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Adequacy of Hybrid AC-DC Grids with Reliability Oriented Modular Multilevel Converter Design - A Case Study Using Modified RTS-24 Network

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***Abstract*—The role of power electronics in advancing electrification and sustainability is pivotal. The Modular Multilevel Converter (MMC) is a leading candidate for connecting offshore wind farms to the power grid. However, one of the primary concerns with MMC is its reliability, primarily due to the high number of components, with semiconductors and capacitors being the main sources of failures. This study examines how the modularity and redundancy of the MMC affect its reliability and, consequently, its impact on power system adequacy. Our findings reveal a substantial influence of MMC's modularity and redundancy on power system adequacy. A high level of modularity with no redundancy leads to the worst-case scenario. On the other hand, lower modularity combined with higher redundancy results in the best scenario for power system adequacy. However, it's important to note that lower modularity and higher redundancy come with increased capital costs of MMC, representing a trade-off between reliability and affordability that we explore in this paper.**

***Index Terms*—Modular Multilevel Converter, reliability, redundancy, modularity, adequacy, power system.**

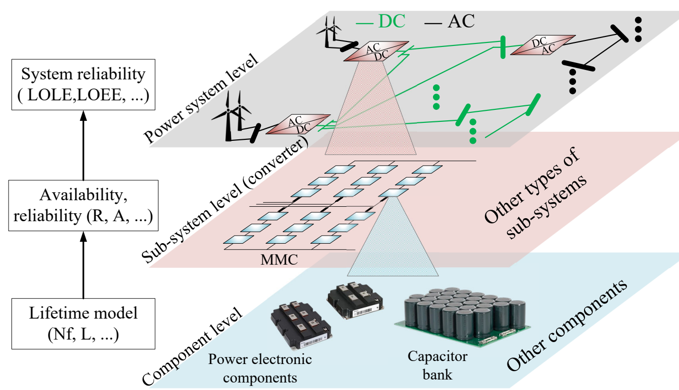

Fig. 1: The connection between PE and the principles of power system reliability.

I. Introduction

As society progresses towards electrification and sustainability, there is an increasing integration of power electronics (PE) based systems into power grids [1]. However, a longstanding concern has revolved around the reliability of these PEs [2]–[4]. It is crucial to note that if these PE-based systems were to replace conventional power plants, the overall availability of the power system could potentially be adversely impacted [5].

Considerable research efforts have examined power system reliability [6]. In parallel, substantial work has been undertaken to assess the reliability of PE converters and components. To illustrate this, please refer to Fig. 1, which provides a visual representation of the various stages of reliability studies, along with their corresponding indicators [7].

At the power system level, authors in [8] outline a reliability assessment methodology for High Voltage Direct Current (HVDC) systems with Voltage Source Converter (VSC) tapping stations, demonstrating their enhanced reliability, especially in energy and power-related indices, particularly at higher load levels. A novel reliability analysis method for HVDC transmission systems is introduced in [9] using the Matrix-Based System Reliability (MSR) approach with Boolean operators, demonstrating efficiency, practicality, and potential for handling incomplete information. [10] presents a reliability model for offshore wind farms connected via VSC-HVDC, incorporating wind speed correlation, demonstrating its accuracy and computational efficiency compared to Monte Carlo simulation. The authors emphasize the importance of considering VSC-HVDC system outages, wind speed correlation, and repair time in reliability assessments. Authors in [11] underscore the importance of considering non-exponentially distributed failures in microgrid reliability assessments and highlight the limitations of Mean Time To Failure (MTTF)

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based availability analysis, emphasizing the need for accurate planning and operation decisions in microgrids with high power converter penetration.

At the converter level, several studies [12]–[14] explore the reliability improvements of the converter. [12] introduces comprehensive reliability models for Half-Bridge (HB) MMC in medium-voltage (MV) and HVDC applications, including active and passive redundancy schemes, highlighting their effectiveness and cost-effective configurations. Authors in [13] present the Reliability-Centered Maintenance (RCM) approach for MMCs, offering a dynamic maintenance interval decision process considering MMC operation states, highlighting the impact of redundancy and mode choice on maintenance intervals. In [14], a cost-oriented approach for selecting the optimal rated voltage of the switch in MMC is introduced, considering modularity-based trade-offs.

At the component level, [15] gives an overview of the reliability factors of various capacitors and a design approach is proposed to improve the capacitor reliability. In [16], authors focus on power semiconductor devices, and the reliability aspects of such devices in converter applications are reviewed.

