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A systematic review of Intelligent Fault-Tolerant Protection Scheme for Multi-terminal HVDC Grids

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Abstract

Due to the advancement of power electronics devices and control techniques, the modular multilevel converter (MMC) has become the most attractive converter for multiterminal direct current (MTDC) grids thanks to its most relevant features, such as modularity and scalability. Despite their advantages, conventional MMCs face a major challenge with: i) fault-tolerant operation strategy; ii) energy losses in conversion; iii) lack of DC fault handling capability. This paper provides a systematic review to identify the gaps in the literature about Intelligent Fault-Tolerant Protection Schemes for multi-terminal HVDC grids. Through the bibliometric analysis, it was possible to identify topics still to be developed within the four main clusters (Offshore wind farms, Wind turbines, Voltage Source Converters, and Wind power). The research topic opens three research paths: the first is the analysis of failures in HVDC (High Voltage Direct Current) grid equipment by the FDD (Fault Detection and Diagnosis) method; the second is failure analysis by the IFDD (Inverse Fault Detection and Diagnosis) method and the third is the possibility of interconnecting the different energy generation zones with different frequencies.

Author Keywords: High Voltage Direct Current, Modular Multilevel Converter, Modeling of MMC-MTDC, Fault Tolerance Operation, Submodules Faults.

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1. Introduction

According to the report Renewable Energy Policy Network for the 21st Century (REN21), wind energy generation in 2020 provided only around 15% of the annual electricity consumed by the European Union members, and around 3% of this amount is from offshore wind farms (REN21, 2021). This value is low considering the goal to be achieved for carbon neutrality in 2050. So, to increase this number, the development of wind power generation technology with higher reliability and security is crucial. Although the nature of renewable energy systems is variable and with intermittent resources, offshore wind energy technology has shown promise in this aspect due to the characteristic of the wind that is based on constant speeds, making it possible to exploit this resource quite efficiently.

The interconnection of offshore wind farms to the onshore grid can be done in High Voltage Alternating Current (HVAC) or High Voltage Direct Current (HVDC). However, currently, HVDC transmission systems are preferred for integration with the onshore grid due to their long-distance power transfer capabilities, fast and accurate control of active and reactive power, interconnecting nonsynchronous power systems, interconnecting power systems with different frequencies of 50 and 60 Hz, and less dielectric losses (de Prada Gil et al., 2015; Javed et al., 2021b). Several researches have been conducted considering offshore wind farms with HVDC power transmission focusing on different issues such as optimal layout design (to maximize energy efficiency over a year), its control and grid integration (Cazzaro et al., 2022; Ciapessoni et al., 2012; Díaz-Sanahuja et al., 2020; Froese et al., 2022; Serrano González et al., 2013; Silva et al., 2014). In offshore wind farms with HVDC systems, there is a close connection between the electronic power conversion and the cybernetic and physical networks. Thus, as digitization of these conversion systems progresses, these network models become more complex with stochastics and subject to greater vulnerabilities. In the electrical systems, a cyberattack can have major consequences (Gauci, 2019):

- If the attack results in a data breach, the attacker may obtain access to load profiles, which could be considered competitive data (e.g., server usage);
- If the attack causes equipment malfunctions, it can be a safety risk to employees or the public;
- If the attack causes a power outage, it can cause large losses, such as the loss of wind turbine monitoring. A loss of power in one of the converters can put lives at risk if backup power systems fail.

In order to ensure greater reliability of these networks, it is of paramount importance to develop an intelligent fault diagnosis system, as the occurrence of one or more faults can lead to a forced system shutdown and unscheduled maintenance operations, which results in loss of energy generation and an increase in operation and maintenance costs. According to the literature (Isermann, 2006), it is possible to develop advanced fault detection and diagnosis methods based on the systematic use of mathematical processes and signal models, identification and estimation methods and computational intelligence methods. Recent advancements in data-based and physics-based diagnosis provide possible novel approaches to address the challenges relating to high voltage direct current system integration.

The present study seeks to identify gaps in the literature about the intelligent fault diagnosis system in the High Voltage Direct Current grid, using a systematic review based on three main pillars: identification, screening, and eligibility.

