challenges can be classified into three categories including challenges caused by microgrid operation, challenges associated with proliferation of renewable energies and challenges posed by power electronics. Different aspects and issues raised by these technologies are summarized in Fig. 5 and discussed in the following.

1) *Microgrid operation induced challenges*

The paradigm shift towards distributed, bottom-up structure and operation of power systems has intensified the operation of distribution power systems as being microgrids. The microgrid mode operation introduces a wide range of challenges in design, planning and operation of modern power systems. Unlike the conventional power systems, a microgrid must be adequate enough to cope with its demand in the islanded mode. Moreover, the stability of microgrid must be guaranteed in the islanded mode despite the lack of sufficient inertia in the system. On the other hand, efficient and economical operation of microgrids require smart solutions, which can be performed by employing ICTs. Integrating ICTs in microgrid operation will expose power systems to cyber issues. In general, the microgrid operation

induced challenges can be categorized into design, operational planning, control and operation, and cyber-security.

▪ **Design of distribution systems:**

DGs are increasingly installed in distribution systems. According to decarbonization, most of the DGs are renewable-based resources with intermittent output power such as PV and wind power systems. Operating such technologies in the islanded mode requires energy storages in order to balance the generation and demand as well as form the grid voltage. Therefore, DGs and Distributed Energy Storage Systems (DESS) are the main components of the future microgrids. Taking into account that the structure of microgrids can be dynamically changed according to the fault location in the system as shown in Fig. 4, the placement and size of DESS will be of high importance.

Each segments of distribution system, including single-customer, partial feeder, full feeder and substation microgrids, must have enough energy sources to supply its critical load in the case of islanding. Therefore, unlike the conventional power systems, the modern power systems must locally guarantee the energy adequacy. To achieve such a goal, the size and placement of DESS in the different segments of distribution network must be properly selected and designed. Moreover, the distribution system segmentation should be appropriately performed by protection and monitoring system. A coordinated protection system over the substation can suitably separate the faulty regions and facilitate operating the islanded microgrids to securely supply their demands. Moreover, the size of DESS on each islanded segment must be taken into account for adequately supply the loads. As a result, reliable and resilient operation of the future distribution systems requires suitable design of the protection system locations, placement and size of DESS.

Moreover, MVDC transmission systems among MV distribution networks will facilitate a reliable and resilient operation of distribution systems. The MVDC lines can provide ancillary services such as voltage and frequency support,

generation-load balancing and decoupling the networks dynamics. It can allow a high penetration of renewable resources at the MV level as well. Furthermore, the MVDC systems can enhance the distribution networks resiliency by decoupling the networks and supporting them with black start by a fast frequency response and voltage support. Therefore, the coupling points of MVDC lines between two MV distribution networks and their capacity may affect the overall system adequacy, hence, they must be considered within the planning phase.

▪ Operational planning:

Distribution networks are going to be equipped with various numbers of DGs and DESS operated by private owners. Optimal and reliable operation of distributed resources together with demand side management requires smart energy and power management strategies. This will be more complicated with considering the incorporation of MVDC lines for interconnecting MV distribution networks. Thus, marketing and operational planning of interconnected microgrids will face new challenges that require socio-economical solutions for optimal and reliable decision making. This may affect the local and overall reliability of power systems.

Planning of cluster of microgrids can be even more challenging once the grid becomes unavailable. The main issue can be introduced by private owners, when they may not agree to support the other microgrids due to the importance of their own loads. In this case, the generation-demand balance may not be preserved, consequently the system becomes unstable. In the case of full-, partial-feeder microgrid, single-customer microgrids may prefer to disconnect from the local grid. This issue can be solved by new regulations for the islanded mode operation or suitable design for adequacy considering different islanding scenarios in distribution levels. An optimal solution would be a combination of adequate facility planning and operational regulations. Therefore, advanced and socio-economical strategies must be employed for optimally and reliably operate the distribution networks as microgrids.

▪ Control and operation:

Centralized, top-down operation of DGs and DESSs in distribution networks requires complex communication networks and monitoring systems. Moreover, employing point-to-point communication will make the system more vulnerable subjecting to the data unavailability and cyberattacks. Therefore, distributed or decentralized control strategies can provide reliable operation of microgrids. These control strategies can be performed at active/reactive power sharing control level, power and energy management level, and protection level.

So far, numerous distributed and decentralized power-sharing approaches have been presented for the control of microgrids [31]. These solutions are implemented without or with spars communication links, hence with high robustness in terms of cyber issues. However, optimal energy management strategies considering the dynamic structure of microgrids need to communicate the required information in order to maintain the system reliability. Moreover, the microgrid structure dynamically depends on fault location and protection system function, which communicates with decision centers. Once a fault occurs, an islanding detection algorithm must separate the faulty region and as wide area as possible should be operated without stopping power delivery. Therefore, the control unit of the energy resources must be appropriately adapted with the islanded conditions in order to support the microgrid voltage and frequency. Moreover, the energy management systems of microgrids and protection systems must be suitably coordinated for guaranteeing overall system adequacy and security. This fact can be performed by self-organizing mechanisms, where the local information and resources can be used to fulfill some global objectives. The self-organization of active distribution networks requires strong communication theories and optimization techniques in order to locally operate the distribution systems. As a result, the operation of active networks requires real-time operational planning and control strategies in order to obtain acceptable reliability and efficiency.

