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Multi-Converter System Modelling in Cost for Reliability Studies

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***Abstract*—Designing a system with a certain level of reliability often impacts its cost. This parameter is even more affected for a system with increased installation rate of failure-prone power electronics. Thus, reliability of converters plays key role in multi-converter system reliability and related economic profitability. In this paper, an economic model considering the power electronics reliability cost and power system reliability cost in planning of multi-converter system is presented. A case study including the impact analysis reveals that a multi-converter system cost excluding the two reliability-related costs can be significantly underestimated during system planning. Thus, the cost studies including the two reliability domains are necessary in order to avoid the non-optimal design of future multi-converter systems.**

***Index Terms*—Power electronics, reliability, cost, multi-converter systems, design and planning**

I. Introduction

In recent years, the electrical power systems have undergone a structural and operational change with the integration of renewable energy-based units. This inevitably deemed a large increase in failure-prone power electronics units serving as interface between renewable energy-based units and grid [1]. Field experience in wind power applications from 2016 has shown that power converters are one of components dominantly causing repair activities on system [2]. Their reliability influence the overall system reliability and availability, especially in case of a multi-converter system [3]. Therefore, power electronics reliability needs to be adequately included in the reliability analysis during a multi-converter system design.

Commonly, a system is designed to fulfill a required level of reliability and at the minimum cost. System reliability is assessed by employing standard power system reliability procedure. This procedure is based on the quantitative analysis, with the aim of estimating the severity of the events leading to the interruptions in the designed system [4]. The estimated system reliability is then either used directly within the design procedure or transferred to the cost of reliability. When used directly, the reliability is considered within the optimization procedure, where the economic model representing the cost of designed system is also defined [5], [6]. For example, authors in [5] proposed a method for energy storage sizing in microgrid applications. The problem is defined as an optimization problem with the objective to minimize the system cost as a function of the energy storage size. The reliability is evaluated by using one of the standard reliability indices defined in [4] and included as a constraint in the optimization procedure. Furthermore, in [6], a set of new metrics for reliability and economics evaluation are presented for microgrid applications. They act as supplementary indices, which can also be used during reliability-cost analysis within the planning process. Another approach includes transferring the reliability indices to the cost of reliability. This cost is then used together with other system costs during the design optimization procedure. For example, in [7], [8] the optimization-based methods for microgrid planning are proposed. In both cases, the optimization objective is set to minimize the planning cost. It consists of investment and operation cost of units as well as the cost of unserved energy representing the reliability aspect of the system. Similar is done in [9], where the optimization problem is expanded to three objective functions to minimize the system cost. The reliability-related costs included in the study are cost of loss of load and loss of energy expected, both determined based on the reliability procedure in [4].

In the aforementioned approaches [5]–[9], the power electronics reliability is ignored or its evaluation is greatly simplified. For example, in [6], it is assumed that the power electronics is 100% reliable. Furthermore, authors in [9] included power electronics outage probability as a part of the reliability analysis. The failure rate of power converters for the system is estimated based on the previous reports [10]. The authors pointed out that no available research in the field of power system reliability-oriented design is carried out with respect to power electronics reliability estimation.

Nonetheless, power electronics reliability engineering practices are based on more accurate and sophisticated methods, such as physics-of-failure approach [11]. This approach is based on evaluation of the damage induced by the stress and prediction of time when the dominant degradation mechanisms will be triggered. By using this methodology, the estimation of the converter failure can be determined for the intended operating conditions [12], [13]. Its utilization in the reliability-oriented converter design for wind and photovoltaic applications is discussed in [14], [15]. The economic analysis is performed for a single converter or a group of converters. In case of former, it is often related to the cost of optimal sizing and selection of components to achieve certain level of reliability, as discussed in [16]. For later, the reliability is determined for each converter of the system and connected to the economic analysis through e.g., replacement costs due to wear-out failures [17]. However, for the system consisting of several converters, the reliability analysis on the system level utilizing the procedure in [4] is not performed. Therefore,