To conduct our review, we pose and address three questions:

Q1: What factors influence the use of HVDC-VSC?

Q2: What are the main causes of failure in modular multilevel converters?

Q3: What fault diagnosis methods are used in the HVDC network?

2. Materials and Methods

Our systematic review was performed according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) guidelines (Page et al., 2021). The following databases were used: ScienceDirect, IEEE Xplore, and Scopus. We did an exhaustive search in academic databases considering the years from 2017 until 2022. These years were chosen because 2020/2021 was the most contemporary 2-year period at the beginning of the research and the 5-year periods years before 2022 were chosen to allow comparison. The search strategy includes the use of Boolean logical operators like “OR”, “AND”, and “*” to improve the search sensitivity. The search terms were: fault analysis, HVDC grids, power converters, VSC HVDC, offshore wind farms, security, and contingency analysis (Table 1). Search filters for systematic reviews and meta-analyses were also used to refine the search. Inclusion and exclusion criteria were applied. Inclusion criteria were articles that address search terms (plus fault diagnosis, fault detection), articles published only in journals and conferences, articles published from 2017 to 2022 and studies in English. Exclusion criteria were articles that do not address offshore wind farms, articles out of date and periodicals mentioned above, and studies in which the full article is not available. Bibliometric data collected directly from the databases were stored and analyzed using R Studio software. Duplicate articles were eliminated using Mendeley.

Years of research	Databases	Search terms
2017, 2018, 2019, 2020, 2021, 2022	ScienceDirect, IEEE Xplore, Scopus	Fault analysis, HVDC grids, Power converters, VSC HVDC, Offshore wind farms, Security, Contingency analysis

Table 1: Search terms, databases and years of research.

3. Results

3.1. Results of articles found

In the initial search for articles in the literature, a total of 958 records were obtained. After removing duplicates and screening the article's scope considering the exclusion criteria, a total of 79 articles were included for data extraction, as illustrated in **Figure 1**.

