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Evaluative Methodologies for Resilience and Reliability in Multi-Terminal HVDC Transmission Systems

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Modern energy systems, typified by intricate configurations and dependencies, necessitate advanced analytical methodologies for resilience and reliability assessment. This research delves into two distinct case studies that scrutinize these parameters within varied contexts. The first study methodically ranks the critical components of a transmission system, employing Dynamic Fault Tree (DFT) analysis. This approach elucidates components' significance based on multiple importance measures, thus facilitating pre-emptive maintenance and risk management strategies. The second study focuses on the resilience of multiterminal HVDC-VSC transmission frameworks, especially tailored for expansive offshore wind farms. Utilizing Markov Automata, the study simulates various operational states, from full functionality to detachment scenarios, rendering insights into system behaviors over infinite durations and specific time-bound intervals. These probabilistic and mean time evaluations are pivotal for strategic planning and resource allocation, especially in the face of disruptions. Collectively, the two case studies underscore the importance and versatility of employing advanced analytical tools to address the multifaceted challenges of modern transmission systems, fostering improved reliability and resilience in our energy infrastructure.

Keywords: Reliability, Dynamic fault tree, Markov automata.

1. Introduction

Reliability engineering relies heavily on risk analysis, which is essential for ensuring that medical devices, smart grids, and online services meet dependability standards. Offshore wind projects in Europe, including substantial French installations by 2030, are projected to expand rapidly in number, scale, and distance from shore. The European Wind Energy Association (EWEA) estimates that offshore wind capacity could increase from 480 MW to 18 GW by 2030 (RWE 2023).

Given the limitations of traditional HVAC for distant offshore installations, High Voltage Direct Current (HVDC) systems have emerged as the preferred solution, particularly using Voltage Source Converter (VSC) technology due to its flexibility and compatibility with "weak" AC grids. Multiterminal HVDC systems, introduced in 1963 (Lamm, Uhlmann, and Danfors 1963), have since evolved to include parallel and series configurations (Reeve and Arrillaga 1965), with recent studies exploring optimized control strategies and reliability models for HVDC grids (Lu and Ooi 2003). Several studies have focused on reliability assessment methodologies for HVDC systems, such as the development of reliability models and indices, sensitivity analyses, and contingency analyses for HVDC-VSC systems (Billinton and Sachdev 1968; Zadkhast et al. 2010; Li et al. 2015). These methods account for factors like load levels, component failures, and wind variability, using techniques like Monte Carlo simulation, Capacity Outage Probability Table (COPT), and Frequency and Duration models (Zheng et al. 2019; MacIver, Bell, and Nedić 2015; Guo, Gao, and Wu 2015; Hu, Xie, and Tai 2018, 2017).

Despite these advancements, existing methodologies have limitations that warrant further investigation. For instance, Monte

Carlo simulations and Markov models provide robust probabilistic assessments but often require extensive computational resources and do not fully capture interdependent failure mechanisms. While dynamic fault tree (DFT) analysis enhances traditional fault tree analysis (FTA) by incorporating time-dependent failure behaviors, its applicability to complex multiterminal HVDC systems remains an area requiring further refinement. Additionally, existing studies tend to focus on static reliability indices, leaving gaps in understanding the resilience of HVDC networks under dynamic operational conditions.

Recent developments, such as integrating artificial intelligence (AI) and AI-driven predictive maintenance models have demonstrated effectiveness in identifying early failure indicators, yet their application to HVDC-VSC systems remains underexplored (Hu, Xie, and Tai 2018). Furthermore, resilience-based design approaches, incorporating stress-testing methodologies and system adaptation mechanisms, are gaining traction but require standardized frameworks for HVDC grid applications.

Given these gaps, this paper seeks to enhance current reliability and resilience assessment methods by integrating dynamic fault tree analysis with Markov automata modeling. This approach aims to provide a more comprehensive evaluation framework that captures both probabilistic reliability metrics and resilience indicators. By addressing the existing shortcomings in HVDC system assessments, this study contributes to improving preventive maintenance strategies, optimizing resource allocation, and ensuring the long-term sustainability of offshore wind transmission networks.

The paper is organized as follows: Section 2 covers the methods used, including the reliability analysis procedure. Sections 3 and 4 present two case studies and their results, with numerical studies and sensitivity analyses. Finally, Section 5 provides conclusions, with final remarks summarized in Section 6.

