Availability Modeling in Power Converters Considering Components Aging

Peyghami, Saeed; Blaabjerg, Frede

Published in:
I E E E Transactions on Energy Conversion

DOI (link to publication from Publisher):
10.1109/TEC.2020.3018631

Publication date:
2020

Document Version
Accepted author manuscript, peer reviewed version

Link to publication from Aalborg University

Citation for published version (APA):
Peyghami, S., & Blaabjerg, F. (2020). Availability Modeling in Power Converters Considering Components Aging. *I E E E Transactions on Energy Conversion*, *35*(4), 1981-1984. Article 9173721.
https://doi.org/10.1109/TEC.2020.3018631

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TEC.2020.3018631, IEEE Transactions on Energy Conversion

Availability Modeling in Power Converters Considering Components Aging

Saeed Peyghami, *Member, IEEE*, and Frede Blaabjerg, *Fellow, IEEE*

***Abstract*—Power electronic converters are increasingly used in power systems. However, they are vulnerable components and prone to aging failures, thus affecting overall system reliability. Therefore, their availability modeling especially in large-scale power electronic-based power systems is of paramount importance. This letter introduces four different approaches for converter availability modeling considering aging failures under different maintenance strategies. The accuracy and calculation burden of these approaches are illustrated by numerical analysis. It is shown that the method of device of stages and piece-wise approach are the most applicable methods in the case of corrective and preventive maintenance strategies respectively.**

***Index Terms*—Availability, Exponential failure rate, Power Converter, Wear-out failure, Aging failure.**

I. INTRODUCTION

POWER electronic converters are a frequent failure source in many applications [1], [2]. Converter fragile components such as electrolytic Capacitors (Cap) and Power Modules (PM) are prone to aging failures [2]–[6]. On the other hand, they are increasingly used in power systems [7]. Thus, their reliability modeling considering the aging failures is of utmost importance for power system reliability evaluation.

Equipment aging has been considered in power system reliability analysis especially for maintenance activities e.g., in transformers and distribution lines [8], [9]. Aging availability has been modeled based on posteriori probability in [8] and Piece-Wise Approach (PWA) in [9]. Furthermore, Method of Device of Stages (MDS) has been presented for steady-state availability modeling in systems with non-exponential downtimes [10], [11]. Semi-Markov Process (SMP) has also been presented for availability modeling in non-exponentially distributed systems [12].

In posteriori probability-based approach [8], it is assumed that the aging process is slowed by applying maintenance activities, but the failure rate is gradually increased [13]. However, in power electronics, Cap and PM are not repairable and they should be replaced with a new one once any kind of failure, i.e., chance or aging failures, occurs. Thus, the aging will be fully stopped in the failed components. As a result, applying this approach for converter availability estimation may cause erroneous results. Moreover, it requires calculating the integral of probability function for a small-time intervals [8], hence, introducing higher calculation burden.

On the other hand, the PWA, MDS and SMP seem to be applicable for converter availability prediction. They may introduce different calculation burden and estimation error because of the corresponding modeling process. Notably, the applied maintenance strategy can affect the accuracy of the prediction. This letter explores the applicability and performance of these techniques for modeling the availability of power converters considering their aging failures under different maintenance strategies. Furthermore, a new method based on Markov Chain Technique (MCT) is proposed for verifying the accuracy of different approaches. In the following, these approaches are presented in Section II. The viability of these methods is illustrated by numerical analysis under different failure characteristics and maintenance strategies in Section III. Finally, Section IV summarizes the outcomes.

II. AVAILABILITY MODELING METHODS

The converter reliability is measured by its unavailability which is complementary of its availability. It is modeled by reliability of converter's fragile components. The components are prone to chance and wear-out failures [14]. Considering that these two failure modes are independent, the component availability, A can be modeled by using (1).

$$A = A_c \cdot A_w \tag{1}$$

where A_c and A_w are the availability due to the chance failures and wear-out failures, respectively. For the chance failures with constant failure rate, λ and repair rate, μ, the availability is directly predicted by the Markov Process (MP) [11] as:

$$A_c = \frac{\mu}{\mu + \lambda} \tag{2}$$

However, the wear-out availability with a non-constant failure rate cannot be predicted by MP. Thus, some possible solutions are introduced in the following.