However, it is important to note that there is a limited number of studies that specifically focus on the influence of each of these lower-level factors on the broader, higher-level aspects of reliability. In [17], an approach is introduced to integrate the reliability of PE converters into power system reliability analysis, enabling better decision-making in modern power systems' planning, operation, and maintenance. It illustrates the impact of converter failure rates on different applications. Authors in [18], [19] introduce a two-level reliability framework that connects power converters and power systems, emphasizing the substantial impact of individual converter reliability on modern power system performance.

In this paper, the effect of reliability improvement at the converter level is quantified at the power system level. It shows how the modularity and redundancy at the converter level, focusing on MMC application, can affect the power system reliability indices. Moreover, this paper considers the optimal trade-offs between converter redundancy and modularity in the prospect of system-level reliability. The rest of the paper is organized as follows. Section II overviews MMC and its reliability. Section III gives the overview of how to evaluate its adequacy. In section IV, the case study and results are given, and finally, the conclusion is given in section V.

II. MMC's Reliability and Cost Aspects

The MMC is widely recognized for its high efficiency and scalability in MV and High Voltage (HV) applications. Nevertheless, the MMC poses particular challenges regarding reliability due to its complex structure, complex control system, and extensive use of PE semiconductors and capacitors, as discussed in [20], [21]. To address these concerns, researchers have explored the potential solutions of redundancy and modularity in enhancing MMC reliability, as indicated in references [14] and [22]. Modularity refers to the selection of PE switches with different voltage ratings where a smaller switch rating increases the modularity level in the MMC. These choices, typically ranging from 1.2 to 6.5 kV switches available in the market, significantly influence the MMC system's reliability and cost implications, operational losses, and capital investments. Redundancy means the inclusion of redundant SMs. The operation of the MMC with redundant SMs can take various forms, as explained in [23]. In case of an SM failure, the redundant SM ensures continuous operational functionality, reducing the risk of MMC downtime.

However, it's essential to recognize that there are trade-offs associated with modularity and redundancy regarding costs and efficiency. For instance, opting for high modularity with lower voltage ratings can result in an increased number of components, which can have implications for both reliability and operational as well as capital costs. Conversely, incorporating additional modules invariably leads to higher costs for the MMC and potentially lower operational efficiency. Nonetheless, this trade-off can be justified by the enhancement in MMC reliability that comes with the inclusion of extra modules [14]. It is important to emphasize the significance of the converter reliability, particularly in the context of overall power system reliability. This becomes pronounced when the converter (MMC in this study) is an interconnection point, such as connecting offshore wind farms to the power system. Any failure or downtime in the MMC can disrupt power flow, and it can significantly impact the overall reliability of the power system.

III. Adequacy of Grid-Connected MMC and Methodology

At the power system level, reliability assessments are conducted at three distinct levels: generation units (HL 1), which solely considers generation; generation and transmission (HL 2), which encompasses both generation and transmission; and HL 3, which considers generation, transmission, and load. In this paper, the analysis is focused on HL 1, specifically on the RTS 24 benchmark network.

When high-power, HV renewable generators are integrated into the power system through MMCs, ensuring their reliability becomes even more critical. This paper quantifies the reliability of power systems at HL 1 adequacy level by focusing on MMCs reliability improvements. The key indices at the HL 1 level include the Loss of Load Expectation (LOLE) measured in hr/year, the Loss of Energy Expectation (LOEE) in MWh/year, and the Loss of Load Frequency (LOLF) in Occ/year [7].

In this study, Monte Carlo Simulation (MCS) is applied to evaluate the reliability of the studied system. MCS is a valuable tool for power system reliability studies as it can help them quantify and manage the inherent uncertainties and risks associated with generation assets. By considering a wide range of scenarios, it provides a more robust and realistic assessment of power system reliability, which is essential for maintaining a stable and secure electricity supply [7], [24].