Dynamic structure of microgrids makes it complicated to control the converters in the islanded mode. Depending on the islanded point, one unit may be responsible for grid forming, while islanding from anther node may enforce it to operate under grid following mode.

▪ Cyber-security:

Digitalization and liberalization make power systems to be more and more distributed at the control and generation level. As already mentioned, the optimal and reliable operation of such systems will be feasible by only employing ICTs among different domains including generation, transmission, distribution, consumption, operation, marketing and service providers. Besides the economic planning of microgrids, any uncertainty and contingency in the system might drive any forms of instability depending on the location, size, and type of disturbance. Hence, the ICTs are employed in different domains for exchanging information for the sake of decision making, control, monitoring, protection, and ultimately securing the power systems. For this purpose, three main networks can be implemented to facilitate the smart operation of power grids including (1) Home Area Network (HAN), which interfaces the end consumers to the smart grid in order to supply their energy and provide demand response functionalities, (2) Neighboring Area Network (NAN), which interfaces the HAN with Wide Area Networks (WAN) in the distribution level, and (3) WAN which is in charge of monitoring and control of the generation and transmission systems. These three networks transfer the measured data by smart meters and Remote Terminal Units (RTUs) to the decision-making center and the control signals from decision making center to the different control units, such as protection devices, generation units, and loads.

The power system performance depends on the reliability of cyber and physical layers. The communication and coupling layer can be threatened by the failure of measurement devices (hardware failure) and data latency and unavailability through the communication systems [8]. Device failure may happen in the hardware of decision-making layer which can affect the power system performance. Moreover, this layer is threatened by cyberattacks with malicious intention which may affect the power system decisions, such as protection system malfunction, consequently deteriorating the overall system performance. This

intrusion, which makes decision error, can be induced by hacking sensors and distorting measurements or false data-injection through the communication links [8]. As a result, both cyber layers vulnerability due to hardware failure and data unavailability or decision error can affect power system reliability.

Furthermore, cyber-security management may introduce extra costs for power systems, where the source of these costs should be considered in the planning phase. These costs should be fairly supported by the large power plants, the large-scale renewable units, low-scale DGs, end-consumers (commercial, industrial and residential consumers), or system operators. It could properly be identified which parts highly benefit from having a secure system and which parts have the highest impact on making the system cyber-vulnerable.

2) Renewable energies proliferation challenges

Decarbonization has intensified the role of renewable energies in electric power generation in recent years. Wind and solar energy resources have gained increasing attention and high capacity of wind and solar power plants have been installed worldwide. Increasing of renewable energies despite eliminating the need for fossil fuels and aiding decarbonization, poses technical challenges for moving toward full renewable energy-based grids. These challenges can be classified as adequacy and security issues where the adequacy issues are raised by generation uncertainty and security issues are associated with the low inertia of renewable-based grids.

▪ Adequacy issues:

The adequacy issues are raised by the uncertainty induced by intermittent generated power, which makes generation-demand mismatch in the system. In order to cope with generation-demand unbalance, the overall system must be adequately designed. The system adequacy can be fulfilled by using storage systems, hydropower plant, interconnecting neighboring networks and de-loading renewable power plants.

Installing utility-scale energy storage systems is one of the promising solutions to increase the penetration of renewable energies. The main technical and economic challenges that this solution might face comprise the size, number and location of the energy storage systems. These factors can help the overall system reliability and resiliency in the case of grid splitting. Hence the design of energy storage systems in the utility-scale must be adequately performed.

Furthermore, interconnecting to the neighboring networks through HVDC systems can facilitate increase of renewable energy penetration by supporting the grid frequency and voltage. Therefore, smart control of HVDC systems to support the grid adequacy is of high importance for power grids with high capacity of renewable energies. However, supporting grid reliability by neighboring networks may introduce marketing challenges. HVDC connection can also facilitate incorporating different renewable energies to smoothen out the generation-demand mismatch. For instance, interconnecting South-Europe with high potential of solar energy to the North-Europe with high potential of wind energy considering the reverse seasonal behavior can help smoothing the generation profile. Moreover,

this can affect the size of energy storage systems where the availability of generation is increased.

Operating under maximum allowable power of renewable resources can facilitate the full renewable operation of grids, while it may not be a cost-efficient solution. Thus, there would be a compromise between the loss of energy and the system reliability supported by de-loaded renewable resources. This may also bring new market challenges.

▪ Security issues:

Synchronous machines in power systems can help load-generation balance inherently by the kinetic energy stored in the rotating mass inertia of the turbine-generator, which is called inertial response. The frequency variation due to large load change or loss of generation will be sensed by the droop controller, so-called primary controller, of the generator governor. Afterwards, secondary control will restore the frequency deviation to a reference value. The primary control utilizes the primary reserve for load-generation balancing within short-time. The secondary control releases the generation capacity participating in primary reserve, by employing the spinning reserve. In the long-term, the load change will be supported by the scheduled units at the tertiary-level.

