System-Level Design for Reliability of Microgrids Considering Power Electronic Failures

Davoodi, Amirali; Peyghami, Saeed; Yang, Yongheng ; Dragičević, Tomislav ; Blaabjerg, Frede

Published in:
Proceedings of the 2022 IEEE 13th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)

DOI (link to publication from Publisher):
10.1109/PEDG54999.2022.9923258

Publication date:
2022

Document Version
Accepted author manuscript, peer reviewed version

System-Level Design for Reliability of Microgrids Considering Power Electronic Failures

Amirali Davoodi[1], Saeed Peyghami[1], Yongheng Yang[2], Tomislav Dragičević[3], and Frede Blaabjerg[1]
[1] Department of Energy, Aalborg University, Aalborg, Denmark
[2] Department of Electrical Engineering, Zhejiang University, Hangzhou, China
[3] Department of Electrical Engineering, Technical University of Denmark, Copenhagen, Denmark
amirali.davoodi@energy.aau.dk

***Abstract*—This paper investigates and quantifies the consequences of ignoring power converter failures in the system-level design of microgrids. To achieve this goal, the process of converter-level reliability modeling, calculating the availability, and finally obtaining the system-level reliability indices are explained. A model-based and mission profile-based system-level design methodology has been used, which considers both reliability and cost. Further, the methodology has been implemented in a case study, once considering and once ignoring the power electronic failures. Accordingly, it has been shown that ignoring the converter failures can lead to an unreliable system-level design and jeopardizes its cost-effectiveness in the long run.**

Keywords—Reliability, Adequacy, Microgrid Design, Power Electronic Failures, Power Systems

I. INTRODUCTION

Nowadays, more renewable energies are being integrated into the electrical power grid, which requires an extensive use of Power Electronic (PE) converters. Consequently, due to the intermittent nature of renewables as well as the failures of the power converters, the reliability of the modern power grids and microgrids faces different challenges compared to those of the conventional grid [1]. Therefore, to ensure the modern grid reliability, an adequate system-level design is crucial. In other words, enough generation and storage resources must be considered in the design phase to guarantee that the system will keep its acceptable reliability over time. As categorized in [2], various methods exist for planning and optimizing the distributed generation resources and microgrids. Typically, for the system-level design and when calculating the number of required resources, only the uncertainty of renewable generation is considered, and the PE failures are ignored. In this regard, in [3], a data-driven approach based on the K-means algorithm has been used to design the microgrids, considering the limitations in electricity exchange. Similarly, [4] uses a Mixed Integer Linear Programming (MILP) approach to size the PhotoVoltaic (PV) and Battery Storage System (BSS) units in a microgrid. Notably, both the reliability and economic model of the aforementioned microgrid have been developed and plugged into the MILP. Likewise, [5] uses a multi-objective optimization method based on a genetic algorithm to design active distribution networks considering the reliability and cost. The multi-objective programming has also been used in [6] to find the optimal design of microgrids to minimize the cost while maximizing the reliability. In [7], a method has been developed for the optimal design of off-grid microgrids with a focus on reliability and N-1 criterion. Also, in [8], a method has been presented based on a multi-scenario technique and using bilevel programming to plan the distribution networks with distributed generation. Notably, the uncertainty of generation is tackled by considering a mix of probabilistic and time series approaches. In [9], a method has been proposed for the optimal sizing of residential microgrids to minimize the costs by considering the model predictive control for dispatch. Likewise, [10] proposes a cost-based framework to determine the size and generation mix of renewable resources with respect to converter efficiencies and the growing ratio of DC loads. However, none of these works have considered the PE failures and studied their influence on the robustness of the proposed system-level design methodologies. On the other hand, PE failures and converter aging will result in degradation of the system performance over time. This can eventually make the system unreliable in the long run, if not taken into account in the design phase [11]. Also, due to the costs associated with unreliability, system operating costs will increase over time. In contrast, if the system is overdesigned and more resources are used than what actually is needed, the investment cost increases unnecessarily, and the design would not be cost-effective. Hence, ignoring the power converter failures or using an unrealistic reliability model for them will introduce errors to the system-level design, which in turn, can cause unreliability over time (due to the inadequate system design) or lead to economic losses (due to the overdesign of the system and the cost of interrupted energy).

Therefore, this paper studies the influence of power converter failures on the system-level design of a modern power grid. For demonstration, this paper will determine the adequate number of PhotoVoltaic (PV) and Wind Turbine (WT) units needed for a reliable system design, considering both PE failures and generation uncertainties. Therefore, first, the process of converter-level reliability modeling as well as calculating the converter availability will be explained. Then, this information will be used together with modeling the uncertainty of renewable generation to calculate the system-level reliability indices. Next, these indices will be used to quantify not only the system-level reliability but also the economic consequences of unreliability. Finally, the system-level reliability and cost will be used as the decision variables to determine the required number of PV and WT units based on the reliability-cost-based framework. Further, for a case study, the system-level design will be done, once considering the PE converter aging and once neglecting that, where the impact of mission profiles will be considered too. Finally, the

This work was supported by THE VELUX FONDEN under the VILLUM Investigator grant for the REPEPS project at Aalborg University.

performance of these two design cases will be evaluated and compared with each other in terms of reliability and costs to investigate how ignoring the PE failures influences the adequacy of the system-level design.