2. Method

2.1. *Dynamic Fault Tree Analysis*

Throughout history, numerous techniques have been introduced to aid in the safety and reliability assessment of systems. Of these, Fault Tree Analysis (FTA) stands out as one of the earliest and most esteemed methods, extensively employed for the safety and reliability evaluation of various systems. They depict a Boolean function, showcasing how the breakdown of the whole system is contingent on the malfunction of its fundamental components. Dynamic Fault Trees (DFT) enhance traditional fault trees by facilitating the depiction of intricate behaviors and interactions of system components (Rauzy 2022). Due to their comprehensive nature while remaining user-friendly, DFTs are rapidly gaining traction and favorability among reliability engineers. The probability of a top event in a Dynamic Fault Tree (DFT) can be calculated using the following equation (Cwikowski et al., 2016) :

$$\mathrm{P}(TopEvent) = 1 - \prod_{i=1}^{n}(1 - Gate_i)^{-1} \quad (1)$$

Where $P(Gate_i)$ is the probability of the ith gate in the DFT being successful (i.e. not failing). The probability of a component failure in a DFT can be calculated using the following equation:

$$P(Component\ Failure) = \sum_{j=1}^{m} P\big(FailureMode_j\big) \times P(Mode_j \rightarrow Component)) \quad (2)$$

where $P\big(FailureMode_j\big)$ is the probability of failure mode j occurring, and $P\big(Mode_j \rightarrow Component\big)$ is the probability that failure mode j will cause a failure of the component.

Dynamic Fault Trees (DFTs) (Contreras-Jimenez et al., 2018; Hua, Li, and Wu, 2019; Tuinema et al., 2019) stand out as a prevalent method in analyzing components.

DFTs can handle: (1) the administration and positioning of backup components, (2) understanding functional dependencies, and (3) mapping out the sequence of failures. These trees facilitate modeling the interconnectedness of system components across time and computing the likelihood of various breakdown scenarios.

2.2. *Markov Automata*

The Markov automata are mathematical models that combine the probabilistic transitions of Markov chains with the nondeterministic choices of traditional automata. This hybrid nature allows Markov automata to capture both stochastic and nondeterministic behaviors, making them particularly suitable for analyzing complex systems where decisions might be randomized or where several possible actions can be taken in certain states without a predetermined probability. Examples of their applications include performance and reliability analysis of systems with both probabilistic and nondeterministic events, such as distributed systems or computer networks. As a modeling tool, Markov automata serve as a bridge between purely probabilistic models like Markov chains and purely nondeterministic models like automata, providing a richer and more expressive framework for system analysis.

Dynamic Fault Tree (DFT) incorporates interdependencies among events and component states, necessitating a state space approach to identify every potential system state and their probabilistic transitions. This process leads to the derivation of the system's Continuous Time Markov Chain (CTMC) (Hu, Xie, and Tai 2018).

The duration spent in a state s is characterized by a negative exponential distribution, guided by the exit rate $\lambda(s, s')$ for s' being a reachable state from s. States have associated labels, which help pinpoint specific states. For example, an atomic proposition like A fail can be assigned to all the states where the DFT component A is deemed unsuccessful.

2.3. *SAFEST Tools*

The SAFEST tool (DGB Technologies 2024) offers a comprehensive suite for modeling and analyzing fault trees, accommodating both static fault trees (SFT) and dynamic fault trees (DFT). At its core, SAFEST leverages the Storm-dft library from the renowned Storm model checker, ensuring a high level of accuracy in probabilistic reliability analysis. Unlike traditional tools that rely solely on static analysis, SAFEST integrates state-space exploration methods, allowing it to model complex failure dependencies and system interactions effectively.

The SAFEST tool offers capabilities for modeling and analyzing fault trees, accommodating both static fault trees (SFT) and dynamic fault trees (DFT). At its core, SAFEST leverages the Storm-dft library from the renowned Storm model checker ((VOLK et al. 2024 and Zheng, Z et al. 2019). SAFEST facilitates analysis concerning critical quantitative dependability metrics, including system reliability, mean-time-to-failure, and component criticality. It grants users the latitude to craft bespoke measures, even allowing intricate specifications using mathematical logics. SAFEST has the capability to automatically refine a DFT to enhance its understandability and optimize it for efficient analysis, all while maintaining its original behavior (Cwikowski et al. 2016).