Increasing the penetration of the renewable energy resources such as wind and photovoltaic, the inertial response support will be weak due to the low inertia in the system. This can lead to a high rate of change of frequency (ROCOF) and consequently protection system functioning. In full power electronic systems, it might cause cascaded outages. In order to preserve the system to be stable and reliable, renewable energy-based units should participate in frequency support. The inertial response can be implemented by the control systems to mimic the synchronous generator behavior, kinetic energy of wind turbine blades, energy storage, or de-loading the renewable units under maximum allowable power.

Furthermore, increasing use of renewable energies like solar and wind systems may be possible by employing hydropower units for smoothing out their intermittent power. The hydropower units cause ultra-low frequency associations in the grid. This may cause frequency instability in the power system and should be taken into account for secure power delivery.

3) Power electronic induced challenges

Power electronic converters are increasingly used in a broad range of applications in modern power systems. In fact, the power electronics is becoming an underpinning technology for implementing microgrids and moving toward high proliferation of renewable energies. Besides better controllability, flexibility and operability of power electronic converters, they introduce some challenges at different aspects. A major issue raised by the power converters is their interactions with other parts of grid including other converters, passive components and mechanical systems. The next challenge is reliability issues of converter components. Moreover, protection issues are other challenges of power converters in modern power systems.

▪ Converter interaction issues:

Power electronic converters are equipped with various controllers including inner current control, grid synchronization

controller employing Phase Locked Loop (PLL), AC and DC voltage controllers, active and reactive power controllers, and frequency controller. These controllers are designed with different bandwidths in the range of a few Hertz up to several kilo Hertz, and may interact with magnetic and mechanical components of the system. These electro-magnetic/ electro-mechanic or electro-mag-mech (EMM) interactions, can happen in a broad range of frequencies between sub-synchronous frequencies to switching frequencies [18], [32], [33].

In conventional power systems, the much dangerous interactions are associated with the interaction of different components with the turbine-generator torsional modes at sub-synchronous and super-synchronous. The interaction between series capacitive compensation with turbine-generator torsional modes in some compensation factors causes sub-synchronous resonance (SSR). Also, interaction between HVDC converter control, variable speed drives control system and power system stabilizers with the turbine-generator can lead to sub-synchronous oscillations. Sub-synchronous oscillations may happen between power electronic converters with the other converters or series compensated systems. Moreover, super-synchronous oscillations may occur between a power converter with other power converters, turbine-generator torsional modes, and passive components.

Except the electro-mechanical interaction between series compensated system with the mechanical torsional modes, the other interactions are associated with the control system of at least one device (i.e., converter or generator [34]). The interactions may cause instability in the system with a poor or negative damping factor. This stability has been called harmonic stability in [32], and further classified into sub-synchronous and super-synchronous oscillations in [18], [33]. Moreover, it is called control system stability in [34]. Beyond its title, these stability issues are attributed to the cross coupling between power converters with other converters control system, filters, grid lines components and mechanical systems and could be called electro-magnetic-mechanical (EMM) stability. The EMM becomes more severe with increasing use of power converters in modern power systems at different levels, and it can cause interruption in the power supply and delivery [32], [35]–[38]. Hence, the overall system security and reliability may not be guaranteed.

This issue will be severe when the operator wants to evaluate the system security in terms of any contingency considering the different stability criteria. The first challenge is the accessibility to control system of each unit. Since, the control system interactions depend on the converter and its control models in a wide range of frequency, the overall system security assessment may be a difficult task considering high use of power converters. The next issue in security assessment is the computational burden and analysis time considering that the operator may not have enough time to assess the system security subjected to different types of converter interaction stability at any time of operation.

- ▪ **Reliability issues:**

Industrial experiences show that the converters are frequent failure sources in many applications such as wind and PV systems [13]–[15], [39]–[43]. The converters reliability depend on the operating and climate conditions [44]–[52]. Moreover, the most failure prone components such as capacitors and semiconductor devices are exposed to wear-out failures due to the intermittent operating and climate conditions such as power loading, ambient temperature, humidity, vibration etc. [45], [51], [52]. Hence, the converters failure rate will be time dependent and the end-of-life of components is limited. Furthermore, the converter end-of-life depends on the operating conditions. As a result, the converter reliability should be modeled considering its mission profile [45], [49].

Mission profile analysis in power converters requires electro-thermal modeling of its components and sub-systems to find out key variables affecting their lifetime. These key lifetime variables are related to the lifetime of devices such as junction temperature, operating voltage, current, humidity and so on. Obtaining these variables under given mission profile requires detailed thermal and electrical modeling of converter at different time frames from fast dynamics of switching frequency up to slow dynamics associated with the power sharing control loop. Moreover, at the power system level, power flow analysis should be employed to determine the loading of different converters considering long-term load and generation forecasting in the system.

After obtaining the profile of key lifetime variables, the lifetime of devices can be predicted using corresponding lifetime models. Since, the electro-thermal and lifetime models are exposed to aleatory and epistemic uncertainties, the likelihood of the device lifetime must be predicted. This can be performed by Monte Carlo simulations considering the uncertainties [49]. Therefore, the converter lifetime and its distribution can be predicted using mission profile analysis and Monte Carlo simulations. This procedure is time consuming due to the detailed electro-thermal modeling and Monte Carlo simulations. Even though it is used for design for reliability in power converters [53], for large-scale systems, it will introduce higher calculation burden.

