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A Comprehensive Review of Intelligent Fault Diagnosis and Resilient Fault-Tolerant Control in the Design of Modern Modular Multilevel Converters

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ABSTRACT

The modular multilevel converter (MMC) stands out as a potential power converter technology that is widely used for medium to high-voltage converters, offering the benefits of modularity, scalability, and impressive harmonic performance. These benefits led to a widespread adoption in applications like high-voltage direct current (HVDC), renewable energy systems, battery energy storage systems, and industrial drives. The MMC complex design is highly susceptible to faults, including open and short circuit faults in the SM, and arm voltage imbalances. The reliable and consistent operation of MMC under fault conditions is critical for operating in high-voltage applications. This review paper presents an updated review of the MMC system fault mechanism, intelligent fault diagnosis technique, and resilient fault-tolerant control strategies. This review paper systematically categorizes the various faults that occur in the MMC and provides an analysis of their impact on the converter's performance. The recent advancements in model-based and data-driven fault diagnosis techniques are critically analyzed, which include recent signal processing techniques and AI-based methods, such as the integration of Physics-Informed Neural Networks (PINNs) for MMC-based applications. Furthermore, the advanced FTC-based method and control strategies, including active, passive, and hybrid methods, are discussed in the context of MMC application. The paper also outlines the future research directions, which include digital twin-based monitoring, scalable data-driven control, and real-time diagnosis for the next-generation resilient MMC systems.

1 | Introduction

With the unprecedented rise in distributed energy resources (DERs) within the electric grid system, the need for an efficient power converter is also becoming increasingly essential for maintaining system stability. The MMC was first proposed in a German Patent by Marquardt in 2001, which illustrated its multifaceted advantages in the electric system. The converter is significantly regarded for its modularity, scalability, low switching frequency, and efficient harmonic performance. This converter is widely adopted in various electrical dimensions, including high-voltage DC systems, motor drives, battery energy storage systems (BESS), and static compensators like STATCOM [1–3].

Although MMCs have these benefits, they also have a lot of shortcomings that can make the power system unreliable. These

Abbreviations: AFTCS, active fault-tolerant control system; AI, artificial intelligence; FTC, fault-tolerant control; HFTCS, hybrid fault-tolerant control system; HVDC, high-voltage direct current; MMC, modular multilevel converter; PFTCS, passive fault-tolerant control system; SM, submodule.

problems include submodule failures, variations in the voltage across capacitors, and issues with arm voltage. These weaknesses indicate that fault-tolerant control (FTC) and strong fault detection methods are needed for real-world deployments to be reliable and resilient. Researchers have proposed numerous methodologies over the past decade, including model-based approaches such as Kalman filtering, data-driven techniques utilizing machine learning, and hybrid systems that combine the best aspects of both approaches. The challenge is that there is still a lack of connection between how effectively the methods work in theory and how equipped they are for practical application [4].

The existing review articles discuss the fault-tolerant control techniques of MMC in applications like distributed energy resources or general converter-level reliability. These review articles discuss the FTC techniques in the broader context of MMC application in solar energy or narrowly on converter design and modulation without a specific FDD and FTC strategies for MMC. There are very limited studies that provide a comprehensive review in which they try to unify diagnostic techniques, control strategies, and deployment feasibility within one framework. This gap highlights the need for a comprehensive review that connects theoretical developments with real-world applications [5].

This review paper distinguishes itself from the previous studies by providing a comprehensive assessment of FTC and FDD techniques in MMC. It provides a systematic comparison of the merits and shortcomings of model-based, data-driven, and hybrid models in terms of their diagnostic accuracy, computational complexity, implementation cost, and suitability for real-time applications. This paper provides a comprehensive review of MMC application in HVDC transmission, renewable integration, and power system reliability, which requires a robust FTC system [6].

Moreover, this review paper identifies key unresolved issues, such as the limited scalability of AI-based diagnostic problems, the robustness of FTC under dynamic grid conditions, and the cost associated with a hybrid configuration. It also suggests emerging directions, in particular AI-based predictive control, hardware in the loop (HIL) validations, and cost-effective FTC strategies. By providing a current, systematic, and application-focused synthesis of FDD and FTC strategies, this review paper lays a solid foundation for future improvements in converter reliability and resilient power systems.