A. Piece-Wise Approach (PWA)

In this approach, the failure rate function is discretized into constant failure rates through short time slots as shown in Fig. 1 [11]. Therefore, the item availability is approximately found by using (2) for the time k with the failure rate of $\lambda = \lambda_k$. This approach is suitable for repairable systems, where the aging is not removed after maintenance. However, for power converters, the components will be replaced by a new one after a failure. Therefore, employing this approach may introduce high error in availability approximation for power converters de-

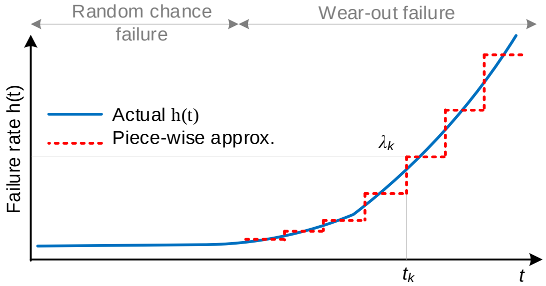

Fig. 1. Piece-wise approximation of a failure rate function.

This work was supported by the Villum Fonden under the Reliable Power Electronic-Based Power System (REPEPS) project. The authors are with the Department of Energy Technology, Aalborg University, 9220 Aalborg, Denmark (e-mail: sap@et.aau.dk; fbl@et.aau.dk).

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TEC.2020.3018631, IEEE Transactions on Energy Conversion

pending on the maintenance strategy.

B. Semi-Markov Process (SMP)

SMP is another approach to estimate the availability of non-exponentially distributed systems [12]. Consider a system with two states of operating state “1” and downstate “0” as shown in Fig. 2(a) with non-constant failure rate, *h(t)* and constant repair rate, μ. The system remains in state $i = \{0, 1\}$ with random time of T_{ij}, $j = \{0, 1\}$, $j \neq i$, which has the Cumulative Probability Function (CDF) of $F_{ij}(t)$ as shown in Fig. 2(b). According to [12], the probability of being in state j if the process starts at state i, ψ_{ij} can be obtained by using (3):

$$\psi_{ij}(t) = \delta_{ij}\left(1 - F_{ij}(t)\right) + \sum_{\substack{k=0 \\ k\neq i}}^{1} \int_{0}^{t} \frac{d}{d\tau} F_{ik}(\tau) \cdot \psi_{kj}(\tau - t)\, d\tau \qquad (3)$$

where $\delta_{ij} = 1$ for $i = j$ and $\delta_{ij} = 0$ for $i \neq j$. The availability, $A(t)$ considering that the system was in operating state “1” at the beginning, is obtained by using (4).

$$A(t) = \psi_{11}(t) \qquad (4)$$

C. Method of Device of Stages (MDS)

The MDS has been introduced for availability prediction of systems under a non-exponential repair strategy [11]. In this approach, the non-exponential repair time distribution function is approximated by combination of exponentially distributed devices. Here, this approach is employed for availability prediction considering the non-exponential failure rates. As a result, the system shown in Fig. 2(a) can be represented by the one shown in Fig. 2(c). The state “1” is replaced by m devices in series modeling the wear-out failure by a gradual failure rate [11]. If the wear-out failure density function is modeled by a Weibull distribution with scale and shape factors of α and β [11], the number of series devices, m and the transition rate, ρ can be found by using (5).

$$m = \left[{M_1^2}\big/{M_2 - M_1^2} \right] \; and \quad \rho = {M_1}\big/{M_2 - M_1^2} \qquad (5)$$

$$M_1 = \alpha \cdot \Gamma\left(1 + 1/\beta\right),\; M_2 = \alpha^2 \cdot \Gamma\left(1 + 2/\beta\right)$$

where M_1 and M_2 are the first and second moments of Weibull distribution function. $[\cdot]$ denotes as the nearest integer function, and $\Gamma(\cdot)$ is the Gamma function. Therefore, by replacing the system with exponentially distributed devices, the availability can be obtained by using MP described in [11].

D. Markov Chain Technique (MCT)

This approach is proposed in this letter to verify the accuracy of other methods. In this approach, the different failure possibilities are considered at different times as shown in Fig. 3. The system starts to operate at $t = 0$ in state “1_0”. For the next small time of T, it will be failed with the probability of Q_0 and will be survived with the probability of 1-Q_0. If it fails it will be replaced with the probability of G and restored to the state “1_0” or it will remain at stat “0” with the portability of 1-G. However, if it survives, it will enter to the state “1_1”. This process will continue by the end of the target mission time. The probability of the replacement is defined by exponential distribution function by using (6). Moreover, the failure probability at each time of k, can be obtained by the posteriori function [11] given in (7), where $h(\cdot)$ is the failure function and $F(\cdot)$ is the failure CDF.