II. System-Level Design Methodology

The process of obtaining the system-level reliability indices for a microgrid is shown in Fig. 1, where the first step is modeling the converter-level reliability. PE converter system failures can be classified into wear-out and random-chance failures. The wear-out failures can be modeled according to Fig. 2 [12]. First, the mission profiles (loadings) must be translated into the component stressors. Since the temperature and its cycling are the main stressors of PE components [13], in the wear-out modeling only the temperature is considered. The translation of the mission profiles to the temperature can be done by using the electro-thermal models. In other words, first, the power losses must be calculated by using the electrical models, and then the power losses should be mapped into the temperature of reliability-critical components. Next, the rainflow counting algorithm must be used to classify the temperature profile into several cycles, which determines the stress on the component (i.e., intensity and duration of the cycles). Subsequently, the component lifetime model (which determines the strength of the component) together with the component stress is input to the Miner's rule to calculate the Damage of the component. Due to small differences during the manufacturing processes, no two components are exactly the same, and thus, some uncertainties are introduced here. So, by using the Monte Carlo simulation, this Damage variation is transformed into a probability distribution (i.e., a Probability Density Function (PDF)) to account for these uncertainties. Finally, when the process is done for all the reliability-critical components and their Damage distributions are obtained, the converter-level reliability, $R(t)$, can be calculated by using the Reliability Block Diagram approach (RBD) [14].

It is worth mentioning that wear-out failures have their roots in the accumulated damage over time and originate from the inside of the components. On the other hand, random-chance failures originate from external sources such as the converter failure, e.g., due to lightning. This type of failure can

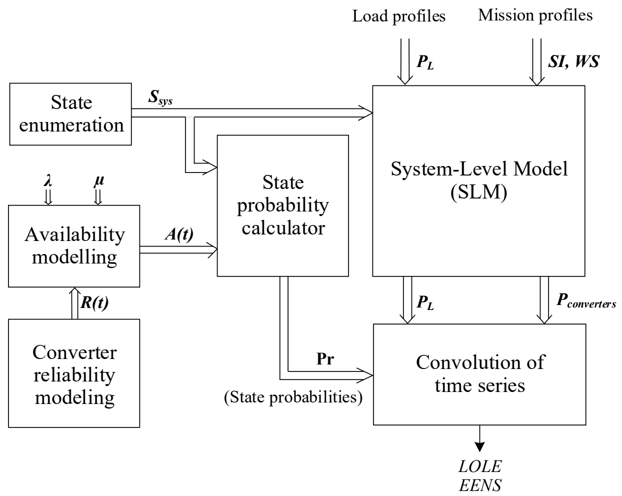

Fig. 1. Obtaining the system-level reliability indices for a microgrid (*SI*: solar irradiance profile, *WS*: wind speed profile, P_L: load power profile, *Pconverter*: output power profile of power converters, *LOLE*: Loss Of Load Expectations, and *EENS*: Expected Energy Not Supplied).

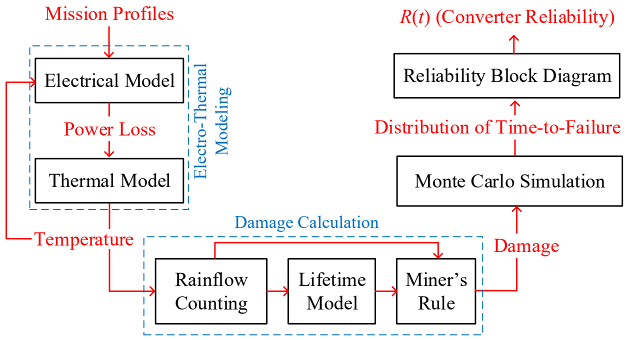

Fig. 2. Power electronic converter reliability modeling process (converter reliability modeling block in Fig. 1).

be modeled with a constant failure rate, λ, which can be obtained from the field data [16].

For each converter, the random-chance failure rate, λ, together with the converter repair rate, μ, and the converter-level wear-out reliability, $R(t)$, are needed. This information is used to calculate the availability of each converter, $A(t)$, according to the algorithm shown in Fig. 3, where Δt is the time step, N_t is the number of time points, and $f(t) = -dR(t)/dt$. This algorithm is based on the method explained in [17], where more details for the implementation of it have been provided. Afterward, the system-level reliability indices are to be calculated based on the block diagram shown in Fig. 1. The availability of each converter, together with the system state, which is calculated based on the state enumeration technique [18], will then be used to calculate the state probabilities, Pr. In addition, as shown in Fig. 1, mission profiles (solar irradiance profile, wind speed profiles) are given to the performance model of the microgrid (which includes modeling of PV, WT, and BSS) to calculate how much power is available at any given moment. Eventually, the available power profiles, $P_{converter}$, as well as load profiles , P_L, and state probabilities, Pr, are convolved over time to calculate the system-level reliability indices, i.e., the *LOLE* and *EENS*.