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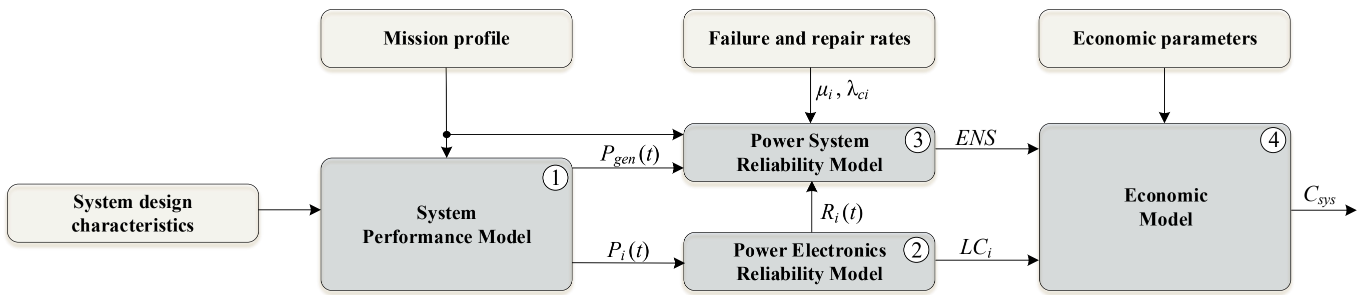

Fig. 1. Proposed model for cost for reliability studies including system performance, power electronics reliability, power system reliability, and economic models. The input are environmental conditions and load demand, the output is cost of the designed system C_{sys} including power electronics and power system reliability costs. $P_i(t)$, LC_i , $R_i(t)$, μ_i and λ_{ci} are loading, lifetime consumption, reliability, repair rate and constant failure rate of of i-th converter in the system respectively, and ENS is energy not served representing relevant power system reliability index.

the cost for reliability studies are independently conducted in power system and power electronics reliability domains. The impact of both on overall cost of the designed system have not been investigated before. In fact, the connection between the two domains (i.e., power system reliability and power electronics reliability) has only recently become of research interest [3], [18]. However, in those studies, economic assessment and its connection with the reliability concepts are not discussed. Therefore, this paper proposes a model integrating power electronics and power system reliability analysis and their mutual impacts on cost estimation. The connection between the standard power system reliability procedure, physics-of-failure based reliability modelling approach of power converters and economic profitability studies is defined. Therefore, the proposed model is suitable for planning of economical and reliable multi-converter system.

The rest of the paper is organized as follows. The proposed model for cost for reliability studies is described in Section II. In Section III, a case study for multi-converter system is described. The key results are presented in Section IV, together with the impact analysis of power electronics and power system reliability costs. Finally, the concluding remarks are provided in Section V.

II. Model for Cost for Reliability Studies

The proposed model for cost for reliability studies is shown in Fig 1. It consists of four main parts, notably system performance, power electronics reliability, power system reliability, and economic model. It can be used to investigate the cost of a multi-converter system designed with a certain level of reliability. The output of the model is cost of the system C_{sys} including both power system reliability and power electronics reliability aspects. In the following, the modelling approach for each part of the proposed model is described.

A. System Performance Model

By means of performance model, the generation profiles of system components $P_{gen}(t)$ as well as loading of power converters $P_i(t)$ are obtained. A detailed diagram of the system performance model is shown in Fig. 2. The model has two sets of inputs, i.e., system under design and external. The first set of inputs include relevant technical characteristics of the system and its components. For example, the size and architecture of the components, as well as energy management strategy of the system. The second set of inputs are mission profiles representing the environmental conditions and load demand for the planning horizon PH. The horizon can vary for different applications, but commonly includes 20-30 years [17], [19]. Both sets of input parameters are necessary to determine the energy flow of the system. This is done by defining the models of the components and energy management strategy of the system for the given inputs. For this purpose, various models with different complexities can be employed. The choice should be based on models ability to capture the dominant characteristics of the units as well as generation of the necessary output profiles. The obtained power profiles $P_{gen}(t)$ and $P_i(t)$ are then used in the power electronics and power system reliability models.

B. Power Electronics Reliability Model

The purpose of the power electronics reliability model is to estimate the lifetime consumption LC_i and reliability $R_i(t)$ of converters for given operating and environmental conditions. The model employs wear-out modelling based on physics-of-failure approach. This approach is based on evaluation of converter damage due to stress accumulation and prediction of time the dominant failure mechanisms are triggered. It provides more accurate estimation of converter reliability than empirical, handbook-based analysis [12].

