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Fast and Accurate Modeling of Power Converter Availability for Adequacy Assessment

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Abstract—This letter proposes a method to model the power converter availability for power system adequacy assessment. The proposed method considers wear-out as well as chance failures and calculates an equivalent failure rate accordingly. In this regard, it is shown that neglecting the wear-out failures and the dynamic behavior of adequacy indices can lead to considerable errors. Moreover, the performance of the proposed availability modeling method is compared to that of the existing solutions through calculating the Expected Energy Not Supplied (EENS) in a case study. The comparison confirms the superior performance of the proposed method in terms of high accuracy and low computational burden.

Index Terms—Adequacy, Reliability, Availability, Power Electronics, Converters, Power Systems.

I. INTRODUCTION

WITH the continuous integration of renewable energies and technologies such as High Voltage DC (HVDC) transmission, modern power grids have incorporated many Power Electronic (PE) converters in their structure. Similar to other components of the grid, converters are prone to failure and must be considered in the system adequacy studies.

Typically, adequacy indices are reported as constant values. More specifically, constant failure rates are assumed for the grid components, and only the steady-state values of adequacy indices are used [1]. However, the actual failure rate of a power converter is not constant and varies over time [2], and thus, the adequacy indices will change accordingly. Consequently, approximating the converter failure rates with a constant value may introduce considerable errors to the estimation of adequacy indices. Hence, the time-dependent behavior of adequacy indices, rather than simply steady-state values, will be of more interest in converter-based power systems.

As shown in Fig. 1, availability modeling is an integral part of the adequacy assessment procedure. With respect to that, the main contribution of this letter is on the availability modeling part, and not the input data or load-generation convolution. Conventionally, various methods have been used for availability modeling in the literature. These methods have certain shortcomings, making them impractical or impossible to

calculate time-dependent probabilities considering non-constant failure rates. Notably, the Continuous Markov Process (CMP) is a popular method to calculate time-dependent probabilities, where the state space representation of the system is formed and solved using Chapman–Kolmogorov equations [3]. Nevertheless, these equations only hold when the time-to-failure of components are exponentially distributed, i.e., only for constant failure rates [4]. To model the reliability of a system with non-constant failure rates, several methods have been proposed, namely, the PieceWise Approach (PWA) [5], Method of Device of Stages (MDS) [3], Semi-Markov Approach (SMA) [6], and Monte Carlo Simulation (MCS) [7]. The PWA and MDS are based on certain approximations, which makes them computationally efficient, but can also result in significant errors. In contrast, the SMA and MCS give good accuracy, while they have a high computational burden [7], [8].

Thus, this letter proposes a new method to model the time-dependent availability of converters considering the non-exponentially distributed time-to-failures of power converters. Based on the proposed method, state probabilities and adequacy indices of a converter-based power system can be obtained. Compared to existing solutions, the proposed method has good accuracy with a substantially lower computational burden.

II. PROPOSED AVAILABILITY MODELING

Consider a power converter that stays in continuous operation as long as it is healthy. In case of failures, the

Fig. 1. Simplified schematics of the adequacy assessment procedure, besides the existing solutions to undertake each part (SSA: Stress-Strength Analysis, MSM: Multi-State Matrix, MCS: Monte Carlo Simulation, SMA: Semi-Markov Approach, MDS: Method of Device of Stages, PWA: Piece-Wise Approach, CMP: Continuous Markov Process, SET: State Enumeration Technique, BN: Bayesian Network, UGF: Universal Generating Function).

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converter is repaired as soon as possible and restored to the new condition by replacing the entire reliability-critical devices with new ones [8]. As a result, during the repair time, the converter is in the faulty state, and after the repair, the converter is regarded as good as new. Typically, the time-to-repair is modeled with an exponential distribution with a constant repair rate of μ_0 [9]. Concerning the converter failures, there are two main categories: chance failures and wear-out failures. Chance failures, originating from external root causes (e.g., semiconductor short-circuiting events due to overvoltage caused by lightning), can be modeled with a constant failure rate [9]. In contrast, wear-out failures are caused due to the aging of devices and accumulated damage over time and have an increasing failure rate (non-exponentially distributed time-to-failure) over time [10]. Thus, the overall failure rate of the power converter can be decomposed into

$$\lambda(t) = \lambda_0 + \lambda_w(t) \quad (1)$$

where λ_0 is the rate of chance failures derived from field data of failures, and $\lambda_w(t)$ is the wear-out failure rate over time, t , predicted from the established Stress-Strength Analysis (SSA) technique [11]. It is worth mentioning that, as shown in Fig. 1, the Multi-State Matrix (MSM) method can also be used to predict the wear-out failure rate [12]. Accordingly, the Probability Density Function (PDF) of the time-to-failure for the converter can be written as