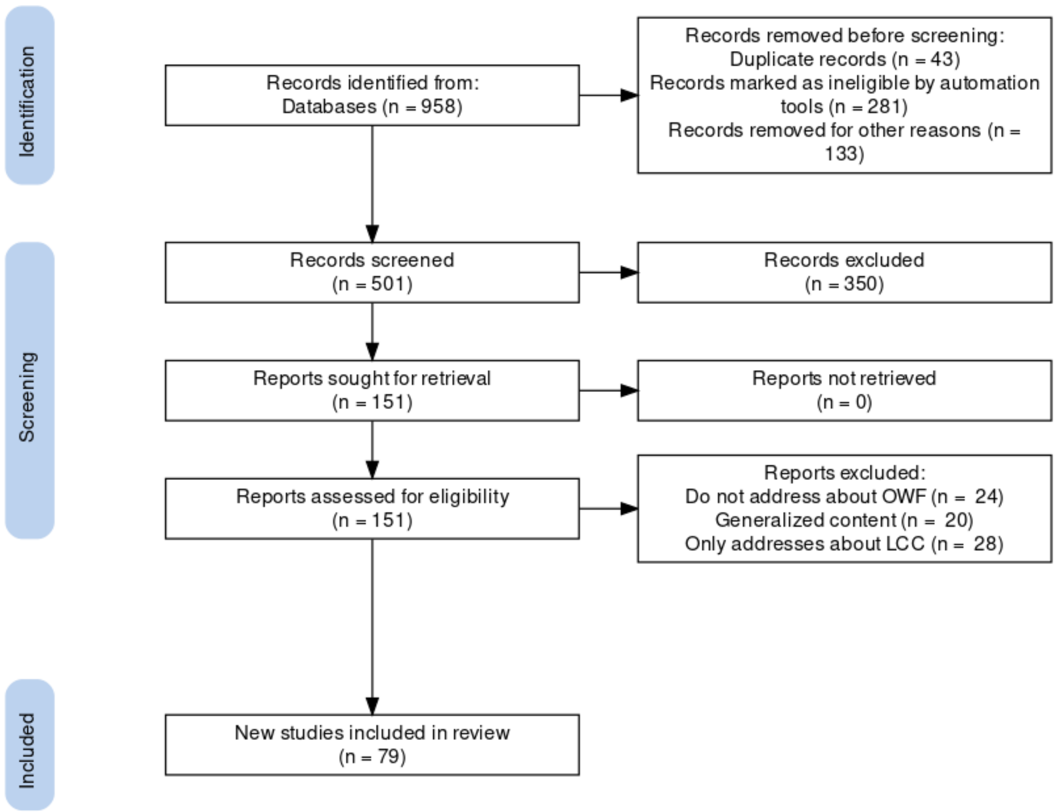

Figure 1: PRISMA flow diagram showing article selection process.

The characteristic study is presented in Table 2, including the databases, the search strategy, the number of articles found and the number of duplicates. Considering the subject under analysis, the ScienceDirect database presented a total of 433 articles, equivalent to 45.20%. Although it has a high number of duplicates, we consider it to be the database with the most information. In Scopus we obtained a total of 244 articles, equivalent to 25.47% and finally in IEEE Xplore we obtained a total of 281 articles, equivalent to 29.33%. It is worth noting that the high number of articles obtained in a generalized search (without quotation marks) collects any article that has one of the words of the search phrase.

Databases	Search strategy	Nº of Articles	Nº of duplicate articles excluded
IEEE Xplore	“fault analysis” and “power converters” and “offshore wind farms”	32	8
	Faults analysis of MMC in HVDC grids	219	
	Contingency analysis in HVDC grids	27	
	Security in MMC of offshore wind farms	3	
Scopus	“fault*” and “power converters” and “offshore wind farms”	49	6
	Faults analysis of MMC in HVDC grids	187	
	Contingency analysis in integration of HVDC grids	5	
	Security in MMC of offshore wind farms	3	
ScienceDirect	“fault analysis” and “power converters” and “offshore wind farms”	2	29
	faults analysis of MMC in HVDC grids	250	
	Contingency analysis in integration of HVDC grids	156	
	Security in MMC of offshore wind farms	25	

Table 2: Number of articles by the search strategy.

3.2. High Voltage Direct Current System

High Voltage Direct Current (HVDC) systems have shown promise in the transmission of electrical energy over long distances, as well as in the interconnection of different sources of renewable energy generation. For offshore wind farms, an HVDC system is formed by a rectifier connected to the wind farm, a direct current (DC) cable circuit, and an inverter connected to the onshore grid (Gomis-Bellmunt et al., 2011).

According to the literature, the main HVDC system configurations are: Monopolar HVDC systems (monopole with ground return, monopole with metallic return, monopole with grounded midpoint) (Korompili et al., 2016); Back-to-back HVDC systems (Efobi et al., 2019); Bipolar HVDC systems (bipole, bipole with metallic return, bipole with series-connected converters) (Yang & Huang, 2020); Multi-terminal HVDC systems (Karaagac et al., 2017).

Comparative studies by Zhang et al. (Zhang, Zou, et al., 2017) proved that to ensure additional controllability in the transmission system, multiterminal HVDC systems are of greater interest in this function, due to their flexibility and low cost of energy dispatch. Although the HVDC system has considerable advantages, Javed et al. (Javed et al., 2021) claim that this system itself is not very efficient for interconnecting power sources with different frequencies. So, in his literature review, he proposes the hybrid HVAC-HVDC system. Future research prospects are identified in his studies, such as security algorithms’ constraints, dynamic contingency modeling, and cost-effective and reliable operation.

3.2.1.Comparison

The chain of power converters is the heart of the HVDC system, since it performs the conversion from AC to DC (rectification) at the sending end and from DC to AC (inversion) at the receiving end of the DC link (Korompili et al., 2016). As a result, reliability is an important concern in these power converters. High Voltage Direct Current (HVDC) transmission systems are based on Current Source Converters (CSCs), also called Line Commutated Converters (LCC), and Voltage Source Converters (VSCs) (Liu et al., 2022). Although there has been an evolution in LCC converters to improve power quality, comparative studies have proven that VSC converters, especially the Modular Multilevel Converters (MMC) technology, present greater efficiency for AC grid interconnection purposes due to their modularity and scalability to meet any voltage level requirements, reduced voltage ratings and dV/dt stress of switches and capacitors, high efficiency, improved power quality for filter-free applications and inherent fault-tolerance capability to improve the performance of the MMC-based HVDC systems (Nougain et al., 2021; Zhang, Zou, et al., 2017). According to (Parker et al., 2017), the industry needs to get more experience with VSC-HVDC, especially when used in offshore wind power, as these systems can generate problems such as harmonics in the offshore grid, potentially due to interactions between the converter station and wind turbines and frequent interruptions.