The main steps in determination of the power electronics reliability model outputs are shown in Fig. 3, while a detailed step-by-step description is provided in [11]. The power electronics reliability evaluation is divided into deterministic and probabilistic approach. As a part of the deterministic modelling, the loading of the power converters $P_i(t)$ (determined in the previous step) needs to be translated to the associated stress. This is done by means of electro-thermal model [11]. To compare the stress with the strength of the components, a lifetime model is used [20], [21]. As output of the procedure, the lifetime consumption of the converter components for given loading LC_i is obtained. In case of irregular thermal stress profiles, an intermediate step needs to be taken. The

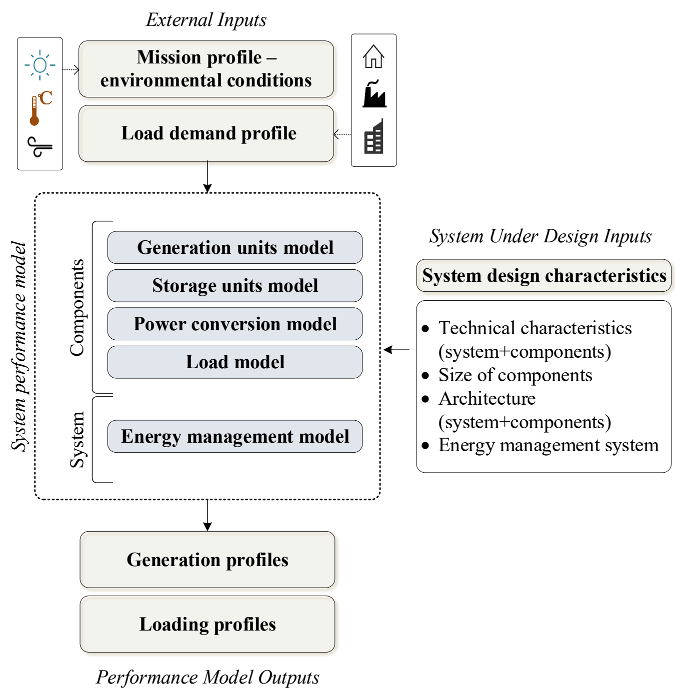

Fig. 2. System performance model diagram. Model inputs are mission profile representing environmental conditions and load demand profile, as well as system design characteristics. The model outputs are generation and loading profiles of multi-converter system components.

profile needs to be decomposed to set of regular reversals by means of thermal cycling counting model [22]. This deterministic process can be used for each converter of the system to determine its LC_i. This output parameter is directly used in the economic model to account for power electronics reliability cost. Furthermore, by applying a probabilistic approach, the reliability curves of each converter are obtained $R_i(t)$. Monte Carlo simulation is used to account for parameter variations and mission profile uncertainties [23]. The reliability curve of each converter is, further on, used within the power system reliability model.

C. Power System Reliability Model

The purpose of the power system reliability model is to translate the power and load profiles as well as the failure and repair characteristics into the Energy Not Served, ENS. The chance failure characteristics is needed for the power system reliability model, which can be extracted from the historical data [3], and it is denoted with λ_{ci} in Fig. 1. In this regard, the chance failures are the type of converter failures that originate from external over-stresses and events. Furthermore, the repair and maintenance are the inseparable parts that must be considered when modeling the reliability. Therefore, the impact of system repair can be incorporated into the model by introducing the repair rate, denoted with μ_i in Fig. 1. At the same time, the effect of wear-out failures must be taken into account by considering the power electronic reliability curves, $R_i(t)$, which is explained in the previous subsection. By combining the wear-out and chance failure characteristics in addition to the repair rate, the availability of the converters can be calculated. To do so, the method presented in [24] is used to investigate the simultaneous effect of above parameters and calculate the converter availabilities. It is worth mentioning that the availability indicates the probability of finding the converter in a healthy state. Accordingly, a Capacity Outage Probability Table (COPT) [4] can be formed based on the converter availabilities, their power profiles, $P_i(t)$, and the system load profile. In COPT, the probability of various system states are listed together with their corresponding generation capacity. Subsequently, the system-level indices such as ENS can be calculated in terms of time, representing the amount of energy that is expected to be lost due to system unavailabilities annually. To calculate the ENS from the COPT, the State Enumeration Technique can be utilized [25]. This is done as a part of the load-generation convolution process. Next, the ENS can be translated into the costs by considering the price of energy. An overview of the whole process and its connection to the rest of the model are shown in Fig. 3.