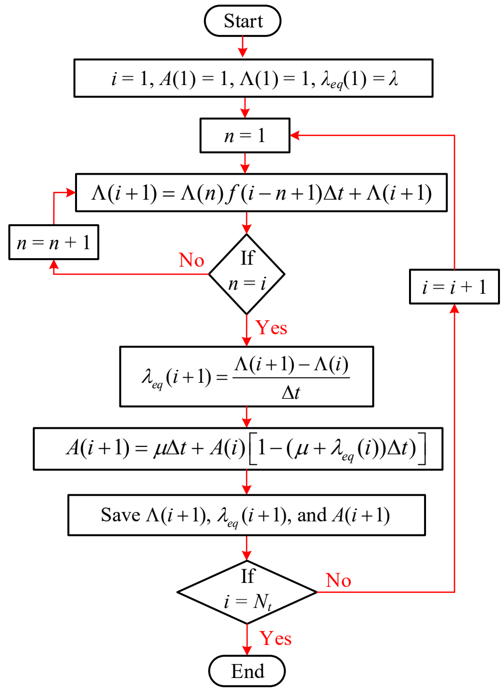

Fig. 3. Algorithm for converter availability modeling block in Fig. 1.

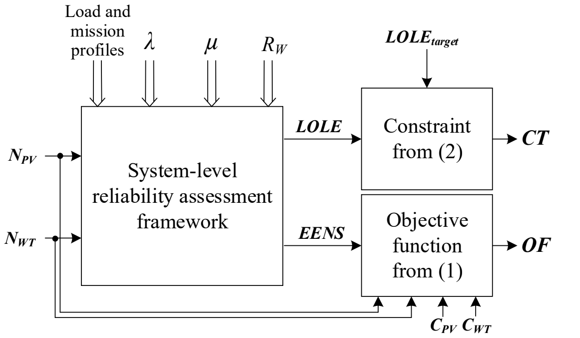

Fig. 4. Reliability-cost-based system-level design methodology (N_{PV}: number of photovoltaic units, N_{WT}: number of wind turbine units, *LOLE*: loss of load expectation, *EENS*: expected energy not supplied, λ: random-chance failure rate, μ: repair rate, *R*: converter wear-out reliability, *OF*: objective function, *CT*: constraint, and the system-level reliability assessment framework was shown in Fig. 1).

The *LOLE* is a prediction of the annual interruption duration, which must be lower than a certain value (typically, 4 [hr/yr] < $LOLE_{target}$ < 8 [hr/yr]) decided by the policy-makers. Therefore, in order to have a reliable system design, the condition $LOLE < LOLE_{target}$ must be met at any given time. Similarly, *EENS* is a prediction of the amount of energy interrupted annually. Notably, this index can be translated into monetary values and used for economic studies by using the concept of *VoLL* (Value of the Lost Load) [19], which indicates the cost associated with the interruption of each unit of energy, and it is typically multiple times of the energy price. In other words, the EENS determines how much energy will be interrupted due to unreliability, and the VoLL determines the monetary value of the interrupted energy.

In this paper, it is assumed that PV units and WTs have already been designed at the converter level with a given rated power. However, at the system-level design, it should be decide how many PV units (N_{PV}) and WTs (N_{WT}) must be used. To make this decision, this paper models the problem as an optimization problem, where N_{PV} and N_{WT} are decision variables, and the accumulated cost at the end of the planning horizon is the "objective function", *OF*, whereas the system-level reliability is a "constraint", *CT*. A block diagram of the problem has been shown in Fig. 4. Two costs are considered in this case, the cost of investment and the cost of unreliability. The cost of investment can be calculated as a product of the cost of each unit (C_{PV} and C_{WT}) and the number of units (N_{PV} and N_{WT}). Similarly, as explained before, the cost of unreliability can be obtained by multiplying the *EENS* and *VoLL*. Therefore, the objective function can be defined as the accumulated costs at the end of the planning horizon, T_{PH}, which can be written as

$$OF = N_{PV}C_{PV} + N_{WT}C_{WT} + VoLL.\sum_{y=1}^{T_{PH}} EENS(y) \qquad (1)$$

Also, to check whether the optimal solution meets the constraint conditions (i.e., required reliability target), the following equation can be used

$$CT = \begin{cases} 0 \ , \ LOLE > LOLE_{target} \\ 1 \ , \ LOLE \le LOLE_{target} \end{cases} \qquad (2)$$

When $CT = 1$, the solution meets the reliability requirements and therefore is acceptable (and vice versa).