The tool harnesses diverse analytical strategies. Static Fault Trees (SFTs) are optimally analysed using binary decision diagrams (BDD). Through evaluations, the BDD-focused approach has showcased performance on par with established tools for SFT assessment (Van Hertem, D., and M. Ghandhari 2010). Dynamic Fault Trees (DFTs), on the other hand, undergo analysis via state-centric methods, which involve translation into a Markov model (Cwikowski et al. 2016). By leveraging DFT's irrelevant failures and symmetries, our translation process results in more concise models. Following this, the state-of-the-art probabilistic model checker, Storm, conducts an analysis, ensuring precise results efficiently.

2.4. *Data Collection and Model Validation*

A crucial aspect of reliability assessment is the quality and relevance of input data. In this study, component failure rates, maintenance schedules, and operational profiles were derived from a combination of manufacturer specifications, historical failure databases, and reliability benchmarks established by industry standards (Xie et al. 2016). The data sources include operational records from HVDC transmission projects, published literature on high-voltage equipment failures, and empirical studies on offshore grid reliability.

To validate the model, the failure probabilities and system response times generated by SAFEST were compared against real-world failure statistics from existing HVDC-VSC systems. Sensitivity analyses were conducted to assess the robustness of the model across varying operational conditions, ensuring that the results remain consistent with observed reliability patterns.

One of the primary challenges in reliability modeling is ensuring that the methodology scales effectively for larger and more complex systems. The SAFEST tool addresses this challenge by implementing advanced state-space reduction techniques and model abstraction strategies. These enhancements enable its application to multiterminal HVDC networks with a large number of components and interconnections, mitigating the exponential growth in computational complexity.

3. Case Study 1- Reliability Analysis of a Bipolar 12-pulse Ultra-high Voltage dc Transmission System

The study is made on a previously reported project deployed in China (Xie et al. 2016). This study offers an in-depth examination of the reliability and resilience of bipolar multiterminal HVDC offshore transmission systems. To assess system reliability, dynamic fault tree analysis is implemented, taking into account a myriad of failure modes and the interplay between components. To gauge the system's resilience across diverse operational states, Markov automata are utilized, with a particular focus on a system comprising four offshore parks configured in a ring topology.

4.1. *General Overview*

To convert electricity from alternating current (AC) to direct current (DC) and vice versa, while adhering to power system safety and quality standards, an HVDC converter station consists of key components such as converter valves (CVs), CTs, SRs, AC and DC switchgears, AC filters, reactive power compensators, control and protection systems, and telecommunication systems, among others (Reeve and Arrillaga, 1965). Most HVDC transmission system converter stations, whether two-terminal, multi-terminal, or back-to-back setups, incorporate these similar components.

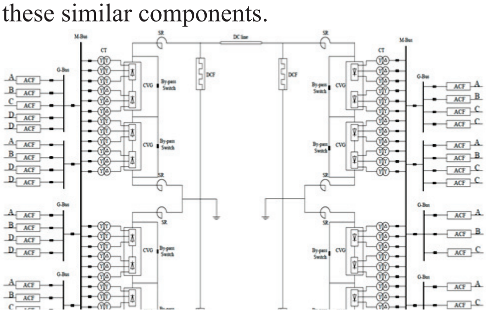

Fig. 1 standard ±800kV ultra HVDC transmission system (Xie et al. 2016).

4.2. *Specifics of Ultra HVDC Transmission Systems*

Typically, six-pulse or 12-pulse CV groups are integrated into actual engineering projects (Reeve 1980). For instance, a ±500kV HVDC transmission system, seen in Chinese projects like Ge-Nan, Long-Zheng, and Gui-Guang, will have a single 12-pulse CV group in each pole. However, a ±800kV ultra HVDC system, like Yun-Guang, Nuozhadu, and Xiang-Shang projects, houses two 12-pulse CV groups in each pole (Van Hertem, D., and M. Ghandhari 2010). A standard ±800kV ultra HVDC transmission system, as illustrated in Figure 2, is a dual-terminal, bipolar system with two serial 12-pulse CV groups in each pole. Major elements of this system include:

- CV Group (CVG): Each pole contains two serial 12-pulse CVGs, with a rated DC voltage of 400 kV for each CVG.
- AC Filter (ACF): The converter/inverter stations house diverse ACFs, grouped into four categories. These are connected to group buses (G-Bus) that are then linked to main AC buses (M-Bus) using breakers.
- CT: Every pole station possesses 12 single-phase double-winding CTs. These include 3 Y/Y and 3 Y/△ CTs at both high and low voltage ends. There are also 4 spare CTs at each station, mirroring the ones mentioned.
- SR: Each station in a pole has two smoothing reactors. One connects to the pole bus and the other to the neutral bus. Thus, each station houses four SRs and a spare SR.