D. Economic Model

The economic model is used to assess the cost of the designed system. It is a pivotal part of the proposed model, where power electronics and power system reliability connection to the cost evaluation is defined. The model has three inputs, as shown in Fig. 1. The first one is the external input representing the values of the economic parameters. Those are necessary to adequately estimate the cost of the system components. The chosen economic parameters need to reflect actual market conditions as well as be thrust-worthy source for prediction of market movement for the planning horizon PH. The second and third inputs are related to the power electronics reliability and power system reliability, respectively.

The economic model consists of three main cost components. The first part accounts for capital cost C_{cap} and operation and maintenance (o&m) cost $C_{o\&m}(t)$. They are defined as:

$$C_{cap} = \sum_{i=1}^{N} C_{cap_i}^{gen} + C_{cap_i}^{storage} + C_{cap_i}^{PE} \tag{1}$$

$$C_{o\&m}(t) = \sum_{i=1}^{N} C_{o\&m_i}(t), \text{ for } 1 < t < PH \tag{2}$$

where $C_{cap_i}^{gen}$, $C_{cap_i}^{storage}$ and $C_{cap_i}^{PE}$ are the capital cost of the $i-th$ generation unit, storage unit and converter, respectively. $C_{o\&m_i}(t)$ is the o&m cost of the $i-th$ unit in the system at time t. N is number of units in the system and PH is the planning horizon.

The capital cost includes the cost of the components, ancillary equipment and their installation. o&m cost is the fixed o&m cost of each unit charged on yearly basis for keeping the system at adequate level of operational performance [26]. This includes system inspection and monitoring, operations administrations, etc. [27]. The cost of reliability is added to the

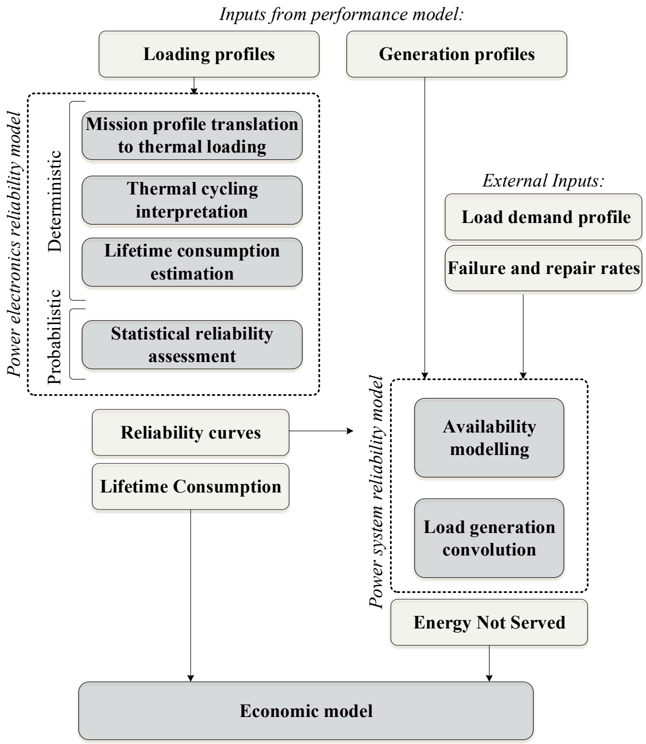

Fig. 3. Diagram of the power electronics reliability and power system reliability models.

capital and o&m cost. A relevant power electronics reliability parameter LC_i, and a relevant power system reliability parameter ENS are translated to the cost domain. LC_i provides information on the expected failure time of converter due to wear-out. When the converter fails, its replacement takes place. This inherently imposes additional cost to the system, i.e., replacement cost. Therefore, the time at which this cost occurs is directly related to the associated level of reliability defined by the converter design. The power electronics reliability cost is then defined as:

$$C_{PE_i}^{rep}(t) = \begin{cases} C_{PE_i}^{rep},\ LC_i(t) = 1 \\ 0, \text{ otherwise} \end{cases} \tag{3}$$

$$C_{rel}^{PE}(t) = \sum_{i=1}^{N} C_{PE_i}^{rep}(t), \text{ for } 1 < t < PH \tag{4}$$

where $C_{PE_i}^{rep}$ is the cost of replacement of $i-th$ converter in the system.