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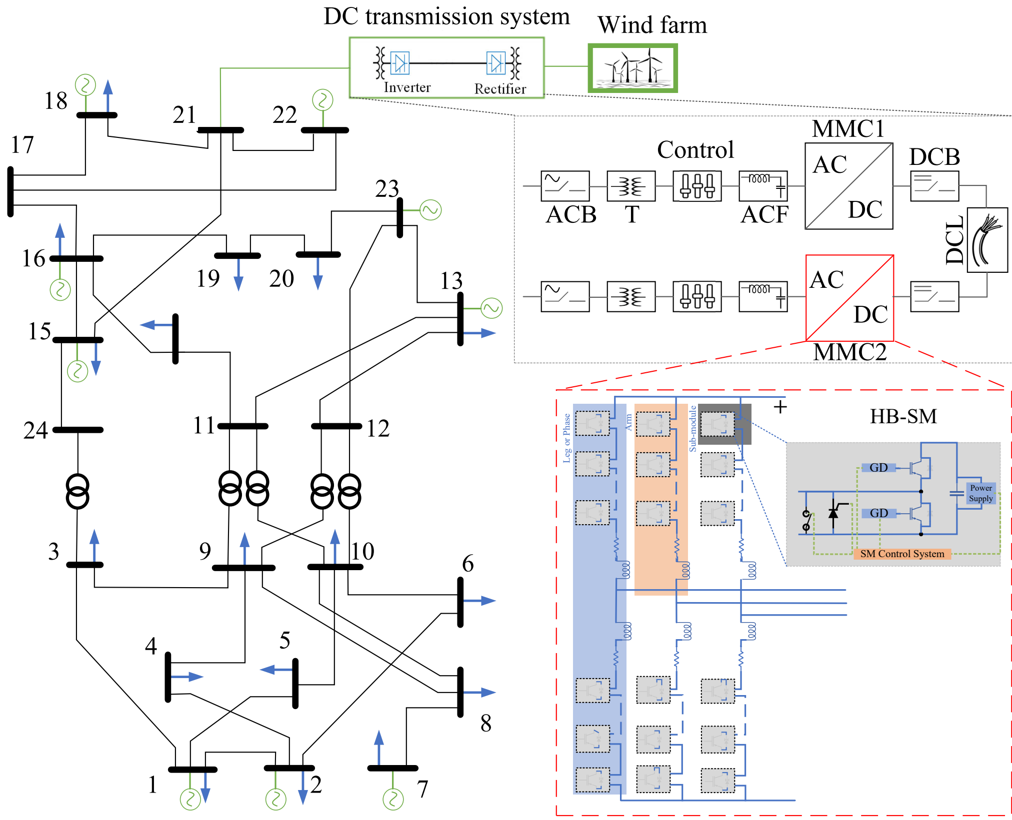

Fig. 2: Configuration of RTS 24 with the integration of wind farms through MMC.

IV. Case Study and Results

In this study, the reliability of the RTS 24 is assessed by integrating a wind farm into bus number 21 through the DC transmission system [4], [17], [18], as illustrated in Fig 2. Wind power is integrated into the power system through a rectifier (MMC1) and an inverter (MMC2). RTS 24 operates at two voltage levels: 230 kV in the upper part and 138 kV in the lower part. Therefore, the DC voltage of the point-to-point DC transmission system should be 391 kV, with a modulation index set to 1. Additional information about the characteristics of the MMC and reliability parameters is provided in the appendix. Also, the information about loading and other reliability parameters of the RTS 24 is defined in [7].

To evaluate the reliability of RTS 24 with integrated MMCs at HL1, MCS is employed. In this level of the study, LOLE, LOEE, and LOEF indices are used as indicators. Fig. 3 illustrates one trial of the generation and load, from which it is possible to estimate the HL 1 reliability indices. Fig. 3 top shows the available capacity and load demand of the RTS 24 grid for a 1-year operation, representing a single MCS trial. For example, in this specific trial shown in Fig. 3 top, where the margin presented in Fig. 3 bottom is below 0 around 7800h, it is considered the system's failure, and the indices can be calculated, which are explained in detail in [7]. However, it's crucial to repeat this trial multiple times to converge to the final value. Typically, the thumb rule is 10,000 trials for this purpose. Nevertheless, in this study, MCS is conducted with 50,000 trials to ensure more accurate results.

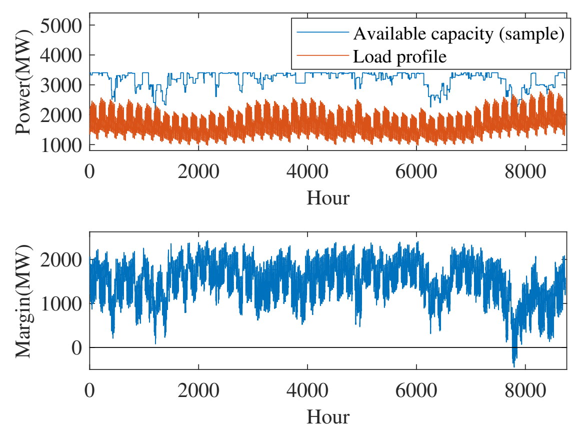

Fig. 3: One trial of MCS in RTS 24.