To mitigate the effects of CT or CVG failures, a CVG set (representing 1/4 of the total rated capacity) can be isolated using by-pass switches.

The system under examination is a bipolar HVDC transmission setup with two distinct poles. If one pole fails, the second operates independently. Each pole consists of two stations, onshore and offshore. Within the offshore station, two CVG groups are present: CVG Group One and CVG Group Two. Each group is linked to six transformers – three Y/Y transformers and three Y/Δ transformers. As summarized in Table. 1, the total system comprises 48 active transformers, 16 spare transformers, and 8 CVG groups. Notably, if a CVG group malfunctions, the system is designed to operate independently, ensuring uninterrupted transmission.

Table I Components Breakdown

Component	
Transformers:	48 active, 16 spares.
CVG groups:	8 (with hot redundancy).
AC filters:	32.
Smoothing reactors:	8 active, 4 redundant.
Buses:	8 group buses, 2 main buses.
Circuit Breakers:	86.

4.3.*Results*

The case study provides a reliability analysis of a bipolar 12-pulse ultra-high voltage DC transmission system used in China. The methodology employed dynamic fault tree analysis and Markov automata to gauge system reliability and resilience. The poles play a crucial role in ensuring transmission continuity even if one pole fails.

Additionally, the system features components to ensure redundancy and reliability, such as spare transformers, CVG groups with hot redundancy, and various AC filters.

4.3.1.DFT Analysis

The SAFEST tool is used to generate the dynamic fault trees. Figure 3 illustrates the total fault tree generated by SAFEST tool for this study. The analysis was supported by a dynamic fault tree (DFT) consisting of 252 basic events and 157 gates, of which 64 are dynamic gates(56 SPARE, 8 PAND), 252 basic events.

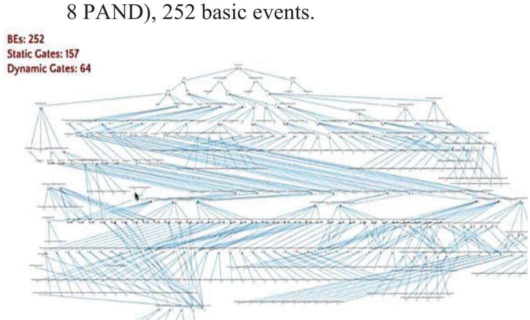

Fig.2 the total fault tree generated by SAFEST tool for this study

4.3.2.Reliability Metrics & Critical Components Ranking

Table 2 presents the reliability results after a one-year study period. The system exhibited a reliability of 0.886, with an average failure probability per day of 0.00028. These values indicate that the system maintains a high level of reliability over time, though minor failures occur intermittently. The system unreliability of 0.104209 suggests that while the HVDC transmission system is robust, preventive maintenance strategies may further enhance its performance.

Table. 2 Reliability results

Reliability Measures After 1 year	
Ave. Failure probability per day	0.0002855
System Unreliability	0.104209

To identify the most critical components affecting system reliability, Table 3 ranks key subsystems using multiple importance measures, including Birnbaum Index (BI), Criticality Importance (CI), Risk Achievement Worth (RAW), Risk Reduction Worth (RRW), and Diagnostics Importance (DI). The results highlight that offshore and onshore AC filters, along with Pole ½, have the highest influence on overall system reliability. Specifically, offshore AC filters have a BI of 0.907×10^{-2}, a RAW value of 9.603×10^{-1}, and a CI of 0.108×10^{-3}, making them the most critical components for system operation. This suggests that failures in AC filters have a significant impact on the overall system reliability and must be prioritized for maintenance.