Since the ENS represents the amount of energy that is expected to be lost annually, it is the amount of energy that would not be delivered by the multi-converter system to its local loads. In fact, the amount of lost energy needs to be delivered from the grid. This imposes additional cost of delivering energy to the system. Hence, the level of reliability of the designed system is the main driving factor for this cost. The power system reliability can be translated into cost considering the price of energy and it is defined as:

$$C_{rel}^{PS}(t) = ENS \cdot C_{energy}(t), \text{ for } 1 < t < PH \tag{5}$$

where C_{energy} is the price per unit of energy delivered from the grid at instant t.

Finally, the overall cost of the system can be defined as:

$$C_{sys}(t) = C_{cap} + C_{o\&m}(t) + C_{rel}^{PE}(t) + C_{rel}^{PS}(t) \tag{6}$$

III. Case Study

The main aim of the case study is to showcase the usage of the model for cost for reliability studies. Furthermore, to investigate the impact each of the reliability costs, i.e., C_{rel}^{PE} and C_{rel}^{PS} have on the total cost of the system C_{sys}.

A. Multi-Converter System Design Characteristics

A photovoltaic (PV)-battery system shown in Fig. 4 is the multi-converter system used in this study. The PV-battery system main design characteristics are given in Table I. The generation and storage units are PV panels and lithium-ion battery, respectively. They are modelled by PV and battery performance models, as described in details in [28]. The load is a household load represented by a load demand profile. There are overall three power converters. Generation unit is connected to a uni-directional DC/DC boost converter. Storage unit is connected to a bi-directional DC/DC converter. It operates as boost converter during discharging periods and as buck converter during charging. A DC/AC inverter is used to synchronize to the AC grid and transfer power from the system to the grid and load (AC side). A full-bridge single-phase inverter with four active switches is employed for that purpose. The reliability-critical components considered in the study are power semiconductor devices. A relevant lifetime model used within the power electronics reliability design is outlined in [15]. Furthermore, a self consumption energy management strategy defines a power flow in the system. It implies that the power produced by the generation unit is prioritized to supply the load and charge the battery. If any excess power is left, it is delivered to the grid. Similarly, if there is not enough power to supply the load internally (generation and storage), the power is delivered from the grid [29].

B. Mission Profile

An installation site in Denmark is considered. A relevant mission profiles representing the environmental conditions are solar irradiance S and ambient temperature T_a. The planning horizon PH is 25 years, which is characteristic for PV applications [30]. In this analysis, the impact of load demand P_{load} growth and mission profile characteristics change over PH are not accounted. This implies that the historical data of one year shown in Fig. 5 are used repetitively to create the mission profile for a given PH. To account for impact of changes in environmental and operating conditions on the power electronics loading and reliability, the resolution of data is 5 minutes.

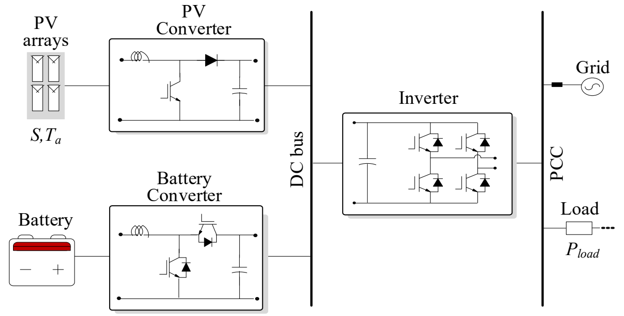

Fig. 4. Configuration of photovoltaic system with energy storage used in a case study. It consist of two DC/DC converters and one DC/AC converter which represent a multi-converter system.