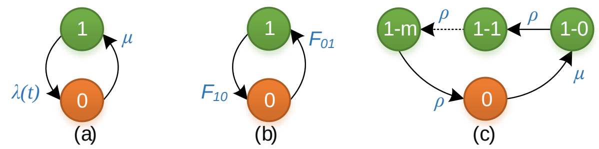

Fig. 2. State space representation of an item, (a) general model, (b) semi-Markov model, (c) method of device of stages.

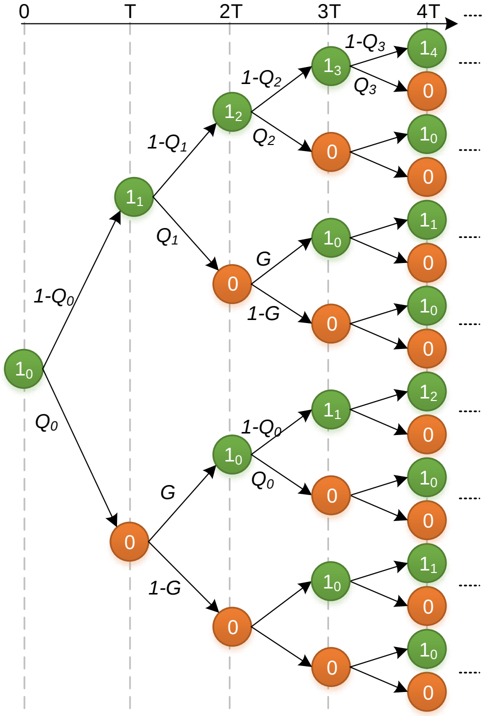

Fig. 3. Tree diagram of a system considering non-exponential failure rate.

$$G = 1 - exp\left(-\mu T\right) \qquad (6)$$

$$Q_k = \frac{F\left(kT + T\right) - F\left(kT\right)}{1 - F\left(kT\right)} \approx h\left(kT\right)T \qquad (7)$$

The transitional probability matrix of this process can be written as (8). This process is similar to a Markov Chain with *n+1* states, thus, the probability of each state at any time of $x.T$ can be obtained by B^x [11].

$$B = \begin{array}{c} \\ 0 \\ 1_1 \\ 1_2 \\ 1_3 \\ \vdots \\ 1_n \end{array} \begin{array}{c} \begin{array}{cccccc} 0 & 1_0 & 1_1 & 1_2 & \cdots & 1_n \end{array} \\ \begin{bmatrix} 1-G & G & 0 & 0 & \cdots & 0 \\ Q_0 & 0 & 1-Q_0 & 0 & \cdots & 0 \\ Q_1 & 0 & 0 & 1-Q_1 & \cdots & 0 \\ Q_2 & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ Q_n & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \end{array} \qquad (8)$$

III. NUMERICAL AND COMPARATIVE ANALYSIS

In this section, the performance of the four introduced approaches is explored by predicting the availability of a converter. It is assumed that the converter has two failure-prone components including Cap and PM. Four case studies are considered with different failure and repair characteristics of converter components as summarized in TABLE I. The aging of Cap in Case I & III is faster than in Case II & IV. Moreover, the employed maintenance strategy in Case I & II is corrective while in Case III & IV is preventive. In the following, the availability of the converter and its components are presented.

TABLE I
Failure characteristics of converter components.

Case	Comp.	λ	α [y]	β	r	Maintenance	
		[y^{-1}]			[h]	type	t_0 [y]
Case I	**PM**	0.2	6	3	120	Corrective	–
	Cap	0.3	8	2.5	120	Corrective	–
Case II	**PM**	0.2	6	3	120	Corrective	–
	Cap	0.3	12	2.5	120	Corrective	–
Case III	**PM**	0.2	6	3	120	Preventive	3.8
	Cap	0.3	8	2.5	120	Preventive	5.2
Case IV	**PM**	0.2	6	3	120	Preventive	3.8
	Cap	0.3	12	2.5	120	Preventive	7.9