Table 3. The critical ranking and risk index for main subsystems

Critical Components Ranking after 1 year based on Importance Measures					
Comp.	BI	CI	RAW	RRW	DI
Offshore AC Filters	(0.907)-2	(0.108)-3	(9.603)-1	(1.122)-3	(0.119)-3
Onshore AC Filters	(0.909)-1	(0.125)-2	(9.603)-1	(1.143)-2	(0.137)-2
Pole ½	(0.254)-3	(0.646)-1	(9.603)-1	(2.825)-1	(0.739)-1
Offshore Stn. ½	(0.194)-4	(0.068)-4	(9.603)-1	(1.074)-4	(0.103)-4
Off/Onshore SR ½	(0.094)-6	(9.105)-6	(9.603)-1	(1.000)-6	(0.0003)-6
Rectifier/Inverter ½	(0.190)-5	(0.028)-5	(9.603)-1	(1.029)-5	(0.043)-5

Furthermore, the results show that the rectifier/inverter and smoothing reactors (SR) exhibit lower criticality, with DI values of 0.043 $\times$ 10^{-5} and 0.0003 $\times$ 10^{-6}, respectively. This implies that while these components contribute to system performance, their failure likelihood and impact are relatively lower compared to AC filters and poles. However, their presence in the reliability ranking emphasizes the necessity of continued monitoring and redundancy planning.

5. Case Study 2- Resilience Analysis of Multi-Terminal HVDC Transmission System

The second study delves into the topologies of multiterminal HVDC-VSC transmission frameworks tailored for expansive offshore wind farms as reported by (Xie et. al. 2015). In Fig. 4, the General Ring Topology (GRT) of a multiterminal HVDC system is depicted. This topology entails an arrangement where lines are interconnected, forming a ring that connects all nodes. Consequently, specific lines might be required to transmit the system's entire power when the ring opens. The GRT can operate in two modes: closed-loop, where all circuit breakers and isolators remain closed during standard procedures, and open-loop, where a breaker or isolator within the ring remains open. When confronted with a converter or DC grid malfunction, the immediate response is to open the two circuit breakers linked to the malfunction, thus positioning the system in an open-ring configuration. Once the fault current diminishes to zero, isolators can then segregate the faulted zone, permitting the relevant circuit breakers to be reconnected.

5.1.*General Overview*

To analyze the system's resilience, we consider a scenario where there's a disruption in the cable connection:

1. In its standard state, the system forms a closed ring, as illustrated in Fig. 4(a).
2. At time t0, a malfunction occurs in L12, as seen in Fig. 4(b).
3. By time t1, the ring opens, leading to the disconnection of WF1, depicted in Fig. 4(c).
4. At the t2 mark, when L12 carries no current, IS12 disconnects, as illustrated in Fig. 4(d).
5. By time t3, CB14 re-establishes a connection with WF1, as displayed in Fig. 4(e).

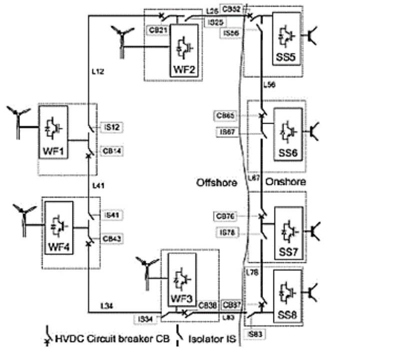

Figure 3 General ring topology (Gomis-Bellmunt et. al. 2010)

Following these events, L38 is burdened with the power outputs of PWF1, PWF3, and PWF4. The most challenging scenario would be if faults were to occur in either L38 or L25. Such a situation would necessitate a single circuit handling the system's entire power, denoted as WWFi. The modes of operation which are examined during the analyze are summarized in Table 3.

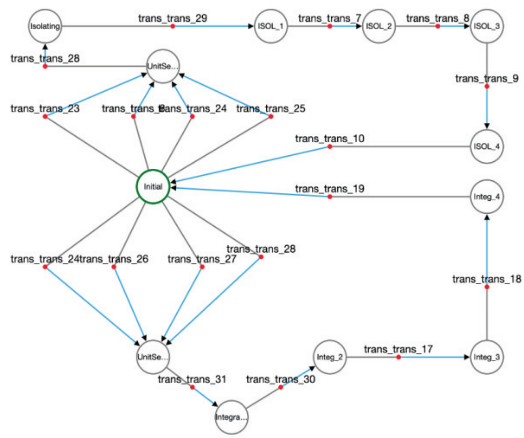

Fig. 4 Typical Markov models constructed for the study

5.2.*Results*

The HVDC transmission system analyzed connects four offshore wind turbines to onshore substations using a ring topology. In the event of a failure at any onshore station or cable, energy is redirected to the next available substation. The analysis, based on a Markov model, examined various system states, including fully operational, degraded, and scenarios where certain substations are detached. A significant finding was the system's average energy loss of 1.52 MW per year over an infinite duration, calculated using advanced simulation tools such as SAFEST and Storm Markov automata (Figure 5). This analysis provided a comprehensive assessment of system resilience, factoring in potential fault scenarios and recovery processes. Table 4 presents key metrics that offer a detailed view of the system's performance.