So far, the converter reliability in power system analysis is considered as a constant failure rate obtained from historical data [10], [54]–[62]. Employing constant failure rate of converters for reliability evaluation in power system analysis will introduce erroneous reliability and risk prediction [63]. Thus, non-optimal decision-making for planning and operation of power system with high penetration of power converters can be obtained. In order to accurately predict the reliability of power electronic based power systems for system-level analysis, the converter reliability should be included to the power system reliability model. This can affect the power system reliability analysis in two domains. First, the limited end-of-life of converters should be considered within facility planning for cost-effective replacement of converters using appropriate maintenance planning strategies. Second, the time-varying and condition-based failure rate of converters should be taken into account in the operational planning. Therefore, depending on the application, the converter reliability may affect the power system reliability and performance [44], [63]. As a result, bridging the converter reliability to the power system reliability is of paramount importance.

- ▪ **Protection issues:**

Electro-mechanical facilities such as generators can supply 10-20 times of the rated current for 0-10 seconds during a fault. Thereby, the existing protection systems can sufficiently detect and clear the fault without interrupting the system continuity. However, the current limit of semiconductor-based devices is much lower than the electromechanical devices. For instance, the overloading current of Silicon devices is 1.5-2 times of the rated current for several seconds, and Silicon-Carbide and Gallium-Nitride technologies can supply 2-3 times for 3-5 seconds in [64]. Therefore, advanced protection algorithms and devices should be developed in order to detect and clear the fault and/ or separate the faulty regions in a sufficient timeframe. Inappropriate protection system response may cause loss of converter-interfaced sources and thus cascaded outages and finally loss of energy in the affected areas. As a result, this will change the protection system coordination and dynamics especially in the systems with both synchronous machine and converter-interfaced units or operating the system in the microgrid mode.

V. NEW RELIABILITY FRAMEWORK

In order to tackle the induced challenges with the new power system technologies, a new framework for reliability analysis in modern power systems should be introduced. It could preserve the main concepts of adequacy and security with inclusion of impact of grid modernization.

▪ **Adequacy:**

In order to explain the adequacy of modern power system, its cyber-physical structure is shown in Fig. 2 [8], where it includes three layers, which are power, communication and coupling, and decision. The conventional adequacy definition has been modified by Cigre C1.27 working group [11], but, this definition has not provided a framework to do the reliability assessment in modern power systems. Furthermore, [8] has introduced reliability evaluation in cyber-physical power systems considering the ICTs deficiencies. However, the impact of microgrid mode operation has not been addressed in [8] which requires local reliability requirements. Local reliability evaluation in microgrids has been introduced in [12] that also presented new reliability metrics for microgrids. However, this paper did not address the cyber layers impact on the system reliability. In order to cope with all shortcomings of reliability evaluation approaches presented in [8], [11], [12], the proposed adequacy assessment framework is shown in Fig. 6.

According to the proposed framework, the cyber-physical power system adequacy can be evaluated in three hierarchical levels of generation, cyber-physical generation-transmission, and cyber-physical distribution levels as shown in Fig. 6. First of all, the generation system capacity must be adequate so that overall system demand can be supplied. Hence, the generation adequacy in HL I can be evaluated similar to the conventional power system adequacy as shown in Fig. 7(a) [10].

The adequacy of cyber-physical generation-transmission system in HL II requires modeling the impact of cyber-layers as shown in Fig. 2 as well as the impact of DGs in MV distribution systems. Fig. 8(a) shows a simplified power system with large scale generation units and microgrid-based distribution networks. In order to analyze the adequacy of these systems, the microgrids
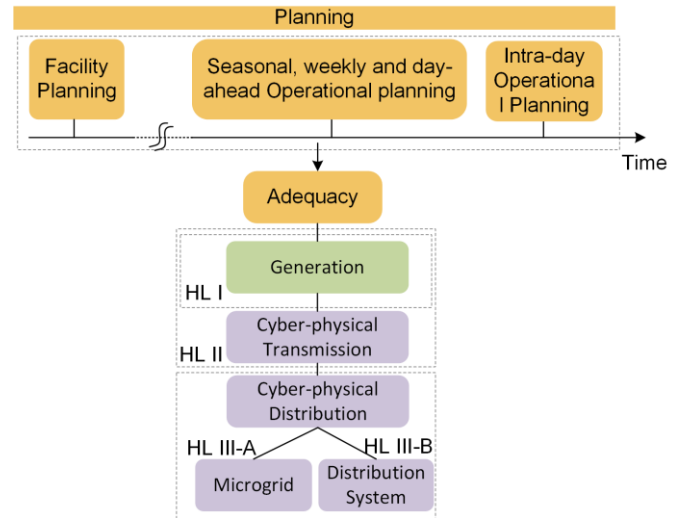

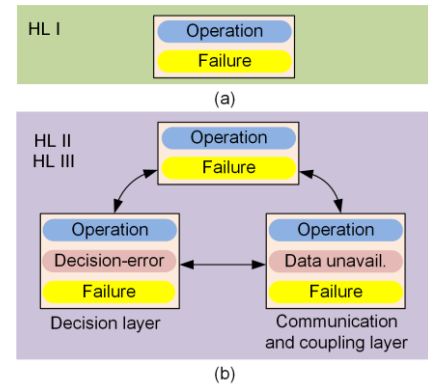Fig. 6. Framework for modern power system adequacy assessment.