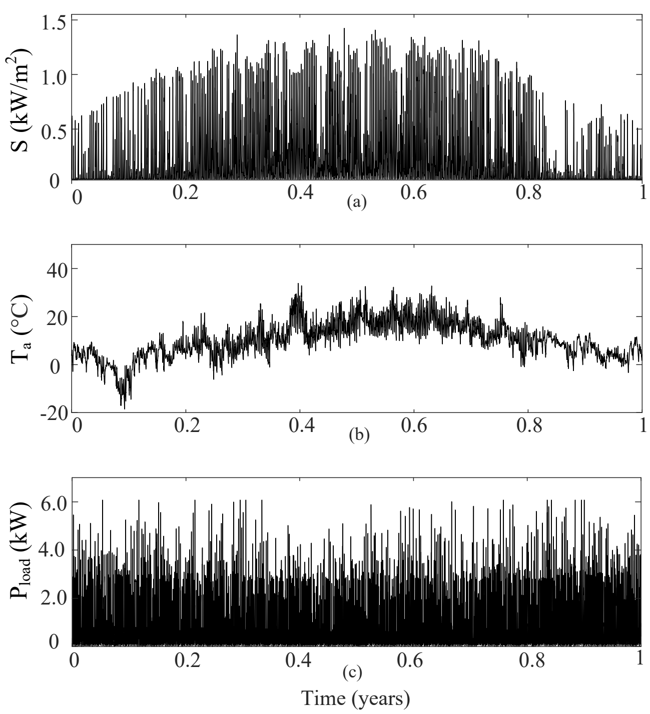

Fig. 5. A one-year mission profile with 5 minutes resolution corresponding to the installation site in Denmark: (a) Solar irradiance S, (b) Ambient temperature T_a, and (c) Load demand P_{load}.

C. Economic Parameters

Relevant economic parameters are provided in Table II. The capital cost of the power conversion system $C_{cap_i}^{PE}$ is included in the capital cost of the PV $C_{cap_i}^{gen}$ and battery system $C_{cap_i}^{storage}$. Power converter replacement cost is considered constant for the entire planning horizon PH. Annual rate of change of electricity price $Cgrid$ is set to +4% from its reference price stated in Table II.

D. Scenarios

To investigate the impact of power electronics and power system reliability on the system cost C_{sys}, three cases are studied. In Case I, the cost only consists of capital cost and o&m cost, while in Case II the cost of power electronics reliability is added. Finally, in the Case III, both power electronics and power system reliability costs are evaluated and the system cost is defined as outlined in (6). An overview of the three cases is provided in Table III.

TABLE I
CASE STUDY INPUT: MULTI-CONVERTER SYSTEM TECHNICAL DESIGN CHARACTERISTICS.

Parameter	Value
PV array rated power	6 kW
Battery rated power and energy capacity	3 kW/3.5 kWh
PV converter rated power	6 kW (3 kW x 2 units)
Battery converter rated power	3 kW
Inverter rated power	6 kW
Energy management of the system	Self-consumption
Reliability-critical components	Power semiconductors
Planning horizon	25 years

TABLE II
CASE STUDY INPUT: ECONOMIC PARAMETERS.

Parameter	Value	Description
C_{cap}^{gen}	1550 USD/kW	PV capital cost
$C_{cap}^{storage}$	400 USD/kWh	Battery capital cost
$C_{o\&m}(t)$	14 USD/kW yearly	PV o&m cost
$C_{o\&m}(t)$	7 USD/kWh yearly	Battery o&m cost
$C_{PE_i}^{rep}$	250 USD/kW	Power electronics replacement cost
C_{grid}	0.32 USD/kWh	Grid electricity reference cost

IV. RELIABILITY IMPACT ON COST OF MULTI-CONVERTER SYSTEM

A. Impact of Power Electronics Reliability

Case study results related to the power electronics reliability are shown in Fig. 6. The lifetime consumption plot indicates that the two out of three converters in the system needed to be replaced within the planning horizon PH. Inverter is the most reliability-critical component of the system, as it fails first. Its replacement takes place after 14 years, followed by the battery converter replacement after 24 years. The two replacements of the converters due to their ageing-related failures directly impact the cost of the system. These costs after 14 and 24 years are seen as the steep increases in the system cost, as shown in Fig. 6 (b). As a result, the system cost C_{sys} including the power electronics reliability cost (Case II) is significantly higher than in the Case I after 25 years.