A. *Impact of corrective maintenance: Case I & II*

In this approach, the converter components will be replaced based on corrective maintenance strategy in which they will be replaced whenever a failure occurs. The unavailability of converter and its components are shown in Fig. 4 and Fig. 5 for Case I and II respectively. As shown in Fig. 4 and Fig. 5, the three methods of SMP, MDS and MCT result in almost the same results where the yellow graph belongs to the MCT indicates the accurate unavailability. However, the unavailability predicted by the PWA is close to the accurate value at the early lifetime, while it becomes divergent eventually as shown in Fig. 4 and Fig. 5. Notably, accurate result of PWA depends on the failure characteristics of components. Comparing Fig. 4(a) and Fig. 5(a) shows that the PWA follows the accurate results for almost 5.25 years in Case II, while for 7.9 years in Case II. This is due to the fact that in Case II, the aging of capacitor is slower than in Case I as given in TABLE I. Moreover, the converter unavailability depends on its most fragile component, e.g., PM in Case I and II. According to these analyses, the PWA is not a suitable approach for unavailability prediction with a fast aging process in a corrective maintenance strategy. However, if the aging process is slow, like the Cap in Case II, the PWA has enough accuracy for almost 8 years.

B. *Impact of preventive maintenance: Case III & IV*

In practice, corrective maintenance may not be a cost-effective solution for enhancing the long-term performance of converters. Therefore, preventive maintenance strategies can be employed to replace the converter components at a suitable time based on their aging process. The replacement time can be determined by minimizing planned and unplanned maintenance costs. According to [15], a Cost Efficiency measure *CE* can be adopted, where the replacement time is the argument of the minimum of *CE* in (9).

$$CE(t_0)=\frac{1+r\cdot F(t_0)}{1+r}\frac{MTTF}{\int_0^{t_0}\left(1-F(t)\right)dt} \tag{9}$$

where r is the ratio of unplanned to planned maintenance costs which is considered to be 2 in this letter. Furthermore, $F(t)$ is the wear-out distribution function. For the given distribution functions for converter components in TABLE I, the CE function is shown in Fig. 6 with the minimum values pointed with green dots. The preventive maintenance times are also summarized in TABLE I for Case III & IV.

The converter and its components unavailability functions are shown in Fig. 7 and Fig. 8 for Case III & IV respectively. It can be seen that employing preventive maintenance, the four approaches result in almost the same unavailability functions. Moreover, the predicted unavailability by the PWA with Purple graph is more close to the accurate values estimated by MCT shown with yellow graph in Fig. 7 and Fig. 8.

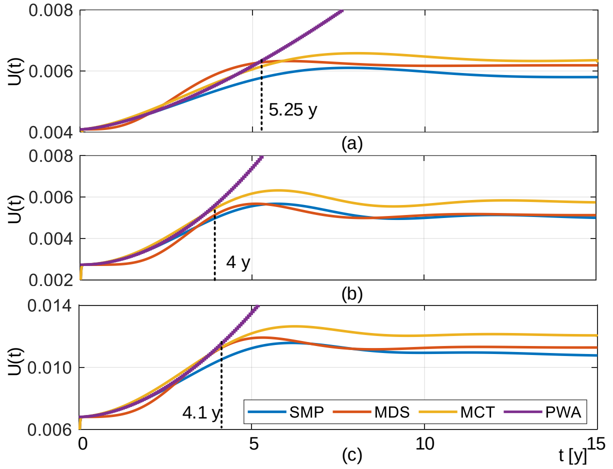

Fig. 4. Case I: (a) Cap, (b) PM, and (c) total converter unavailability.

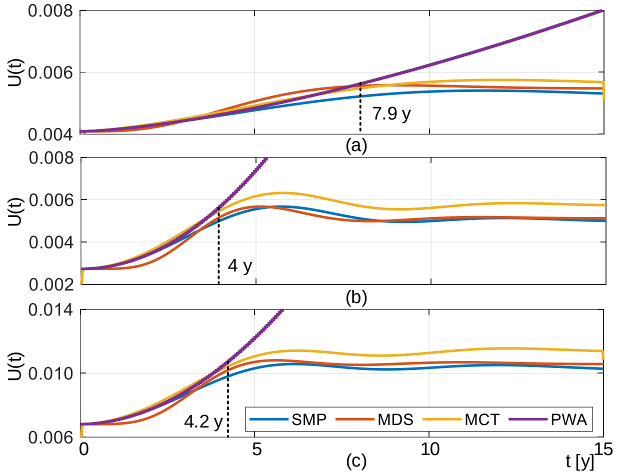

Fig. 5. Case II: (a) Cap, (b) PM, and (c) total converter unavailability.