The review article uses a qualitative research technique and conducts a full literature review of the research paper using databases such as IEEE Xplore, ScienceDirect, and Google Scholar. The search string was used to find papers on fault detection and FTC in MMCs. The emphasis was on the use of MMC in HVDC transmission systems, renewable integration, and power system reliability. To capture the most current improvement in MMC, articles from the previous 11 years are reviewed to offer a complete examination of FTC schemes for making the MMC a more resilient and reliable electrical component. In the start, more than 400 papers were retrieved, which were gradually refined on the basis of relevancy, novelty, and specific scope and contribution to our concern area. As a result, this paper provides an updated and systematic summary of the most recent research in FTC and diagnosis for MMC.

TABLE 1 | Literature search process for this review.

Step	Details
Databases	IEEE Xplore, ScienceDirect, Google Scholar
Keywords	MMC, fault-tolerant control, diagnosis, active/hybrid FTC
Timeframe	2015–2026
Inclusion	Peer-reviewed MMC FTC/diagnosis studies: theory, case studies, HIL
Exclusion	Non-MMC FTC; no empirical validation; only classical control; pre-2015
Initial results	400 articles
Final selection	Key MMC fault detection/FTC works in HVDC, renewables, and reliability.

For inclusion, the research had to be published in peer-reviewed journals and be directly related to FTC methods in MMCs. To maintain transparency between the academic world and the real world, we place greater emphasis on articles that discuss things straight between the academic world and the real world. We place greater importance on articles that talk about theoretical ideas, case studies, and experimental results. Nonetheless, studies that lacked empirical validity, employed only conventional control methods, or were irrelevant to FTC in MMCs were excluded.

The first phase of the literature synthesis involved examining new FTC strategies, assessing the original authors' evaluations of their effectiveness, and utilizing simulation or experimental research to support their findings. A thorough examination of fault diagnostic and FTC schemes in MMCs was developed from the qualitative analysis of the results. Table 1 shows a summary of the literature screening and classification method used in this review. Similarly, Figure 1 shows the papers from different years.

The rest of this paper is organized as follows: Section II describes different types of faults in the MMC system, and Section III describes fault diagnosis and control techniques, including model-based, data-driven, and hybrid approaches. Section IV explores fault-tolerant control strategies that ensure continued system operation under faulty conditions. Furthermore, Section V provides a detailed comparison of the literature review with other papers. Finally, section VI provides the future research directions and section VII provides the conclusion of the paper.

2 | Types of Faults in MMC

There are multiple advantages of MMC, including the continuous flow of current in the arms regardless of high frequency and di/dt, a significant reduction in power losses and the need for filters, and a simpler high-voltage converter compared to other power electronics converters. The MMC consists of many SMs that are used to enhance the capacity and reliability of the converter. The SM consists of a half-bridge topology with a capacitor or a full-bridge topology with a capacitor. The following are the workings of both converters:

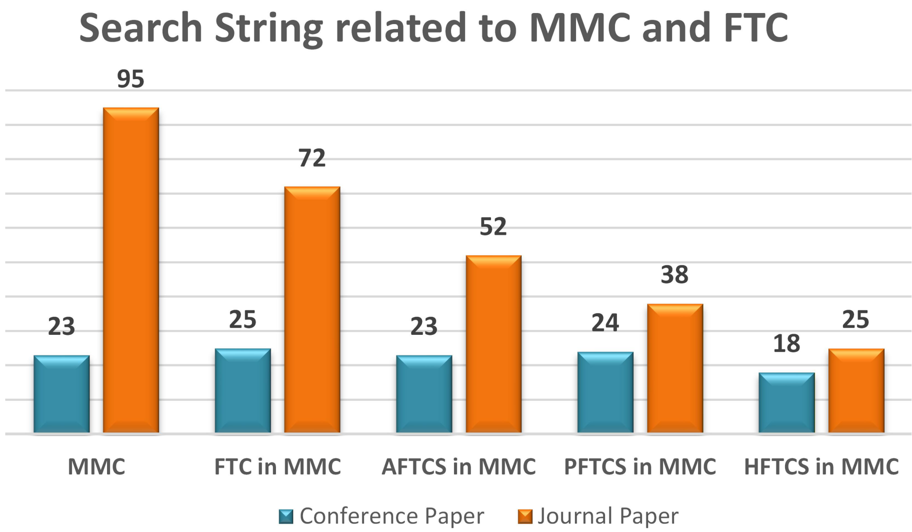

FIGURE 1 | Breakdown of reviewed articles from 2015 to 2026.