$$f(t) = \lambda(t) \exp\left(-\int_0^t \lambda(\tau) d\tau\right). \quad (2)$$

If $N(t)$ is a random variable representing the cumulative number of failures up to time t , $\Lambda(t)$ can be defined as

$$\Lambda(t) \triangleq 1 + E[N(t)] \quad (3)$$

where $E[\cdot]$ denotes the expected value of the random variable. In this case, given that $E[f(t)] \gg \mu_0^{-1}$ (i.e., the time-to-repair is negligible compared to the time-to-failure), according to the renewal theory [13], $\Lambda(t)$ can be written as

$$\Lambda(t) = 1 + \int_0^t \Lambda(\tau) f(t - \tau) d\tau. \quad (4)$$

It is worth mentioning that the above assumption is justified for power converters in grid applications, since their time-to-failure is far greater than the time-to-repair. For example, for an offshore wind turbine converter, the mean time-to-failure is 48667 hours, whereas the mean time-to-repair is 57 hours [14].

From (1), since

$$\frac{\Lambda(t+dt) - \Lambda(t)}{dt} = E\left[\frac{N(t+dt) - N(t)}{dt}\right], \quad (5)$$

the right side of the equation will denote the average number of failures occurring in the interval $[t, t+dt)$. Thus, when $dt \rightarrow 0$, the left side of (5), i.e., the derivative of $\Lambda(t)$, will represent the average number of failures per unit of time, at t . Subsequently, an equivalent failure rate can be defined as

$$\lambda_{eq}(t) \triangleq \frac{d\Lambda(t)}{dt}. \quad (6)$$

$A(t)$, the time-dependent availability, is the probability of finding the converter in the healthy state at t , and it can be calculated as [3]

$$\frac{dA(t)}{dt} = \mu_0 - (\mu_0 + \lambda_{eq}(t))A(t). \quad (7)$$

There are several ways to solve (4) and (7) – namely, Volterra integral equations and Laplace transform. However, they may not provide a straightforward closed-form solution for all PDFs of time-to-failure, e.g., for (2). Hence, the numerical representation of the above equations is presented here.

If the study time frame spans T_s years ($0 \leq t < T_s$), it can be discretized into N_t subintervals with the time step of $\Delta t = T_s / N_t$ such that $t(i) = i\Delta t$, where $i \in \mathbb{Z}^+$ and $1 \leq i < N_t$. Given that the converter starts in the healthy state, its availability can be modeled according to Fig. 2, where all the parameters have been defined in (1)-(7).

From Fig. 1, once the availability modeling is done, the generation capacity and the load must be convolved in order to obtain system-level adequacy indices. To do so, several techniques can be used, namely, the State Enumeration Technique (SET) [9], Universal Generating Function (UGF) [6], and Bayesian Network (BN) [15]. In this letter, the SET has been used. In a converter-based grid with N_c converters, the system can be in 2^{N_c} states, depending on whether the converters are healthy or faulty. The probability of residing in each state must be known to calculate system adequacy indices. For each converter, the time-dependent availability can be calculated from (7) or Fig. 2. Moreover, given that outages are independent, and in the state S , N_H converters are healthy and N_F converters are faulty (i.e., $N_H + N_F = N_c$), the time-dependent probability of the state S can be calculated from SET as [9]

$$P_s(t) = \prod_{m=1}^{N_H} A_m(t) \cdot \prod_{n=1}^{N_F} (1 - A_n(t)) \quad (8)$$

Fig. 2. Flowchart of the proposed converter availability modeling, where parameters have been defined in (1)-(7).

where A_m and A_n are the time-dependent availability of healthy and faulty converters, respectively.

III. APPLICATION OF THE PROPOSED METHOD AND RESULTS

To validate the proposed method, the Expected Energy Not Supplied (EENS) [9] of a case study is calculated and compared with the results from existing solutions – i.e., the PWA, MDS, CMP, SMA, and MCS – in terms of accuracy and computational burden. Not only will the steady-state EENS be calculated, but also the time-dependent dynamics will be studied. A modified Roy Billinton Test System (RBTS) [16], [17] is used as the case study. The RBTS is selected to compare the performance of different methods without the loss of generality, because it is a well-known test system for reliability studies, which has been used in more than 275 journal papers for this purpose [18]. As shown in Fig. 3, the modified RBTS includes a wind farm and three HVDC connections, whose capacities are given in Table I. Also, the capacity factor of the wind farm is 0.49. In [17], using the SSA [11], the wear-out failure rate is predicted for HVDC and the wind turbine converters, given a certain mission profile. Wear-out failures are fitted to a Weibull distribution, whose shape and scale factors are provided in Table I. It should be noted that the validity of the SSA has been verified by performing accelerated lifetime tests in many works, e.g., [10]. In addition, the repair time and the rate of chance failures for HVDC and the wind turbine converters are considered based on data in [19], [14], as presented in Table I. Since this letter focuses on the availability modeling part of the adequacy assessment, the same input data are used for all the methods to have a fair comparison. It should