Fig. 7. Framework for adequacy assessment: (a) generation system (HL I) in physical layer, (b) bulk power cyber-physical system (HL II) [8] and cyber-physical distribution system (HL III).
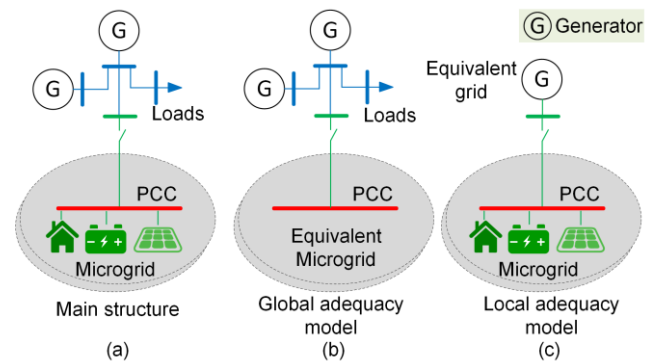
Fig. 8. Scalable framework for modern power system adequacy modeling: (a) main structure as a simplified grid shown in Fig. 3, (b) equivalent model of microgrids from distribution systems, (c) local adequacy for each microgrid.

are modeled as a special node at a Point of Common Coupling (PCC) which is shown in Fig. 8(b). This special node of PCC for each microgrid in a distribution network, i.e., substation, full feeder, partial feeder, and single-customer microgrid, can be a load or generation unit according to the structure and corresponding power management strategy inside each microgrid. For instance, the substation microgrid as shown in Fig. 4 may include medium-scale generation units, which can supply

its load. Therefore, the equivalent load (which is equal to the generation power minus the load power) can be considered at the PCC in Fig. 8(b). Moreover, if the generation of substation microgrid is higher than its load, the equivalent generation can be assumed at the PCC in Fig. 8(b). This equivalent generation unit availability depends on the generation units availability inside the substation, the load power and the upstream switch reliability. As a result, the MV distribution networks can be modeled as equivalent loads or generations for the transmission system analysis. The cyber-physical transmission system reliability can hence be modeled by the cyber-physical availability model as shown in Fig. 7(b) [8].

The reliability of cyber-physical distribution networks can be modeled in HL III, for each microgrid based on its structure in HL III-A as well as for the distribution network in HL III-B as shown in Fig. 6. HL III-A reliability requires local adequacy measures as introduced in [12] for a single microgrid structure. According to Fig. 4, the microgrid structures in distribution networks are divided into single-customer, partial feeder, full feeder and substation microgrid. The adequacy of the single customer microgrid, can be modeled by simplifying its structure as shown in Fig. 8(c). In this structure, the distribution network outside of the single-customer microgrid is modeled as an equivalent generation unit. Its availability is obtained by the availability of grid and generations outside the microgrid and upstream switch. Depending on the application of single-customer microgrid, such as domestic load or hospital load, etc., the local adequacy of the microgrid must be fulfilled. It depends on the availability of physical layer including energy sources and cyber-layer including communication and power/energy management systems. Hence, the local adequacy for single-customer microgrid can be modeled as shown in Fig. 7(b).

The adequacy of partial/full feeder microgrid can be evaluated like the single-customer microgrid considering the single-customer microgrids inside it as a special equivalent node at PCC, which can be a load or generator depending on its power/energy management strategy. Moreover, the adequacy of the substation microgrid is evaluated by modeling the feeder microgrids as special nodes at PCC. The main concern in the distribution network adequacy assessment is not only the availability of energy sources in each sub-grid, but also the accessibility to that sources. This may bring a need for regulations among sub-grids, especially the single-customers that may prefer to be islanded during loss of grid to maintain their adequacy regardless of deteriorating the upstream microgrid adequacy.

A distribution network comprises several substations, which may be connected together through MVAC or MVDC transmission systems and they are also connected to the high voltage grid as shown in Fig. 4. Therefore, the adequacy of the cyber-physical distribution systems can be evaluated by modeling each substation microgrid as a special node at their PCC, being a load or a generator, which are connected to the main grid. This structure is shown in Fig. 8(b) considering that the distribution network is connected to the utility grid through several points, which are modeled as an equivalent generator. In this case, the cyber-physical distribution network reliability can be obtained by the model provided in [8] as shown in Fig. 7(b).

Therefore, the distribution systems reliability, unlike conventional power systems, requires local adequacy assessment due to the presence of DGs and DESS. This proposed scalable reliability modeling for microgrids in distribution networks can guarantee the adequacy of each microgrid. Moreover, it facilitates the reliability evaluation in the whole distribution network with large numbers of DGs, DESS, energy and demand-side management strategies. Moreover, depending on the criticality of the microgrids, e.g., in the case of hospital or data centers, appropriate adequacy measures can be defined for each microgrid which in fact facilitate the efficient design and operation of distribution systems. However, this requires introducing suitable reliability indices for distribution systems, like the ones presented in [12] and then defining standard levels for different applications. Hence, the future distribution systems planning and operation can be reliably guaranteed with new socio-economic regulations among different microgrids and defining standard reliability metrics.