Various submodules (SMs) topologies have been proposed and investigated to improve the fault-blocking performance of the MMC-HVDC systems, such as Half-bridge (HB), Full-bridge (FB), Unipolar-voltage full-bridge (UFB), Clamp-double (CD), Alternate-arm (AA), Three-level/five-level cross-connected (3LCC/5LCC) SMs (Zhang, Zou, et al., 2017).

Ref.	MMC Topology	Characteristics	Limitations
(Ni et al., 2020)	Half-bridge	The efficiency is high due to having only two switches within each SM. During a DC-side short-circuit fault, the fault current, flows from the AC side toward the DC-side through the antiparallel diodes of the SMs.	In case of a DC-side short-circuit fault, the HB-MMC cannot block the fault currents fed from the AC grid.
(Wenig et al., 2018)	Full-bridge	During a DC-side fault, when all of the IGBTs of the SMs are blocked, the capacitor voltages can generate reverse voltages to block the AC-side currents. Thus, the full-bridge SMs can provide the DC-fault-handling capability.	The power losses as well as the cost of these systems are significantly higher than the half-bridge one.
(J. Li et al., 2018)	Clamp-double	In this system, can only generate a reverse voltage per arm, that is, half of the reverse voltage produced by the full-bridge SMs per arm.	This topology has higher semiconductor losses than the half-bridge MMC and lower than the full-bridge MMC. The clamp-double MMC needs more time to drive the fault current to zero.
(Qin et al., 2015)	Five-level cross-connected	During a fault, the two capacitors of the five-level cross-connected SM connected in series can block the short-circuit current. This system can generate a reverse voltage per arm, which is the same as the voltage produced by the full-bridge MMC.	This topology has higher semiconductor losses.
(Benhahma et al., 2017)	Three-level cross-connected	Is a combination of series 2 levels cell and two clamped diodes.	Do not provide any dc-fault-handling capability. High cost and low control.

Table 3: Comparison of MMC submodules (SMs) topologies.

Considering the cost-effectiveness, the half-bridge topology has been more implemented, even with its inability to block DC faults. Although the full bridge and clamp-double typologies can cut DC-side short-circuit faults in seconds, these still have the disadvantages of not providing a trade-off between the number of components needed and the efficiency of the system (extra power losses). For this reason, new models, such as the hybrid MMC proposed by Liu (Zhang, Qin, et al., 2017), open the way for new research in the field of fault-tolerant schemes using modulation of MMC submodules.

Table 4 andTable **5** present some fault protection techniques identified in the literature. Its limitations are addressed to help us understand the need to contribute scientifically if we use one of the techniques.

Reference	Year	Methods	Limitations
(Sarkar & Das, 2021)	2021	MMCs with Fault-blocking Capability	Capacitor overload due to the capability to block the fault current of the submodules. The increased number of semiconductor switches leads to extra power losses.
(Xue et al., 2022)	2022	Coordination of the MMCs with the DCCB	Not a cost-effective solution due to the large number of DC CBs required in meshed DC grids

Table 4: Comparison of some Protection Techniques: Fault Interruption.