Notably, the system remains in a fully operational state for 89% of the time, reflecting high resilience. However, there is a 55.6% probability of reaching a degraded state within a year, although the chance of entering a fifty-percent degraded state is minimal at 0.128%. These figures suggest robust operation under typical conditions, with a low likelihood of significant disruptions.

Table II. The reliability metrics and results

Metric	Results
Percentage time spent in Fully Operational State if system runs for an infinite time	0.89
Percentage time spent in Degraded State if system runs for an infinite time	0.0022
Percentage time spent in Fifty Percent Degraded State if system runs for an infinite time	3.01e-06
Probability to reach to a Degraded State within time 1 year	0.556
Probability to reach to a Fifty Percent Degraded State within time bound 1 year	0.00128
Average Energy loss per unit time if system runs for an infinite time	1.52 MW
Mean time to attach wind turbine 1 to a nearby station once its attached sub-system fails – Recovery Time	4 days
Mean time to repair (MTTR) sub-system 1	69 days

- Degraded: Energy of at least one of the turbines is not injected in the main grid. Detached Substation: At least one sub-station is detached but energy of all turbines is injected in the main grid. Fifty Percent Degraded: Energy of two turbines is not injected in the main grid. Fully Operational: All components are working properly. Wind Turbine 1 Detached: Energy of wind turbine 1 is wasting as it is detached from the system.

The resilience evaluation also emphasizes recovery capabilities. The mean time to reattach wind turbine 1 to a nearby station after its sub-system fails is 4 days, indicating efficient restoration of operations. In cases of complex repairs, the Mean Time to Repair (MTTR) for sub-system 1 is 69 days, which, although extensive, ensures thorough maintenance in such intricate systems.

6. Discussion

The two case studies highlight the complexity and critical importance of assessing resilience in modern energy systems, particularly in HVDC transmission networks. The SAFEST tool, leveraging Dynamic Fault Tree (DFT) and Markov Automata, proved instrumental in evaluating system reliability and response under different configurations and scenarios.

The DFT approach provides a structured method for analyzing reliability and calculating failure probabilities across complex engineering systems, capturing the sequential and dynamic nature of failures. For example, in Case Study 1, the DFT was used to rank components based on several importance metrics, from the Birnbaum Index to Diagnostics Importance. This ranking helps prioritize components that require preemptive maintenance to maintain system reliability. In contrast, Markov Automata focus on state transitions and temporal behavior, essential for systems with varying operational states like HVDC transmission. This tool allowed for calculating probabilities, dwell times, and temporal metrics across states ranging from "Fully Operational" to "Wind Turbine 1 Detached." The ability to analyze the system's behavior over extended durations and specific intervals provided valuable insights into resilience and recovery performance, crucial for strategic planning and resource management.

Together, the case studies underscore SAFEST's adaptability and depth, handling both DFT and Markov Automata analyses to meet different system evaluation needs. Whether ranking components for proactive measures in critical infrastructure or assessing resilience in HVDC systems with dynamic environments, SAFEST emerges as a comprehensive and reliable tool for holistic energy system assessments.

7. Future works

The findings from the dual-case studies using the SAFEST tool open up several promising research directions. Integrating SAFEST with machine learning could enable predictive capabilities, using real-time data to anticipate component failures and improve preventive maintenance. Expanding the study to simulate long-term scenarios would allow for insights into aging, technological progress, and environmental changes, while exploring different geographical contexts could address unique regional challenges. These directions aim to deepen our understanding of energy system resilience and reliability in a dynamic world.

References

Akmali M, R. Plana, and F. Sher. (2022). Evolving PSA Methodologies: Towards Dynamic Reliability in SMR Passive Systems. IAEA Conference

Billinton, R., & Sachdev, M. S. (1968). *Direct current transmission system reliability evaluation*. Transactions of the Canadian Electrical Association, 7(3).

Boussier, H., S. Delpech, V. Ghetta, D. Heuer, D-E. Holcomb, V. Ignatiev, E. Merle-Lucotte, and J. Serp. "The molten salt reactor (MSR) in Genration IV: overview ans perspectives." In 2nd Generation IV International Forum (GIF) Symposium, pp. 95-107. 2012.