- **Security:**

Besides adequacy, the security of modern power systems must be guaranteed considering the different sources of uncertainties in the modern power systems. Like the conventional power systems, the security can be defined as the system ability to withstand sudden contingencies. The security of modern power systems can be analyzed in three domains of static, dynamic and cyber as shown in Fig. 9.

Static security is associated with the steady state performance of the system after any contingency. Therefore, the system frequency, bus voltages, and thermal limit of equipment must retain in an acceptable interval. Compared to the conventional power systems, the thermal limit of converters specially for HV/MV transmission lines (and solid-state transformers in future power systems) must be properly analyzed due to the limited overloading capability. This will be an issue for MV distribution systems where the substation microgrids are connected together through MVDC lines. Therefore, any contingency may cause overloading of the links and hence, remedial actions must be performed to retain the system security.

Furthermore, in the distribution networks, not only the voltage limits must be fulfilled, but also the power quality
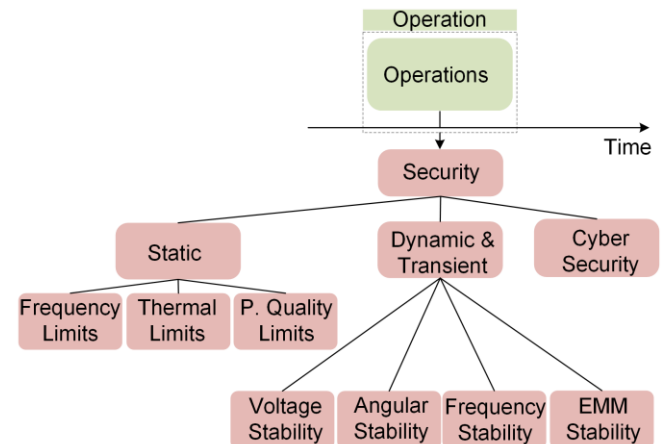

Fig. 9. Framework for security assessment in modern power systems.

requirements need to be guaranteed after any contingency leading to islanding the microgrids. This is due to the fact that the power quality requirements for different applications may not be identical. As a result, active/passive filters must be appropriately displaced in distribution networks to fulfill the static security after islanding the microgrids.

Moreover, power system must be dynamically secure in the case of facing any contingency. Dynamic security is of high importance in modern power systems due to the high penetration of variable energy resources with low inertia. It may introduce voltage and frequency stability issues in the power systems. The intermittent output power or renewable resources can deteriorate the grid voltage and hence, the voltage stability may be affected without appropriate voltage regulators. Moreover, the grid frequency stability can be affected due to the lack of inertia in more/full renewable energy resources. In order to overcome the frequency stability issues in the grid, intercommuting to the neighboring grids with HVDC systems and employing energy storage systems are necessary. The overall system security can enforce the size and location of renewables as well as the connection points, capacity and ancillary services of HVDC systems. By suitable design of system, the overall security can be guaranteed in the power system. Therefore, power system security assessment requires voltage, frequency and angular stability analysis like the conventual power systems.

Furthermore, the EMM stability issues in modern power systems must be considered in security assessment due to the proliferation of power electronic converters. The EMM interactions may cause severe stability issues in power systems and microgrids. Therefore, the system security should be guaranteed due to the EMM interaction issues. The EMM stability assessment within contingency analysis may be a difficult and time-consuming task due to fast dynamics of converter control systems. Therefore, appropriate models and tools should be developed for EMM stability analysis for security assessment in modern power systems.

In addition to static and dynamic security, the modern power systems are prone to cyber-security issues. cyber issues can be associated with the communication and coupling layer and/or decision layer. In communication and coupling layer, physical failure of measurements and monitoring devices as well as unavailability of data can affect the system performance. Furthermore, physical failure of decision equipment can deteriorate the overall security of the system as well as cyberattacks can by hacking the sensors and distorting the measurements as well as false data-injection to the communication links can cause incorrect decision and malfunctions in power systems. Therefore, as explored in [8], the power system security must be guaranteed in terms of physical failure, data unavailability and cyberattacks. These issues may introduce different effects in the system such as angular and frequency stability due to the error in decision making and changing the demand-generation balance, malfunction in islanding detection and grid separation, and also consequences on the equipment overloading, which all can deteriorate the overall system security. Therefore, the cyber-security in modern power systems must be taken into account in security assessment and management.

VI. RELIABILITY ENHANCEMENT STRATEGIES

In previous sections, the future power system challenges and their impacts on the power system reliability have been introduced, and a new framework has been proposed to assess the reliability of modern power systems. This section represents some strategies to enhance the reliability of modern power electronic based power systems. The reliability of these systems can be analyzed in three levels of component, sub-system and system levels [65]. The component level is associated with the device of each sub-systems such as power converters, transformers, protection relays, wind turbine, solar arrays. For instance, the converter components comprise power switches, capacitors, gate drivers, cooling system, control unit and so on. The reliability enhancement efforts in this level could be to strengthen the lifetime of any devices by analyzing the physics of potential failure mechanisms.