Two system design characteristics have impact on the obtained results. Those are the energy management strategy of the system and the size of the components. The energy management strategy defines the power flow in the system. In this case, the self-consumption energy management strategy, prioritizing the internal load supply is employed. This includes power transfer from generation and storage to the load through

TABLE III
CASES STUDY SCENARIOS FOR INVESTIGATION OF POWER ELECTRONICS AND POWER SYSTEM RELIABILITY IMPACTS ON SYSTEM COST.

Case no.	Power electronics reliability	Power system reliability	System cost definition
Case I	✗	✗	$C_{sys}(t) = C_{cap} + C_{o\&m}(t)$
Case II	✓	✗	$C_{sys}(t) = C_{cap} + C_{o\&m}(t) + C_{rel}^{PE}(t)$
Case III	✓	✓	$C_{sys}(t) = C_{cap} + C_{o\&m}(t) + C_{rel}^{PE}(t) + C_{rel}^{PS}(t)$

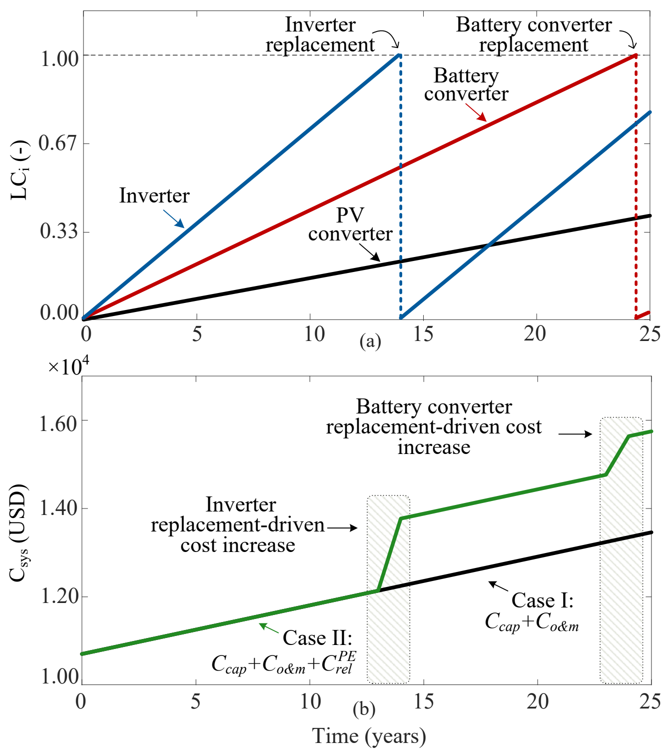

Fig. 6. Power electronics reliability-related case study results: (a) Lifetime consumption of the converter components LC_i, and (b) System cost C_{sys} for Case I and Case II.

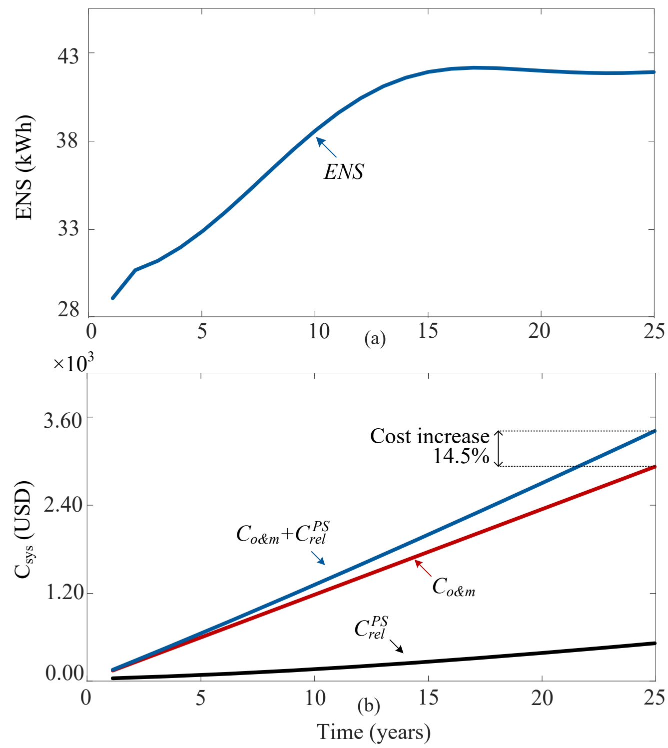

Fig. 7. Power system reliability-related case study results: (a) Energy not served ENS of the PV-battery system, and (b) Cost of power system reliability C_{rel}^{PS} and o&m cost $C_{o\&m}$.