Figure 2 illustrates the basic schematic of the MMC converter. As MMC comprises multiple semiconductor switches, the reliability of the converter in high-power applications can be significantly reduced. As more SMs are integrated into the architecture of MMC, the rate of failure also starts to increase. The faults and fluctuations, like open circuit fault (OC) and short circuit fault (SC), can result in the breakdown of the converter. If the system lacks an efficient FTC system, it results in a disastrous system failure. Therefore, it is of paramount importance to classify these faults and apply robust and innovative FTC to enhance the system reliability and efficiency [7–9]. The common electrical faults are classified into four categories, which are given below.

2.1 | Open-Circuit Switching Fault

During the operation of the MMC, open circuit faults occur due to multiple reasons: band wire lift-off, soldering cracking, gate-driver malfunction, and electrical disconnection. This fault results in the increased capacitor voltage in the faulty SMs, and it will result in cascading damage to the MMC, as there is no discharge path in the circuit [10, 11]. This kind of fault results in distorted voltage and current waveforms that exacerbate the degradation of reliability. For instance, if a medium power motor is running, a short-circuit fault produces a distorted power, which results in the degradation and deterioration of motor health [12].

2.2 | Short-Circuit Switching Fault

The short-circuit faults are highly damaging for Modular Multi-level Converter systems, and they must be addressed quickly for the smooth operation of the system. There are multiple causes behind the occurrence of short-circuit faults, which include parasitic turn-on, malfunction of gate drivers, electrical stress on the equipment, and thermal issues. These short-circuit currents are highly detrimental to the electrical switches, and they provide a very short time to overcome such faults. The advanced devices need a quick detection mechanism to reduce thermal capacity owing to their small size, like wide bandgap devices [13, 14]. Therefore, the detection circuit is directly integrated into the gate driver circuits for a quick response to the faults. For instance, a widely adopted method is desaturation protection, where the on-state voltage is checked in real-time, and when it increases from a certain threshold, it is assumed that a short-circuit has occurred. The gate-driver circuit turns off the switch in case a short-circuit fault is detected, but it results in moving toward an open-circuit fault afterward [15–17].

2.3 | Short-Circuit Fault on DC Side

The Half-Bridge Modular MMC, like other Voltage Source Converters (VSCs), is susceptible to a short-circuit problem on the DC side. The discharge of the SM capacitor causes the fault current to travel via the arms and the DC bus. As soon as the fault current is detected, the semiconductor switches are turned off, and the converter goes into blocking mode. In blocking mode, the AC source continues to provide DC-fault through the anti-parallel diodes of the half-bridge topology used in SMs [18, 19]. As a result, a considerable quantity of fault current flows across the half-bridge, potentially destroying the semiconductor switches. Similarly, excessive back EMF in motor drives can result in a huge fault current from a DC short-circuit, degrading both the converter and the motor. This DC short-circuit current might severely damage the converter component and disrupt the entire system [20, 21].

2.4 | Single Line-to-Ground Fault on AC Side

In a point-to-point MMC-HVDC transmission system, an SLG fault could occur in any of the AC lines leading to ground. SLG faults can occur in three locations: the main side of a $Y - \Delta$ transformer, the secondary side of the same system, or a system without a transformer. An SLG fault between the MMC and the transformer could result from insulation failures in the transformer wall bushings. An SLG failure may result in an abrupt decline in MMC power and AC voltage sags [22–24].