Reference	Year	Methods	Limitations
(Tang & Dong, 2019)	2019	DC current direction	The faulty line can only be identified in the process of clearing the fault
(Wang et al., 2018)	2018	Nearest Level Modulation	There is no economic feasibility due to the additional cost of detection equipment
(Huai et al., 2021)	2021	Traveling-wave	Impossible to accurately identify the fault location when the value is low.
(C. Li et al., 2019)	2019	Mixed kernel support tensor machine	This algorithm is not suitable for large data sets. In cases where the number of features for each data point exceeds the number of training data samples, the SVM will underperform
(Silveira & Araújo, 2020)	2020	Inversion model (with an integrated fuzzy logic scheme)	Need to improve response time
(Xu et al., 2018)	2018	Open loop nearest level modulation (NLM) and carrier phase shifted sinusoidal PWM (CPS-SPWM)	Delay to drive the fault current to zero
(Sabug et al., 2020)	2020	Real-time boundary wavelet transform (RT-BWT)	Shift sensitivity and low directionality
(Gutiérrez-Alcaraz et al., 2020)	2020	Jacobian-Free Newton-Krylov	The numerical solution is influenced by the high number of iterations.

Table 5: Comparison of some Protection Techniques: Fault Detection and Location.

There are still other emerging technological innovations that will be implemented in the coming years in the electronics industry, specifically in the conversion system, such as: Adaptive and predictive controllers; Preventing aging and failure controllers; Neural network-based and Artificial Intelligence controllers and Internet of Things applied to power management (Farshad, 2021; Gauci, 2019; Shi et al., 2020; Xiang et al., 2020; Zhai et al., 2020).

3.3. Solved and Opened Studies

To understand the solved and open topics, we resorted to bibliometric analysis of the articles on the subject under analysis. Thus, considering a search in the Scopus database as a sample and using the search strategy "High voltage DC grid" OR "HVDC" AND "offshore wind farms" to obtain a more open search, we obtained a total of 514 articles published in journals and in conferences from 2017 to 2022. With the help of the R Studio software, we were able to visualize the trend of topics according to the four quadrants shown in Figure 2, which we now explain:

- *Quadrant I:* this quadrant contains themes with high centrality and density, themes capable of influencing the field of research and well developed.
- *Quadrant II:* this quadrant contains the transversal themes for a discipline, which may influence other topics (that is, they have a high degree of relevance), but are poorly established internally (that is, they have a low degree of development).
- *Quadrant III:* this quadrant highlights topics that are emerging or disappearing due to their low relevance and development. The low density in many cases is justified by the complexity of the subject.
- *Quadrant IV:* This quadrant contains niche themes among academics, which are internally well developed (high density), but are not able to influence other themes (low centrality) because they have already been explored a lot.

Therefore, from Figure 2, we can see that the topics in the second quadrant (HVDC transmission, rectifying circuits and wind turbines) are the most relevant and capable of influencing other topics, but they have a low degree of development, which opens up possibilities for further research. The disadvantage is that they can generate gaps for future research. The other topics belonging to other quadrants were considered resolved depending on the number of publications. So, we consider resolved topics with more than 50 publications and open topics with less than 50 publications.