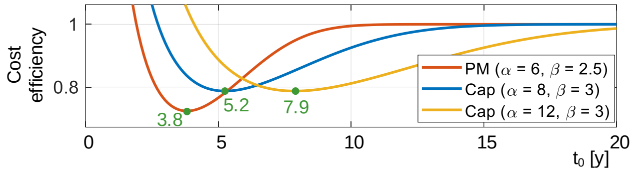

Fig. 6. Optimal replacement time of converter components based on the age-replacement policy.

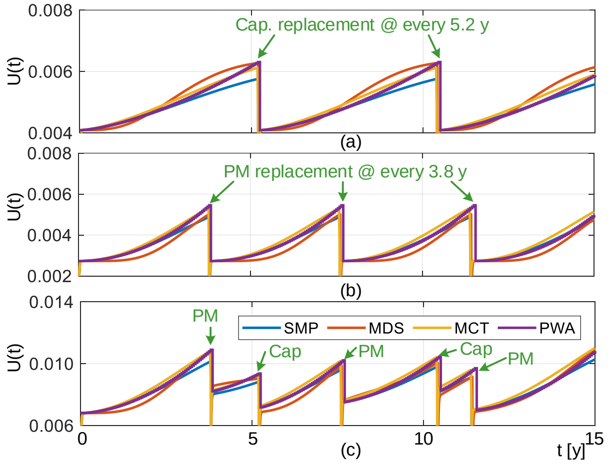

Fig. 7. Case III: (a) Cap, (b) PM, and (c) total converter unavailability.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TEC.2020.3018631, IEEE Transactions on Energy Conversion

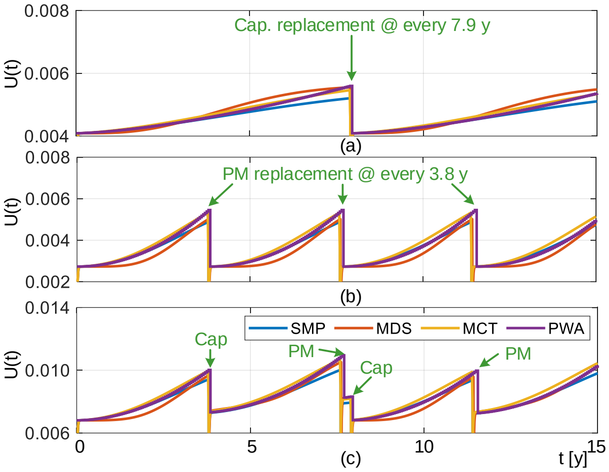

Fig. 8. Case IV: (a) Cap, (b) PM, and (c) total converter unavailability.

C. Comparison

The performance of the introduced approaches including simulation time and maximum estimation error is summarized in TABLE II. The simulations have been run in MATLAB environment on a personal computer with Intel (R) Core (TM) i7-7600U CPU @ 2.8 GHz and 8 GB memory. Notably, the error values show the maximum difference between each approach and MCT during transient and steady-state.

Obtained results show that the error of PWA is significantly high in the case of corrective maintenance. This is due to the fact that the components will be replaced by a new one after any failure, thus, it is returned to the useful life period. Whereas, the PWA considers the minor repair on a component where is it still operated in the wear-out phase. However, the PWA introduces the highest accuracy (2-3% error) and the fast calculation time (less than 1 sec) in the case of preventive maintenance. The MCT is the most accurate approach, while it requires quite high computation time. Furthermore, the accuracy of SMP and MDS is almost similar and the induced error is acceptable, while the simulation time of the MDS is remarkably low.

As a result, in the case of corrective maintenance strategy, the MDS can be a suitable approach for availability prediction. Moreover, in the case of preventive maintenance, the PWA approach introduces a remarkably low calculation burden and acceptable prediction error. Therefore, in large-scale power electronic-based power systems with preventive maintenance strategies, the PWA can be a suitable approach for reliability modeling of power systems considering converter aging.

TABLE II
Performance of different approaches for the cases summarized in TABLE I.