Since the developed models (shown in Fig. 1 to Fig. 4) are fast, different combinations of N_{PV} and N_{WT} can evaluated to check which solution yields the best results. By using the methodology explained above and is shown in Fig. 4, the corresponding *OF* and *CT* are calculated. Finally, the optimal solution is the one that has the minimum *OF* and, at the same time, its *CT* = 1.

III. Results and Discussion

In this section, the consequences of ignoring power converter aging on the system-level design will be investigated by analyzing a case study. The goal of the case study is to determine the number of PV and WT units N_{PV} and N_{WT} (as shown in Fig. 5) that are required to ensure the system reliability within a 10-year planning horizon, i.e., T_{PH} = 10 [yr]. It is assumed that the PV units and WT units are already designed at the converter level, and their power ratings are assumed to be 7 and 5.5 [kW], respectively. The power converters used in this study for PV and WT systems are shown in Fig. 6 and Fig. 7, respectively. Additionally, the corresponding parameters for these converters are presented in Table I. Also, grid parameters are provided in Table II. Moreover, a battery storage unit is assumed with a fixed power rating and storage capacity, which are 51 [kW] and 5.5 [MWh], respectively. Also, the price of units are C_{PV} = 7952 [$] and C_{WT} = 7233 [$], while and the *VoLL* = 42 [$/kWh] [20], [21]. It is also worth mentioning that power semiconductors and capacitors are considered as reliability-critical components for this study.

Furthermore, Fig. 8 shows the mission profiles (yearly profile of solar irradiance and wind speed profiles) used for the first case study, whose location is Aalborg, Denmark. Also, the ambient temperature has been used for the converter-level wear-out modeling.

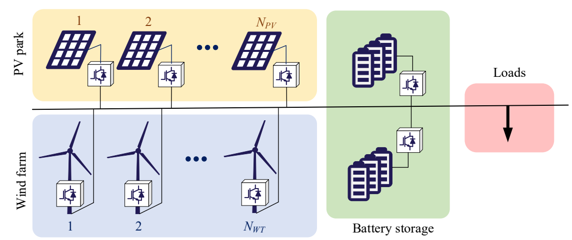

Fig. 5. Overall schematic of the case study.

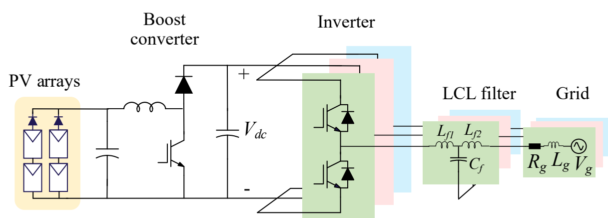

Fig. 6. Schematic of the PhotoVoltaic (PV) system used for case studies.

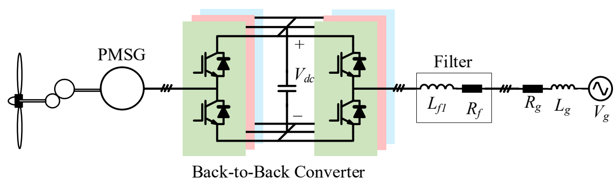

Fig. 7. Schematic of the Wind Turbine (WT) system used for case studies.

TABLE I. CONVERTER PARAMETERS FOR THE PHOTOVOLTAIC (PV) AND WIND TURBINE (WT) SYSTEM SHOWN IN FIG. 6 AND FIG. 7

Parameter	Value for PV inverter	Value for WT converter
Output power	7 (kW)	5.5 (kW)
V_{dc}	800 (V)	500 (V)
f_{sw}	2500 (Hz)	10000 (Hz)
L_{f1}	3.5 (mH)	1.5 (mH)
L_{f2}	0.5 (mH)	-
C_f	22 (μF)	-
R_f	-	0.1 (Ω)

TABLE II. GRID PARAMETERS FOR THE CASE STUDY

Parameter	Value
V_g	230 (V)
f_g	50 (Hz)
R_g	0.5 (Ω)

According to the method explained in section II, the optimal (N_{PV} , N_{WT}) has been found for two cases, where case I ignores the power converter aging while case II considers it. In this regard, Fig. 9(a) shows the objective function, *OF*, for case I, where the value of *CT* has also been shown. From the above method and from Fig. 9(a), the optimal values for case I are (N_{PV} = 7, N_{WT} = 8). Similarly, Fig. 9(b) shows the *OF* for case II where PE converter aging is taken into account. As Fig. 9(b) shows, the optimal point for (N_{PV} , N_{WT}) changes in this case and more generation resources are needed. As a result, when the PE converter aging is considered, the optimal solution will be (N_{PV} = 10, N_{WT} = 15). This is reasonable because, in this case, the degradation of the system-level performance due to converter aging is considered. Therefore, to compensate for it in the long run, more generation resources must be used in the system (design margin). Notably, by using the design method proposed in this paper, this margin can be calculated effectively.