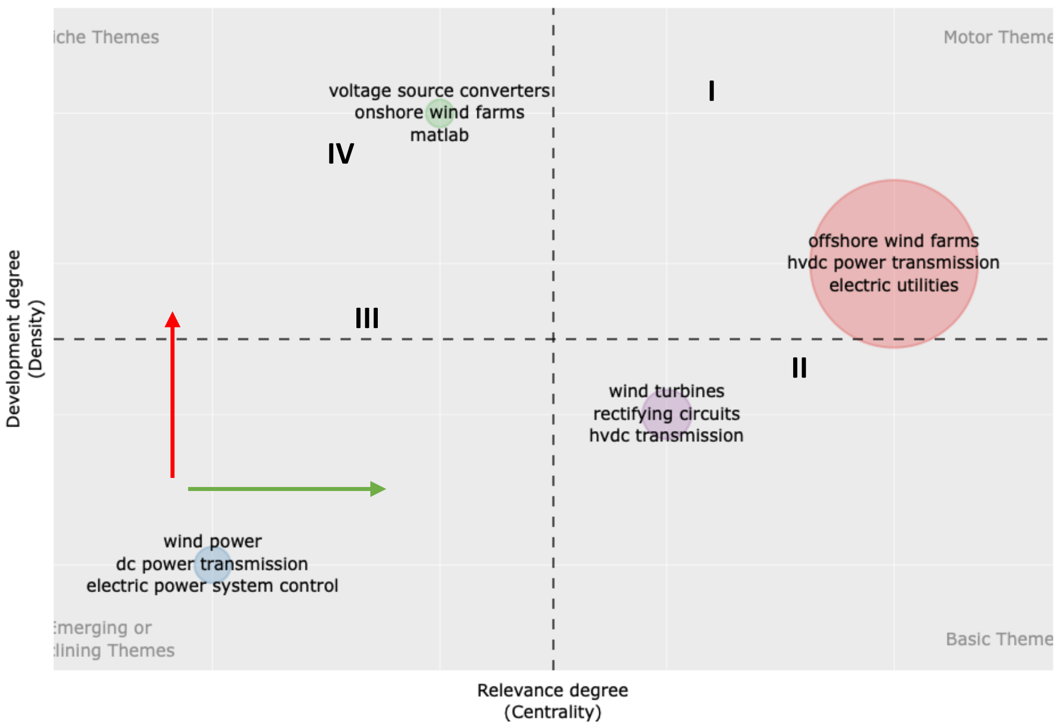

Figure 2: Thematic evolution of the topic - RStudio.

4. Discussion

According the results obtained, we can claim that conventional HVDC converters cannot withstand large fault currents; therefore, they need more protection. DC fault current is difficult to isolate because it has no zero crossings. The models created to isolate faults in the DC network do not have conversion efficiency due to the number of semiconductors in the converter model. Schemes developed for fault identification do not predict faults depending on the performance of the submodules, which opens the need for dynamic contingency analysis here. Little has been explored about inertia and drop control (Ramos & Araujo, 2020).

Therefore, considering these gaps, this review opens three research paths, considering the main clusters identified in the literature (Beza & Bongiorno, 2019; Raza et al., 2020): the first is the analysis of failures in HVCD network equipment by the Fault Detection and Diagnosis (FDD) method, in which the input data are acquired by supervision and measurement; the second is the analysis of failures using the IFDD method, in which failures of unknown origin are studied, such as cyberattacks on the electrical network and the third is the possibility of analyzing the failures of hybrid networks used to interconnect the different energy generation zones with different frequencies. On this last point, there is a great opportunity for countries that wish to interconnect their energy systems with neighboring countries.

4.1. Theoretical implications

The compilation of this report can be a good basis for future research on modulation of MMC converters based on product development. Knowledge about converters can also be a basis for theory development in conjunction with other mechanical studies. This report can also serve as a preliminary basis for designers and engineers to design unique products that utilize converters.

4.2. Practical implications

With this analogy of various fault identification methods and comparison of various innovative converter topologies, a new improved converter model can be developed by designers and engineers. Fault-blocking capability and on-the-fly conversion efficiency can be radically improved and optimized with the development of an intelligent fault-tolerant scheme. These aspects improve your outlets and attract the attention of shoppers who often review a product's reliability and efficiency. A drive with fault blocking capability can help reduce submodule faults, reduce circuit breaker costs and potentially improve the level of safety in the workplace. Workers will be able to experience a better quality of life and greater job satisfaction with a safer work environment.

5. Conclusions

The present literature review was based on a systematic review and meta-analysis. Through the bibliometric analysis of the data, we were able to verify the evolution of the theme about intelligent fault-tolerant protection scheme for multi-terminal HVDC grids. With the help of bibliometric analysis, it was possible to identify gaps in the literature, which resulted in the identification of topics still to be developed within the four main clusters (Offshore wind farms, Wind turbines, Voltage Source Converters, Wind power). The research topic opens three research paths: the first is the analysis of failures in HVDC network equipment by the FDD method; the second is failure analysis by the IFDD method and the third is the possibility of interconnecting the different energy generation zones with different frequencies.

Aware of the limitations in the search for published articles on the suggested keywords, we consider that the subject initially suggested for research needs some adjustment. According to the review, many issues such as "new submodule configurations of multilevel modular converters", "analysis of the optimal power flow in the buses of the multiterminal grid", "converter failure prediction scheme", "data-driven fault diagnosis (DDFD)" and "inverse fault detection and diagnosis (IFDD)" are still open, which will influence useful in adjusting the further topics.

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