the inverter. Therefore, resulting in higher stress of the inverter unit which needs to be replaced first. Similarly, the PV array rated power and battery energy and power capacity impact the loading of the battery converter. For example, over sizing the battery unit could have beneficial impact on the converter loading. However, even though such design decision could lead to improved converter lifetime, they might impose additional capital costs. For that reason, supplementary analysis needs to be carried out to study the impact of the two parameters. Nonetheless, the power electronics reliability cost needs to be included in the analysis, as it can significantly influence the accuracy of the final system cost estimation.

B. Impact of Power System Reliability

As Fig. 7 results show, the power system reliability costs C_{rel}^{PS} starts with a constant value and it increases over time. The constant part occurs due to the chance failures and the resulting unavilablities. Moreover, the ENS, and consequently the power system reliability costs, increase over time as a result of the wear-out failures and aging of power converters. It is worth mentioning that the price per unit of energy also increases with time, which further intensifies the growth of power system reliability costs.

Moreover, the power system reliability costs can form a considerable part of the running costs of the project at the same time with o&m expenses, especially when the converters age. In this regard, as can be seen in Fig. 8, the power system reliability costs can account for increase of the project's running costs at the end of the project's lifetime. Therefore, neglecting it will introduce errors to the profitability studies and will result in non-optimal decision making. Contrary to the power electronics reliability cost, the power system reliability cost has consistent, but lower impact on the overall cost throughout the project lifetime.

Similarly to power electronics reliability cost, system design and external inputs influence the results. For different

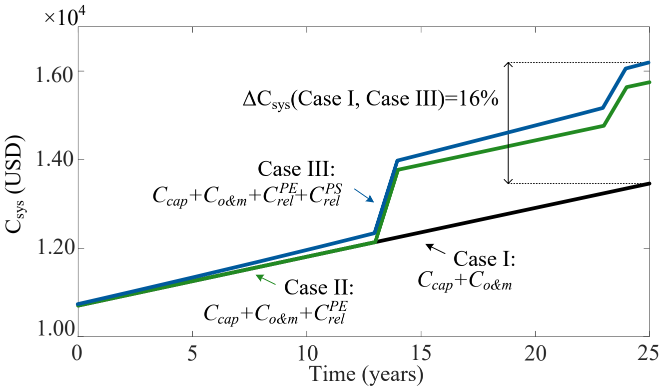

Fig. 8. Case study results: System cost C_{sys} of 25 years for three cases investigated.

converter-level design and mission profiles, the power system reliability costs can be even larger than the ones obtained in this case study. For example, in a location with an intense solar irradiance profile (e.g., Spain, Arizona), the wear-out failures dominate, and the converter ages faster. As a result, a higher ENS will be expected, thereby increasing the cost of power system reliability. Therefore, including this cost in the overall system assessment is necessary.

C. General Guidelines

The case study results summarized in Fig. 8 indicate that both power electronics and power system reliability cost impact the overall cost of the system. The difference in accumulated cost at the end of the planning horizon equals 16%. This refers to that the profitability of the systems designed without considering the two reliability aspects would be diminished in real-time operation. The proposed model can therefore be utilized during the design and planning stage of the multi-converter system to obtain more accurate reliability and cost results. Furthermore, the model can be used to extend the impact analysis on a variety of mission profiles, converter designs, energy management strategies, etc. In such way, a more complete understanding of reliability cost can be obtained. Finally, the proposed model can be used to assess the power electronics reliability and power system reliability for the predefined cost target of the multi-converter system under planning.

V. Conclusion

In this paper, the model for conducting cost analysis for reliability studies in a multi-converter system is presented. The connections between the cost assessment and the power system and power electronics reliability domains are introduced. Therefore, the proposed model can be used to evaluate the impact of power electronics and power system reliability on the system cost. The case study results indicate that neglecting the cost of power electronics and power system reliability can lead to underestimation of the total system cost. Therefore, to yield optimal design solution, the proposed model can be utilized in the cost for reliability studies during the planning stage of multi-converter based systems.

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