Now for these two different system designs, that is (N_{PV} = 7, N_{WT} = 8) for case I and (N_{PV} = 10, N_{WT} = 15) for case II, the values of *LOLE* and *OF* are calculated for a 10-year planning horizon. The value of *LOLE* for these two cases in addition to the $LOLE_{target}$ are shown in Fig. 10(a). As Fig. 10(a) shows, at the beginning of the planning horizon where the converters are new, both cases meet the $LOLE_{target}$ requirements (i.e., $LOLE < LOLE_{target}$). However, at the end of the planning horizon, for case I (where the system was designed without considering PE converter aging), the *LOLE* exceeds the required level. In other words, even though the system performance is acceptable when it is new, the system violates its reliability requirements after a few years, due to the aging of power converters and the increased failure rate. In contrast, since more resources have been used for the case II design, even though the system performance degrades over time due to converter aging and even though the *LOLE* increases, the *LOLE* will still remain below the required level even at the end of the planning horizon.

Also, Fig. 10(b) shows the accumulated costs over time within the planning horizon. As it can be seen from Fig. 10(b), at the beginning of the planning horizon, where the converters are new, case I seems more cost-effective because fewer units are used in the design, and therefore less investment cost has been expended. Nevertheless, as the converters age, the *EENS* increases and the system becomes more unreliable.

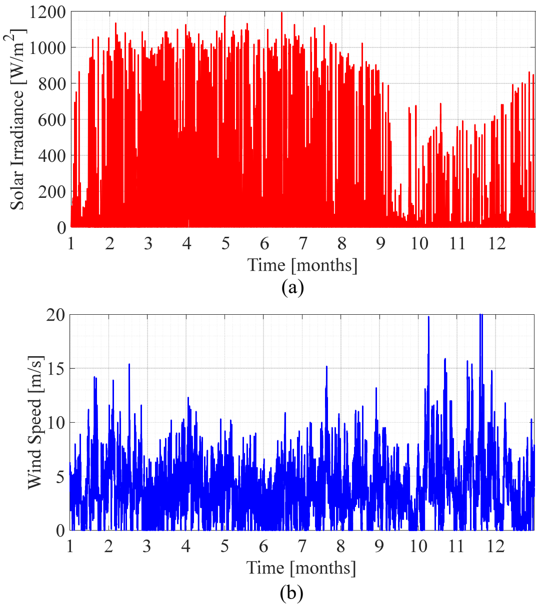

Fig. 8. Aalborg mission profiles: (a) yearly profile of solar irradiance and (b) yearly profile of wind speed.

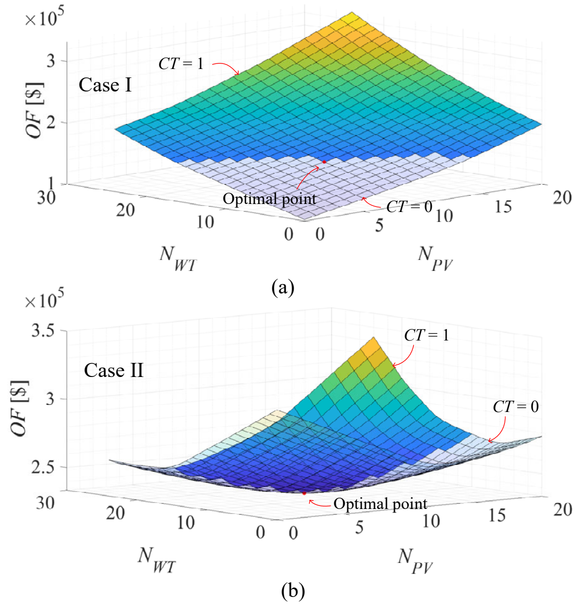

Fig. 9. Variation of the objective function, OF, in terms of the number of PV and WT units (N_{PV} , N_{WT}) given Aalborg mission profiles, where *CT* shows whether the constraint is met or not: (a) case I ignoring PE failures, and (b) case II considering PE failures

Accordingly, the cost of unreliability increases over time such that, at the end of the planning horizon, the total cost in case I overtakes that of case II. This means that in the long run, case II would be more cost-effective compared to case I.

To study the effect of mission profiles on the robustness of the system-level design, a new set of mission profiles will be studied hereafter. These mission profiles are shown in Fig. 11 and are related to a location is Las Vegas, NV [22]. A similar process will be repeated given these new profiles to study the effect of mission profiles and generation uncertainty on the reliability and cost-effectiveness of the system-level design.