Fig. 4 illustrates the impact of integrating wind power through the MMC-connected transmission system on the LOLE of the power system. It becomes apparent that the redundancy of the MMC significantly enhances the system's reliability. However, it's important to note that high modularity

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TABLE I: LOEE IN MWH/YEAR

		Redundancy (%)										
		0	1	2	3	4	5	6	7	8	9	10
Switch (kV)	1.2	2791.8	1146.1	963.5	901.5	870.1	847.9	806.6	806.5	820.6	812.3	799.8
	1.7	2338.6	1076.7	943.4	914.7	861.7	842.1	815.4	805.8	821.3	810.3	810.8
	3.3	1662.7	985.2	929.3	884.9	858.4	820.3	809.6	807.7	807.4	804.5	794.8
	4.5	1423.8	993.8	897.6	889.2	871.8	841.5	824.9	800.6	815.3	791.0	800.1
	6.5	1245.6	905.4	872.2	864.1	833.6	832.9	829.1	814.3	819.5	786.1	753.4

TABLE II: LOEF IN OCC/YEAR

		Redundancy (%)										
		0	1	2	3	4	5	6	7	8	9	10
Switch (kV)	1.2	4.1868	1.8671	1.6017	1.5283	1.4663	1.4237	1.3935	1.3992	1.3953	1.3704	1.3764
	1.7	3.5415	1.7531	1.5794	1.5283	1.4600	1.4346	1.4024	1.3993	1.3820	1.3848	1.3747
	3.3	2.5943	1.6539	1.5385	1.4811	1.4519	1.4228	1.3988	1.3921	1.3903	1.3773	1.3677
	4.5	2.2671	1.6357	1.5270	1.4977	1.4498	1.4131	1.4069	1.3767	1.3854	1.3675	1.3659
	6.5	1.9984	1.5350	1.4843	1.4695	1.4240	1.4128	1.4048	1.3914	1.3951	1.3605	1.3695

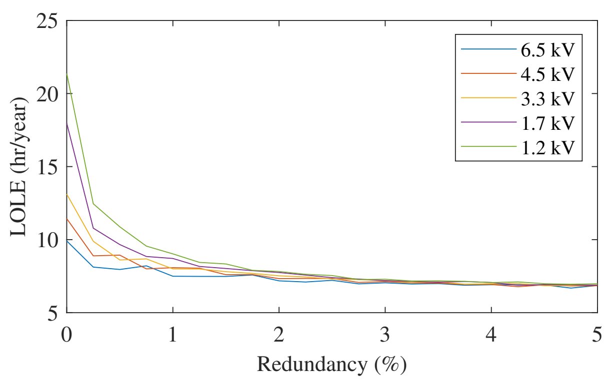

Fig. 4: LOLE of power system with various modularity and redundancy of the MMC.

also exerts a noticeable negative effect on power system reliability. Therefore, it can be inferred that opting for lower modularity and higher redundancy can enhance power system reliability. Yet, it's crucial to emphasize that reliability is just one aspect of the decision-making process, as there are several factors to consider, including modularity, redundancy, efficiency, and the cost of the MMC explored in [14]. Particularly in relation to LOEE and LOEF, and their results are quantified in Tables I and II. Consequently, similar conclusions can be drawn regarding LOEE and LOEF. Nonetheless, it's worth noting that as long as there is at least 5% redundancy at the MMC level, the choice of modularity should primarily be based on converter-level efficiency and costs.

V. CONCLUSION

In this paper, the critical issue of PE reliability and its implications for power system reliability towards electrification and sustainability are examined. This study has highlighted the growing integration of PE-based systems into power grids and the potential challenges they pose. As conventional power plants are replaced with PE-based systems, ensuring their reliability is paramount to maintaining the overall availability and stability of the power system. The paper has highlighted the significance of MMC reliability, especially in the context of power systems, emphasizing that MMCs, when serving as interconnection points, can significantly impact power system reliability. Any failure or downtime of MMCs can disrupt power flow, underscoring the need for robust and reliable MMC systems. The analysis carried out in this study has primarily focused on HL1 reliability assessments, quantifying the impact of MMC reliability improvements (modularity and redundancy) at the power system level. Moreover, MCS is applied to evaluate reliability, providing a comprehensive understanding of the system's performance under various scenarios.

APPENDIX

In this part, the reliability parameters of the DC transmission system are given in Table III. The MMC's characteristics are provided in Table IV.

TABLE III: MMC CHARACTERISTICS

Symbols	Item	Value
k	Minimum number of SMs	598, 422, 218, 160, 111†
V_{dc}	DC link voltage	391 kV
S_{MMC}	Rated power	400 MVA
V_{IGBT}	IGBT Rated Voltage	1.2, 1.7, 3.3, 4.5, 6.5 kV
S_f	Safety factor of IGBT	0.6

† Consequently for different switch ratings

TABLE IV: RELIABILITY PARAMETERS

Component	Item	Failure rate (Occ/year)	Repair Rate (Occ/year)
IGBT	-	0.000876	-
Capacitor	-	0.001752	-
ACB	AC breaker	0.045	175.2
T	Transformer	0.1308	146.6
Control	Control system	1.3096	1095
ACF	AC filter	0.183	182.5
DCB	DC breaker	0.121	121.7
DCL	DC line	0.6613	988.8

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