Case	Approach	PWA		SMP		MDS		MCT	
Case I	Time (sec)	< 1	×	1289	×	9	✓	5254	×
	Max Error (%)	> 100		10		7		0	
Case II	Time (sec)	< 1	×	1283	×	10	✓	5296	×
	Max Error (%)	> 100		9		8		0	
Case III	Time (sec)	< 1	✓	390	×	34	✓	160	×
	Max Error (%)	3		7		8		0	
Case IV	Time (sec)	< 1	✓	457	×	31	✓	423	×
	Max Error (%)	2		6		8		0	

IV. CONCLUSION

This letter has introduced several methods for availability modeling of power converters considering components aging. Furthermore, a new approach based on the Markov Chain model is proposed to evaluate the accuracy of different methods. The accuracy and calculation burden of these methods have been illustrated under different failure characteristics and maintenance strategies. Among different approaches, the MDS is the most applicable method (fast and accurate enough) for availability prediction in the case of corrective maintenance. Moreover, in the case of age-replacement preventive maintenance, the PWA has a fast and accurate prediction performance compared to the other approaches. As a result, it can be used for reliability modeling in large-scale power electronic-based power systems with remarkably low calculation burden and acceptable accuracy.

REFERENCES

[1] L. M. Moore and H. N. Post, “Five Years of Operating Experience at a Large, Utility-Scale Photovoltaic Generating Plant,” *Prog. Photovoltaics Res. Appl.*, vol. 16, no. 3, pp. 249–259, 2008.

[2] K. Fischer, K. Pelka, A. Bartschat, B. Tegtmeier, D. Coronado, C. Broer, and J. Wenske, “Reliability of Power Converters in Wind Turbines: Exploratory Analysis of Failure and Operating Data from a Worldwide Turbine Fleet,” *IEEE Trans. Power Electron.*, vol. 34, no. 7, pp. 6332–6344, 2018.

[3] H. S. Chung, H. Wang, F. Blaabjerg, and M. Pecht, “*Reliability of Power Electronic Converter Systems*,” First Edi. London: IET, 2016.

[4] J. Ribrant and L. M. Bertling, “Survey of Failures in Wind Power Systems With Focus on Swedish Wind Power Plants During 1997–2005,” *IEEE Trans. Energy Convers.*, vol. 22, no. 1, pp. 167–173, Mar. 2007.

[5] F. Spinato, P. J. Tavner, G. J. W. van Bussel, and E. Koutoulakos, “Reliability of Wind Turbine Subassemblies,” *IET Renew. Power Gener.*, vol. 3, no. 4, p. 387, 2009.

[6] J. Carroll, A. McDonald, and D. McMillan, “Reliability Comparison of Wind Turbines With DFIG and PMG Drive Trains,” *IEEE Trans. Energy Convers.*, vol. 30, no. 2, pp. 663–670, Jun. 2015.

[7] H. E. Johan, G. W. Steven, and H. Ramtin, “Third EGrid Workshop Maps the Grid of the Future: Attendees Engage to Examine the Role of Power Electronic Applications in Modern Electric Power Systems,” *IEEE Power Electron. Mag.*, vol. 6, no. 1, pp. 48–55, 2019.

[8] W. Li, “Incorporating Aging Failures in Power System,” *IEEE Trans. Power Syst.*, vol. 17, no. 3, pp. 918–923, 2002.

[9] A. Abiri-Jahromi, M. Fotuhi-Firuzabad, and E. Abbasi, “An Efficient Mixed-Integer Linear Formulation for Long-Term Overhead Lines Maintenance Scheduling in Power Distribution Systems,” *IEEE Trans. Power Deliv.*, vol. 24, no. 4, pp. 2043–2053, 2009.

[10] C. Singh and R. Billinton, “Reliability Modelling in Systems with Non-Exponential Down Time Distributions,” *IEEE Trans. Power Appar. Syst.*, vol. PAS-92, no. 2, pp. 790–800, Mar. 1973.

[11] R. Billinton and R. Allan, “*Reliability Evaluation of Engineering Systems*.” New York: Plenum press, 1992.

[12] W. R. Nunn and A. M. Desiderio, “Semi-Markov Processes: An Introduction,” *Cent. Nav. Anal.*, pp. 1–30, 1977.

[13] L. Wenyuan, E. Vaahedi, and P. Choudhry, “Power System Equipment Aging,” *IEEE Power Energy Mag.*, no. june, pp. 52–58, 2006.

[14] S. Peyghami, Z. Wang, and F. Blaabjerg, “A Guideline for Reliability Prediction in Power Electronic Converters,” *IEEE Trans. Power Electron.*, no. 10.1109/TPEL.2020.2981933, pp. 1–9, 2020.

[15] M. Rausand and A. Høyland, “*System Reliability Theory*,” Second Edi. Hoboken, New Jersey: John Wiley & Sons, Inc., 2004.