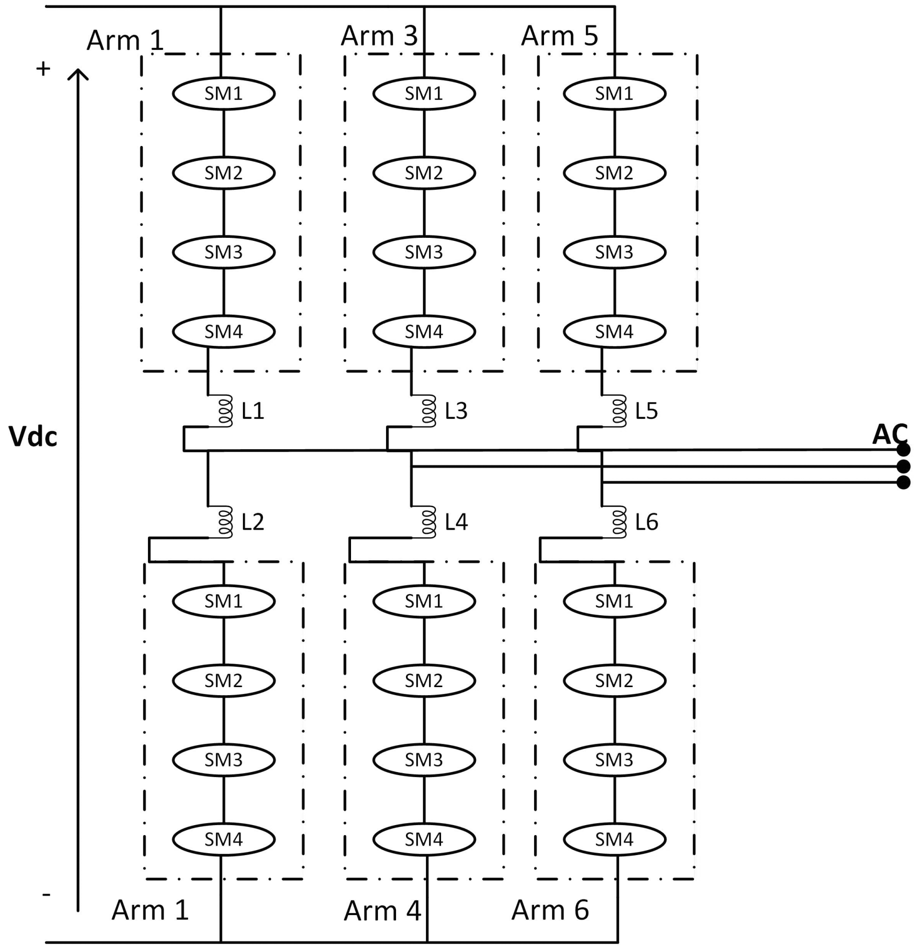

FIGURE 2 | General architecture of the three-phase MMC with six converter arms and distributed submodules.

The DC bus voltage can also be oscillated at a double line frequency. In addition to raising the voltage stress on the MMC's power components, transmitting the double-line frequency fluctuation to the other converter station is likely to cause the protective system to fail. When the MMC is run in inverter mode to deliver active power to the associated grid, the average SM capacitor voltage rises dramatically. This would cause a transient overvoltage on the DC bus. This is because the DC bus voltage is increased simultaneously with the average SM capacitor voltage [25–27].

2.5 | Device Level Faults

There are multiple device-level faults in MMC, which are discussed below:

2.5.1 | IGBT Short Circuit Failure

One of the most prone converter components to failure is the power semiconductor switches, IGBTs. It is more likely that an IGBT will fail in an MMC because there are typically multiple of them. Converters with problems with IGBTs may act erratically, putting other devices at risk and maybe jeopardizing the stability and reliability of power sources. Therefore, MMCs need an efficient and prompt fault-tolerant system [28–30].

2.5.1.1 | T_1 Short Circuit. When $I_{arm} > 0$ and $S = 1$, a T_1 short-circuit does not interfere with the capacitor's capacity to charge. When S is 0 and T_2 is activated, the capacitor rapidly drains because the T_1 short-circuit causes the capacitor to short-circuit via T_1 and T_2. The present process is depicted in Figure 3. Similarly, when $I_{arm} < 0$ and $S = 1$, the T_1 short-circuit does not affect capacitor discharge. Only when S is zero, a short circuit in T_1 causes a short circuit in the capacitor. This is illustrated in Figure 3.

2.5.1.2 | T_2 Short Circuit. A T_2 short-circuit does not affect the charging capacity of the capacitor when $I_{arm} > 0$ and $S = 0$. When $S = 1$, the switch T2 is short-circuited, causing the capacitor to be short-circuited via T1 and T_2 [31]. The capacitor switches from a charged to a defective discharged state because of this process. The capacitor goes from a normal to a fault discharging condition when $I_{arm} < 0$ and $S = 1$ due to a T_2 short-circuit.