Similar to the previous study, two cases will be investigated with the new mission profiles, where case I ignores the power converter aging while case II considers it. In this regard, Fig. 12(a) shows the objective function, *OF*, for

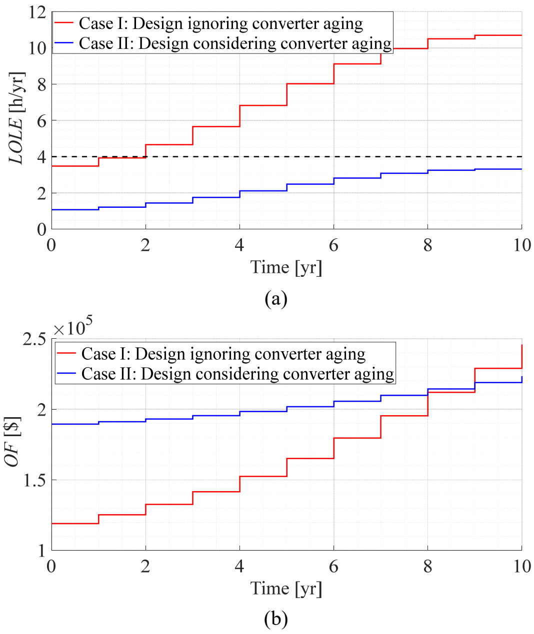

Fig. 10. Comparison of case I and case II designs using Aalborg mission profiles: (a) system-level reliability by comparing the *LOLE* over time, and (b) cost-effectiveness by comparing the *OF* showing the accumulated costs over time.

case I, where the value of *CT* has also been shown. From the above method and from Fig. 12(a), the optimal values for case I are (N_{PV} = 9, N_{WT} = 0). Similarly, Fig. 12(b) shows the *OF* for case II where PE converter aging is taken into account. In case II, the optimal values are (N_{PV} = 12, N_{WT} = 3). As it can be confirmed by these results, even with the new set of mission profiles, more generation resources must be considered in the design phase when the PE failure are taken into account. It is reasonable to consider some design margin at the beginning to avoid unreliability due to PE failures and costs associated with it in the long run. Notably, the method proposed in this paper, enables quantifying this margin.

Furthermore, for case I that is (N_{PV} = 9, N_{WT} = 0) and for case II and (N_{PV} = 12, N_{WT} = 3), the values of *LOLE* and *OF* are calculated for the 10-year planning horizon. The value of *LOLE* for these two cases in addition to the $LOLE_{target}$ are shown in Fig. 13(a). From Fig. 13(a), it can be seen that at the beginning of the planning horizon where the converters are new, both cases meet the $LOLE_{target}$ requirements (i.e., $LOLE < LOLE_{target}$). Nevertheless, at the end of the planning horizon, for case I, the *LOLE* exceeds the required level. As a result, if PE failures are not considered in the design phase, the system would not be able to meet its reliability standards in the long run. Further, as shown in Fig. 13(b), at the end of the planning horizon, the total accumulated costs in case I (ignoring PE failures) will exceed that of case II (considering PE failures. In other words, case II design will be more cost-effective in the long-term since its running costs will be lower due to a lower cost of unreliability.

Since the proposed method in this paper is mission profile-based, it is possible to study the influence of mission profiles and generation uncertainty on the system-level design. For example, it can be seen that, for the designs based on Aalborg mission profiles (Fig. 8) the share of WTs is considerable, while in the designs based on Las Vegas' mission profile, the optimal design is PV-dominated. This is also reasonable because in Aalborg, Denmark there is an abundance in the

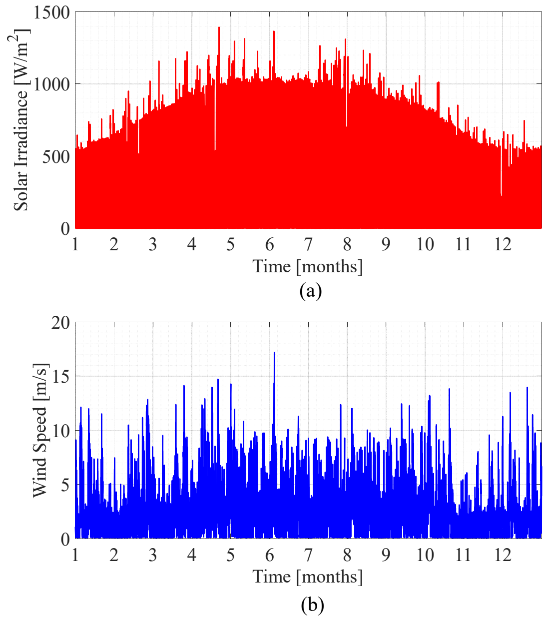

Fig. 11. Las Vegas mission profiles: (a) yearly profile of solar irradiance and (b) yearly profile of wind speed [22].