In the sub-system level, for example in a power converter, the reliability is in charge of lifetime of its components and operating conditions. Design for reliability in power converters considering an applied mission profile will guarantee a desired long term performance with an acceptable level of reliability [49], [66]. In this approach, the converter component sizing will be performed based on the applied stress in a specific application. Different factor will affect the converter reliability [13]–[16] including its topology [66], control strategy [45], [67], application [45], operation condition and climate conditions [45], [68]. Therefore, in order to enhance the converter level reliability, the operation and climate conditions known as mission profiles, its application and topology and the control strategy must be taken into account during converter design.

In the power system level, availability of sub-systems is of high importance. Availability is associated with the failure frequency and maintenance period of items. The availability can be improved by reducing the failure rate and/or maintenance period. This requires modeling the reliability of components. For instance, the converters suffer from poor reliability, and hence their reliability modeling can help to either decrease the failure rate [45] or planning for optimal maintenance times [65]. Furthermore, at the system level, the power and energy management strategies based on reliability of power sources can remarkably improve the overall system reliability [44].

From security point of view, it is important to accurately model the converters impact on the system stability. Power converters introduce side range of stability issues in power systems due to the electro-mechanical, electro-magnetic interactions [32]. Appropriate control system and output filter design considering the impact of other parts of power system can help to avoid stability issues with high penetration of power converters. Moreover, the cybersecurity becomes an issue for smart operation of power systems. The control system of converters must be resilient enough to prevent malicious intrusion in especially inner controllers which can remarkably affect the overall system stability.

VII. CASE STUDY

In this Section, the adequacy of a power system shown in Fig. 10(a) is analyzed. Two generators namely G1 and G2 are
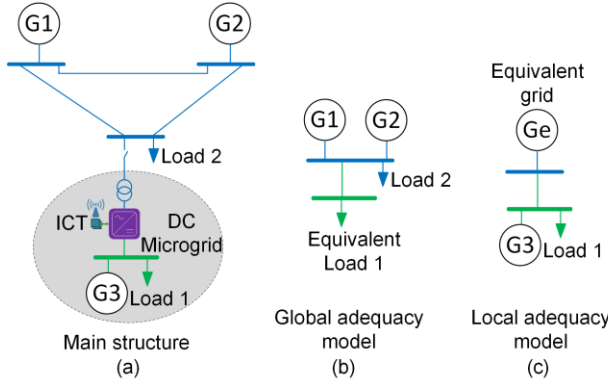
Fig. 10. Case study: (a) main grid structure, (b) equivalent model of the microgrid, (c) local adequacy for the microgrid.

connected to the main grid and the distribution system is operated as a DC microgrid. The DC microgrid is connected to the grid through a converter. The converter communicates with the energy management system. In this case, the microgrid is designed to supply its demand (Load 1) and the main gird is a backup for that load. Moreover, the microgrid will not supply the main grid load (Load 2). The capacity and availability of different components are summarized in TABLE I. The Load 1 is considered having a constant profile over a year, and the load 2 has three peak loads with the given probability in TABLE I.

In order to obtain the reliability of the system, Loss Of Load Expectation (LOLE), as a reliability index of power systems [10], is calculated for both main grid and microgrid. Since the microgrid is design to supply its load, it should be modeled at the connection point to the main grid according to Fig. 8. Considering the operating condition of Microgrid, the Load 1 is only supplied by the main grid whenever the G3 is not available and the converter and ICT is available. This time can be obtained by:

$$T = \left(1 - A_{G3}\right) A_{Con} A_{ICT} \tag{1}$$

where A_{G3}, A_{Con}, A_{ICT} are the availability of G3, converter and ICT. T is the normalized time period that the Load 1 must be supplied by the main grid. As a result, the total load model for the main grid will be the combination of Loads 1 and 2 (shown in Fig. 10(b)) with the probability given in TABLE II.

TABLE I. RELIABILITY DATA OF GRID SHOWN IN Fig. 10.

Component	Capacity	Availability
G1 & G2	10 MW	$A_G = 0.99$
G3	10 MW	$A_{G3} = 0.99$
Converter	10 MW	$A_{Con} = 0.97$
ICT	–	$A_{ICT} = 0.99$
Load 1	8 MW	$P_{11} = 1$
Load 2	14 MW	$P_{21} = 0.3$
	8 MW	$P_{22} = 0.3$
	2 MW	$P_{23} = 0.4$

TABLE II. EQUIVALENT LOAD MODEL FOR MAIN GRID SHWON IN Fig. 10(b).

Load Power (MW)	Duration (%)
22 = 14+8	$P_{21} \times T$
16 = 8+8	$P_{22} \times T$
14 = 14+0	$P_{21} \times (1-T)$
10 = 8+2	$P_{23} \times T$
8 = 8+0	$P_{22} \times (1-T)$
2 = 2+0	$P_{23} \times (1-T)$

TABLE III. EQUIVALENT GEBERATION MODEL FOR MICROGRID SHWON IN Fig. 10(c).