Table 2 depicts the capacitor's condition under various IGBT short-circuit failures, based on the previous analysis. Because both IGBTs are "ON" in the same SM, any capacitor short-circuit will cause the other IGBT to flicker. The capacitor discharges quickly due to the small value of the time constant. The voltage and current across the capacitor are rapidly falling. The short-circuit detection method can be observed by the capacitor's voltage and current saturation, which are prevalent in short-circuit scenarios.

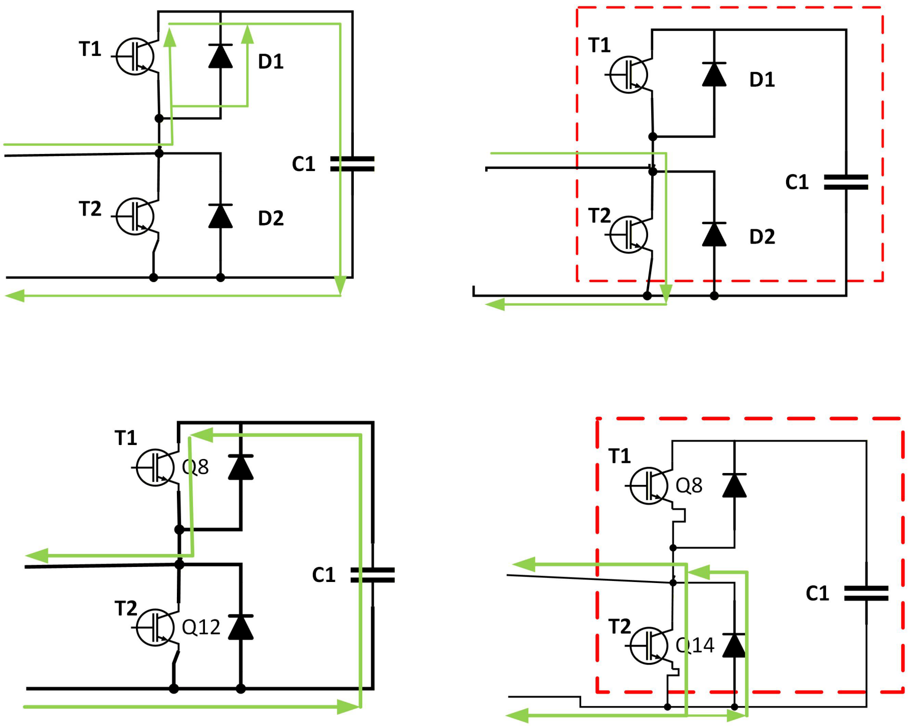

FIGURE 3 | MMC topology with T1-IGBT short circuit.

TABLE 2 | Fault conditions of IGBT switches and corresponding states.

IGBT	SM state	S	I_{arm}/capacitor	Result
T_1	On	1	$I_{\text{arm}} > 0, V_c < 0$	Normal
T_1	Off	0	$I_{\text{arm}} > 0, V_c < 0$	Short circuit
T_2	On	1	$I_{\text{arm}} > 0, V_c < 0$	Normal
T_2	Off	0	$I_{\text{arm}} > 0, V_c < 0$	Short circuit

- *Capacitor voltage calculation*: When the IGBTs undergo a complete short-circuit, the capacitor voltage starts to discharge. The equivalent discharge circuit consists of the on-resistance of T1 and T2:

$$Ic = -C\frac{d}{dt}Vc \tag{1}$$

$$Vc + RC\frac{d}{dt}Vc = 0 \tag{2}$$

$$\frac{d}{dt}Vc(t) = -\frac{Vc(t)}{RCo} \tag{3}$$

where V_c is the capacitor voltage and I_c is the capacitor current. In this way, we can approximate the capacitor voltage in the SM of MMC [32, 33].

2.5.2 | IGBT Short Circuit Failure

Due to the complex nature of MMC, it is essential to assess the reliability of each component thoroughly. One of the most important parts of the MMC is the capacitors, which are responsible for generating voltage levels and preserving the voltage in the SM. Capacitors, like all other components, wear down over time due to the mechanical and electrical stresses they experience in operation [34–36].