Castro, L., Acha, M., & Rodriguez-Rodriguez, J. (2018). *Efficient method for the real-time contingency analysis of meshed HVDC power grids fed by VSC stations. IET Generation*, Transmission & Distribution, 12(13), 3158-66.

Contreras-Jimenez, J., Rivas-Davalos, F., et al. (2018). *Multi-state system reliability analysis of HVDC transmission systems using matrix-based system reliability method*. International Journal of Electrical Power & Energy Systems, 100, 265-78.

Cwikowski, O., Chang, B., et al. (2016). *Fault current testing envelopes for VSC-HVDC circuit breakers*. IET Generation, Transmission & Distribution, 10(6), 1393-400.

Gouda, O., Ibrahim, D., & Soliman, A. (2019). *Parameters affecting the arcing time of HVDC circuit breakers using black-box arc model*. IET Generation, Transmission & Distribution, 13(4), 461-67.

Gomis-Bellmunt Oriol, Jun Liang, Janaka Ekanayake, Rosemary King, Nicholas Jenkins, *Topologies of multiterminal HVDC-VSC transmission for large offshore wind farms*, Electric Power Systems Research, Volume 81, Issue 2, 2011.

Hu, B., Xie, K., & Tai, H. (2018). *Reliability evaluation and weak component identification of a Â±500 kV HVDC transmission system with double-circuit lines on the same tower*. IEEE Transactions on Power Delivery, 33(4), 1716-26.

Hua, Y., Li, S., & Wu, Z. (2019). *Short-term reliability assessment of UHVDC systems based on state aggregation with SMP*. IEEE Transactions on Reliability, 68(3), 790-99.

Lamm, U., Uhlmann, E., & Danfors, P. (1963). *Some aspects of tapping HVDC transmission systems*. Direct Current, 8(5), 124-29.

Li, C., Hu, X., Guo, J., & Liang, J. (2015). *The DC grid reliability and cost evaluation with Zhoushan five-terminal HVDC case study*. 50th International Universities Power Engineering Conference (UPEC).

MacIver, C., Bell, K., & NediÄ, D. (2015). *A reliability evaluation of offshore HVDC grid configuration options*. IEEE Transactions on Power Delivery, 31(2), 810-19.

RWE. (2023, July 5). *France passes renewable energy acceleration bill*. Retrieved from https://www.en-former.com/en/france-passes-renewable-energy-acceleration-bil.

Reeve, J. (1980). *Multiterminal HVDC power systems*. IEEE Transactions on Power Apparatus and Systems, PAS 99(2), 729-37.

Reeve, J., & Arrillaga, J. (1965*). Series connection of converter stations in an HVDC transmission system*. Direct Current, 10(2), 72-78.

Rauzy, A. (2022). Model-based reliability engineering: An introduction from first principles.

DGB Technologies (2024). SAFEST Presentation for Nuclear Applications. Available at https://www.safest.dgbtek.com/

Van Hertem, D., & Ghandhari, M. (2010). *Multi-terminal VSC HVDC for the European Supergrid: Obstacles*. Renewable and Sustainable Energy Reviews, 14, 3156-63.

VOLK, M., SHER, F., KATOEN, J.-P., AND STOELINGA, M. 2024. *SAFEST*: *Fault Tree Analysis Via Probabilistic Model Checking*. Annual Reliability and Maintainability Symposium (RAMS), Albuquerque, NM, USA, pp. 1-7.

Xie. K, B. Hu and C. Singh, *Reliability Evaluation of Double 12-Pulse Ultra HVDC Transmission Systems,* in IEEE Transactions on Power Delivery, vol. 31, no. 1, pp. 210-218, Feb. 2016

Yousefi, H., Mirzaie, M., & Aminifar, F. (2016). *Reliability assessment of HV substations equipped with fault current limiter considering changes of failure rate of components*. IET Generation, Transmission & Distribution, 10(7), 1504-09.

Zadkhast, S., Fotuhi-Firuzabad, M., Aminifar, F., & Billinton, R. (2010). Reliability evaluation of an HVDC transmission system tapped by a VSC station. IEEE Transactions on Power Delivery, 25(3), 1962-70.

Zheng, Z., Wang, Y., et al. (2019). *Reliability evaluation model of Zhangbei multi-terminal HVDC transmission system*. IEEE International Conference on Energy Internet (ICEI).