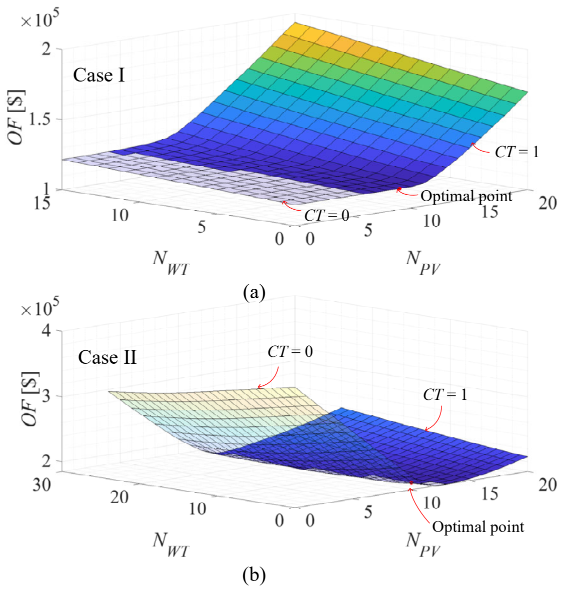

Fig. 12. Variation of the objective function, OF, in terms of the number of PV and WT units (NPV , NWT) given Las Vegas mission profiles, where *CT* shows whether the constraint is met or not: (a) case I ignoring PE failures, and (b) case II considering PE failures.

wind resources compared to solar resources. In contrast, in Las Vegas, NV, the solar resources are copious. As a result, the optimal design for these two locations is different, which can be quantified by using the model-based and mission-profile-based approach proposed in the paper.

It can be concluded from Fig. 10(a) and Fig. 13(a), designing the system without considering the PE converter aging will cause unreliability in the long run, although it might seem fine at the beginning of the system operation. Likewise, from Fig. 10(b) and Fig. 13(b) it can be understood that ignoring the PE converter failures can also lead to economic losses in the long run and challenge the cost-effectiveness of the design due to the cost of energy not supplied and the *VoLL*. Further, the mission profiles and generation uncertainties

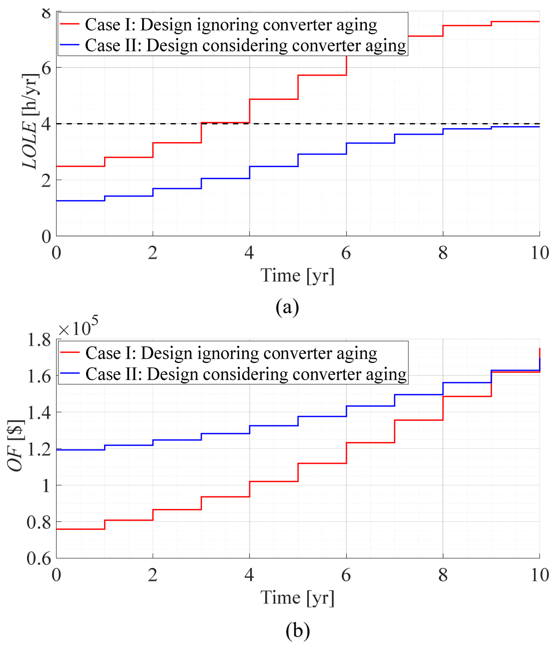

Fig. 13. Comparison of case I and case II designs using Las Vegas mission profiles: (a) system-level reliability by comparing the LOLE over time, and (b) cost-effectiveness by comparing the OF showing the accumulated costs over time.

seriously influence the system-level design, which can be incorporated by using the method proposed in this paper.

IV. Conclusion

Failure of power converters is typically ignored when designing renewable-based grids or microgrids at the system level. However, due to the converter aging and the subsequent degradation of system performance, the system may face challenges in terms of reliability as time passes. Hence, this paper aims to study and quantify the impact of power converter aging on the robustness of the system-level design of the microgrids. To do so, first, the process of reliability modeling of PE converters has been explained. Then, a method has been presented to calculate the converter availability accordingly. Subsequently, the availabilities are combined with the uncertainty of renewable generation to calculate the system-level reliability indices *EENS* and *LOLE*. Then, the system has been designed according to these indices by using a reliability-cost-based approach. By using this approach, the system has been designed once considering and once ignoring PE converters' failures. Next, the performance of the two design cases has been compared in terms of reliability and cost-effectiveness. It was shown that when ignoring PE converter's aging, the system unreliability can increase to the extent that it might surpass the allowed level. However, if the converter failures and aging are considered at the design phase, this unacceptable unreliability at the end of the planning horizon can be prevented by considering some design margin at the beginning. Notably, the value of this design margin can be calculated by using the method proposed in this paper. Also, since the system becomes more unreliable over time and the energy not supplied increases, the consequent economic losses (cost of unreliability) jeopardize the cost-effectiveness of the system design. Moreover, since the method presented in this paper is mission profile-based, the mission profiles can be incorporated into the system-level design and their impact can be studied quantitatively.

References

[1] S. Peyghami, P. Palensky, and F. Blaabjerg, "An Overview on the Reliability of Modern Power Electronic Based Power Systems," IEEE Open J. Power Electron., vol. 1, pp. 34–50, 2020.

[2] M. Sandelic, S. Peyghami, A. Sangwongwanich, and F. Blaabjerg, "Reliability Aspects in Microgrid Design and Planning: Status and Power Electronics-Induced Challenges," Renew. Sustain. Energy Rev., vol. 159, p. 112127, May 2022.

[3] Q. Chen, M. Xia, Y. Zhou, H. Cai, J. Wu, and H. Zhang, "Optimal Planning for Partially Self-Sufficient Microgrid with Limited Annual Electricity Exchange with Distribution Grid," IEEE Access, vol. 7, pp. 123505–123520, Aug. 2019.