be emphasized that this section aims to compare the performance of different availability methods, and the input data is not a contribution of this letter.

The EENS is calculated as a function of time by using six different methods, and the results are shown in Fig. 4. Additionally, the computation time for different methods is presented in Table II, where corresponding computer programs have been run in MATLAB on a personal computer with Intel (R) Core (TM) i5-8250U CPU @ 3.3 GHz and 2 GB memory. In order to measure the accuracy of methods, both the steady-state error and Root Mean Square Error (RMSE) are calculated. The actual steady-state EENS is 39.467 MWh/year, which is calculated according to [20]. Also, the SMA is used as the benchmark for RMSE calculation because it makes no approximations or assumptions when forming its equations. Computation time, steady-state error, and RMSE are presented in Table II for different methods.

The conventional approach (i.e., considering only constant failure rates and neglecting the wear-out failures) is investigated by using the CMP. Notably, it introduced nearly 28% error to the steady-state EENS estimation, as presented in Table II. Therefore, using simply constant failure rates for converters and neglecting wear-out failures leads to underestimating the EENS. Furthermore, as shown in Fig. 4, by using the conventional approach, a constant adequacy index over time will be obtained. In other words, the dynamic behavior of the adequacy indices is ignored, which can lead to an inadequate system over time.

Additionally, while the PWA has a low computation time, its accuracy is acceptable only for short-term studies, e.g., $t < 4$ years in Fig. 4. Therefore, it should not be used for larger time frames, since the error will be substantial, as it can be seen in Table II.

From Table II, the MDS is computationally fast since it approximates the time-to-failure with a series of exponential distributions. For simple distributions such as Weibull, the

Fig. 3. Schematic of the case study [16], [17].

Fig. 4. Variation of the Expected Energy Not Supplied (EENS) index in the case study over time, calculated using six methods.

TABLE I
Reliability Data of Units Considering Converter Failures [14], [19], [17]

Unit converters	Capacity [MW]	Wear-out failures (Weibull distribution)		Rate of chance failures [occ./yr]	Repair time [hr]
		Shape factor	Scale factor [yr]		
HVDC 1	50	3	8	0.04	163
HVDC 2	60	3	10	0.08	151
HVDC 3	50	2.6	7	0.08	123
Wind farm	160	3	12	0.18	57

TABLE II
Comparison of Methods in Terms of Computation Time and Accuracy

Method	Computation time [s]	Steady-state error [%]	RMSE [MWh/yr]
SMA	5220	0.37	0
MCS	273	0.74	0.6697
MDS	0.3	19.12	8.6806
CMP	0.9	27.75	22.1234
PWA	0.2	> 100	> 150
Proposed	3.6	0.07	0.1913

accuracy of the approximation is random but acceptable. By contrast, for the PDFs such as (2), accuracy can decrease drastically – which is the case in Fig. 4.

Furthermore, as shown in Table II, the MCS, SMA, and the proposed have the highest accuracy, with a steady-state error of less than 1% and RMSE less than 1 MWh/year. From Fig. 4, it can also be seen that the results from these methods match well. Therefore, if accuracy is the highest priority in the study, these methods should be used. Notably, among these methods, the computational burden of the proposed method is significantly lower, such that the computation time for the SMA, MCS, and the proposed are 5220, 273, and 3.6 seconds, respectively.

IV. CONCLUSIONS

This letter has presented a methodology to model the availability of power converters in power system adequacy studies. The proposed method considers wear-out and chance failures to calculate time-dependent converter availability and system adequacy indices. It has been shown that ignoring the wear-out failures and time-dependent behavior of the converter availability introduces considerable errors to the adequacy prediction. Furthermore, the accuracy and computational burdens of the proposed availability modeling method have been compared with five other methods, where the EENS was calculated in a case study. It has been confirmed that the proposed methodology has high accuracy comparable to the Monte Carlo simulation and Semi-Markov approach, while its computational burden is significantly lower, and it can be used for large-scale converter-based grids.

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