G_e (MW)	Availability
18 = 10+10-2	$P_{23} \times A_G \times A_G \times A_{Con} \times A_{ICT}$
12 = 10+10-8	$P_{22} \times A_G \times A_G \times A_{Con} \times A_{ICT}$
8 = 10-2	$P_{23} \times 2 \times A_G \times (1-A_G) \times A_{Con} \times A_{ICT}$
6 = 10+10-14	$P_{21} \times A_G \times A_G \times A_{Con} \times A_{ICT}$
2 = 10-8	$P_{22} \times 2 \times A_G \times (1-A_G) \times A_{Con} \times A_{ICT}$
0	$1-\Sigma(\text{Availability of } \{18, 12, 8, 6, 2\})$

TABLE IV. LOLE OF GRID AND MICROGRID FOR THE BASE CASE IN TABLE I.

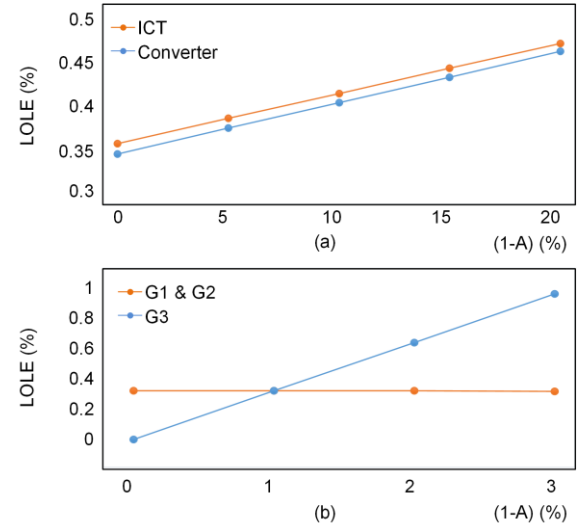| Network	LOLE (%)
Main grid	0.892
Microgrid	0.334

Fig. 11. Microgrid LOLE (local adequacy). (a) Impact of ICT and converter. (b) Impact of grid side generators (G1 & G2) and microgrid side generator (G3).

By convolving the availability model of G1 and G3 with the Equivalent load model in TABLE II, the main grid LOLE can be obtained according to [10]. The obtained LOLE for the base case data given in TABLE I is reported in TABLE IV.

In order to obtain the microgrid LOLE as the local adequacy index, the equivalent grid model must be obtained at the microgrid bus as shown in Fig. 10(c). According to the capacity of the generations in main grid (G1 and G2) and the Load 2 model, the equivalent generation model at microgrid bus can be obtained as:

$$G_e = G1 + G2 - L2 \tag{2}$$

where G_e, G1, G2 and L2 denote the equivalent generation, power of G1 and G2 and Load 2 respectively. Since L2 has different levels, Ge will also have different levels where its availability depends on the availability of G1, G2, L2, converter and ICT. As a result, the equivalent model of grid at microgrid bus can be obtained as summarized in TABLE III. Combining the equivalent generation model in TABLE III with the generation model of G3 will result in generation model in microgrid level. Since this procedure is similar to the conventional power systems, the calculations are not provided here, while detail description can be found in [10]. Finally, the microgrid LOLE can be obtained by

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convolving the Load 1 model with the generation model. This value is calculated and reported in TABLE IV. Obtained results given in TABLE IV shows that the local LOLE is lower than the main grid LOLE for this case study. Therefore, operating distribution grids as a microgrid will improve the local adequacy.

Moreover, the impact of converter and ICT unavailability (1-A) on the local LOLE is show in Fig. 11(a). It is obvious that increasing the unavailability of the converter and ICT will deteriorate the microgrid reliability where as it can be seen in Fig. 11(a), the LOLE is increased by increasing unavailability. Therefore, both interlinking converter to the main grid and the ICT systems will affect the reliability of the microgrid. Furthermore, the impact of gird side and microgrid side generation units unavailability is illustrated in Fig. 11(b). It is shown that the grid side generators impact on local LOLE is negligible, while the microgrid generation unit G3 has a considerable effect on the local LOLE. Therefore, operating distribution systems as a microgrid requires proper design of its component, rather than components out of microgrid, to guarantee an acceptable level of reliability.

VIII. CONCLUSION

This paper has reviewed the reliability concept in the conventional power system by explaining its main elements. Afterwards, the structure of modern power systems with inclusion of new technologies such as smart microgrids, renewable energies, and energy storage systems has been presented. The challenges that the modern power systems are facing have been addressed. Finally, a new framework for reliability assessment in modern power systems has been introduced. Reliable planning and operation of modern power systems require new regulations for smart microgrids and standardization of reliability metrics for cyber-physical distributed power systems. Moreover, reliability analysis at different levels requires suitable and time-efficient tools and approaches for planning and operation of cyber-physical power systems with large number of components and elements, especially with time-variant failure rate of new technologies. As a result, self-organized, distributed approaches can facilitate optimal and reliable planning and operation of future smart grids. Future research will focus on the evaluating the reliability of modern power systems applying the proposed framework taking into account the different reliability aspects.

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