[4] X. Wu, W. Zhao, X. Wang, and H. Li, "An MILP-Based Planning Model of a Photovoltaic/Diesel/Battery Stand-Alone Microgrid Considering the Reliability," IEEE Trans. Smart Grid, vol. 12, no. 5, pp. 3809–3818, Sep. 2021.

[5] V. F. Martins and C. L. T. Borges, "Active Distribution Network Integrated Planning Incorporating Distributed Generation and Load Response Uncertainties," IEEE Trans. Power Syst., vol. 26, no. 4, pp. 2164–2172, Nov. 2011.

[6] H. R. Baghaee, M. Mirsalim, G. B. Gharehpetian, and H. A. Talebi, "Reliability/Cost-Based Multi-Objective Pareto Optimal Design of Stand-Alone Wind/PV/FC Generation Microgrid System," Energy, vol. 115, pp. 1022–1041, Nov. 2016.

[7] S. Chalil Madathil, E. Yamangil, H. Nagarajan, A. Barnes, R. Bent, S. Backhaus, S. J. Mason, S. Mashayekh, and M. Stadler, "Resilient Off-Grid Microgrids: Capacity Planning and N-1 Security," IEEE Trans. Smart Grid, vol. 9, no. 6, pp. 6511–6521, Nov. 2018.

[8] Y. Gao, X. Hu, W. Yang, H. Liang, and P. Li, "Multi-Objective Bilevel Coordinated Planning of Distributed Generation and Distribution Network Frame Based on Multiscenario Technique Considering Timing Characteristics," IEEE Trans. Sustain. Energy, vol. 8, no. 4, pp. 1415–1429, Oct. 2017.

[9] S. Swaminathan, G. S. Pavlak, and J. Freihaut, "Sizing and Dispatch of an Islanded Microgrid with Energy Flexible Buildings," Appl. Energy, vol. 276, p. 115355, Oct. 2020.

[10] H. Lotfi and A. Khodaei, "AC versus DC Microgrid Planning," IEEE Trans. Smart Grid, vol. 8, no. 1, pp. 296–304, Jan. 2017.

[11] S. Peyghami, P. Palensky, M. Fotuhi-Firuzabad, and F. Blaabjerg, "System-Level Design for Reliability and Maintenance Scheduling in Modern Power Electronic-Based Power Systems," IEEE Open Access J. Power Energy, vol. 7, pp. 414–429, Oct. 2020.

[12] S. Peyghami, Z. Wang, and F. Blaabjerg, "A Guideline for Reliability Prediction in Power Electronic Converters," IEEE Trans. Power Electron., vol. 35, no. 10, pp. 10958–10968, Oct. 2020.

[13] H. Wang, M. Liserre, F. Blaabjerg, P. de Place Rimmen, J. B. Jacobsen, T. Kvisgaard, and J. Landkildehus, "Transitioning to Physics-of-Failure as a Reliability Driver in Power Electronics," IEEE J. Emerg. Sel. Top. Power Electron., vol. 2, no. 1, pp. 97–114, Mar. 2014.

[14] R. Billinton and R. N. Allan, "Reliability Evaluation of Engineering Systems," 2nd ed. Boston, MA: Springer US, 1992.

[15] K. Ma, U.-M. Choi, and F. Blaabjerg, "Prediction and Validation of Wear-out Reliability Metrics for Power Semiconductor Devices with Mission Profiles in Motor Drive Application," IEEE Trans. Power Electron., vol. 33, no. 11, pp. 9843–9853, Nov. 2018.

[16] S. Peyghami, F. Blaabjerg, and P. Palensky, "Incorporating Power Electronic Converters Reliability into Modern Power System Reliability Analysis," IEEE J. Emerg. Sel. Top. Power Electron., vol. 9, no. 2, pp. 1668–1681, Apr. 2021.

[17] A. Davoodi, S. Peyghami, Y. Yang, T. Dragicevic, and F. Blaabjerg, "Fast and Accurate Modeling of Power Converter Availability for Adequacy Assessment," IEEE Trans. Power Delivery, vol. 36, no. 6, pp. 3992–3995, Dec. 2021.

[18] W. Li, Ed., "Risk Assessment of Power Systems." Hoboken, NJ, USA: John Wiley & Sons, Inc., 2014.

[19] European Commission, "Identification of Appropriate Generation and System Adequacy Standards for the Internal Electricity Market," Brussels, Belgium, 2016.

[20] IRENA, "Renewable Power Generation Costs in 2020." 2020.

[21] Energinet, "Regler for Forbrugsaflastning (' Load Shedding ') Af Forbrugere På Transmissionsnettet," Fredericia, Denmark, 2018.

[22] A. Andreas and T. Stoffel, "NREL Report No. DA-5500-56509," University of Nevada (UNLV), Las Vegas, Nevada, 2006.