The capacitor mostly used in MMC applications is the aluminum electrolytic capacitor (AEC), and it has a low price and high energy density [37, 38]. When used, the capacitor could be subjected to thermal and electrical stresses, such as voltage and current ripples, electrolyte evaporation, anode foil deterioration, and oxide film degradation, which can occur in AECs due to these pressures [39, 40]. Electrical and non-electrical health markers can be used to monitor the deterioration mechanisms.

Capacitance and ESR are two electrical indicators that are directly associated with end-of-life care needs and may be measured online. It is impossible to analyze non-electrical indications, such as weight and pressure; thus, they must be transformed to verify their useful life. Consequently, research into capacitor condition monitoring mostly focuses on the use of electrical indicators to evaluate the state of health. If any of the following conditions are met, the capacitor will reach the end of its useful life as an AEC [41]. The following are the different fault types given in Table 3.

3 | Fault Diagnosis and Control Techniques

For fault diagnosis in a power electronic circuit, it is first observed whether the MMC is operating under normal conditions or in a faulty state. If the MMC is working under faulty conditions, then it is crucial to deploy a tolerant control system to protect the system. Different methods are discussed below:

TABLE 3 | MMC fault types, causes, and effects.

Fault type	Main cause	Impacts
Open-circuit switch	Solder cracks, gate-drive fault	SM capacitor overvoltage
Short-circuit switch	Thermal stress, parasitic turn-on	High fault current, device breakdown
DC-side short	Insulation failure, line short	Capacitor discharge
AC-side SLG fault	Ground contact, insulation failure	DC oscillation, voltage sag
Arm-level fault	SM/inductor failure	Circulating current, harmonics
Thermal fault	Overheating, overstress	Accelerated aging
Sensor/control fault	Communication error	Wrong control action
SM capacitor fault	Aging, dielectric breakdown	Uneven voltage sharing, imbalance

3.1 | Model-Based Methods

Model-based techniques use mathematical models to determine the system's behavior equations. The first derived equation depicts the system reaction during normal behavior. After the operation, the real system data (voltage, current, etc.) is compared to the derived equations. The residual, or difference between two equations, is a critical component in fault diagnosis and detection. A low residual number shows that the system is operating normally, whereas a high residual value suggests that there has been a system failure [42].

The paper [43] presents a sliding mode observer-based method for locating and detecting open-circuit faults. The prolonged duration needed to elevate the capacitor voltage to the threshold value results in low speed and difficult threshold selection across many systems, as indicated in [44]. These algorithms evaluate the predicted and measured values to see if the SM capacitor voltage exceeds a specified threshold; if so, the issue is recognized. As MMC operates at different voltage levels according to different applications, setting a fixed threshold is a problem that impacts the accuracy and precision of rapid fault diagnosis [45].

To reduce the number of voltage sensors required for MMC, the paper [46, 47] uses the Kalman Filter to predict capacitance in SM. According to this investigation, the voltage of the damaged capacitor is different from that of the other capacitors. As a result, it used the correlation coefficient of the capacitor voltage on the same arm to swiftly diagnose the problem.

KF-based methods have also proven useful throughout the last many decades. In [48], one voltage sensor is employed per stack to estimate SM capacitor voltages. As a result, a three-phase MMC requires just six voltage sensors at the stacks, rather than one for each SM. The test results revealed that the computed waveforms show significant distortion and latency, even though the sensors were greatly reduced. Additionally, a KF for a single-phase MMC that predicts the voltages of the SM capacitors using just current measurements is proposed in [49]. Using this method with a nominal capacitor voltage of 25 V resulted in significant distortion in the computed waveforms and an estimation inaccuracy of greater than 3%.

With this method, estimating the SM capacitor voltage is very difficult in the transient state. The paper [50] uses single-phase KF and deploys 12 sensors for a three-phase MMC, in which one current sensor and one voltage sensor are used. The paper [51] significantly improves the efficiency of the observer method; however, this method requires two stack voltage measurements in each switching period, and it is highly dependent on the algorithm and converter modulation [46, 47].

The paper [52] introduced an Extended Kalman Filter (EKF) to provide an accurate estimation of SM capacitor voltage and converter current by filtering out the high-frequency noise of the sensor without any lag. This study provides an accurate estimation of the model under transient and steady-state responses. However, the major drawback of this technique is that the system model must be accurate to ensure precision and accuracy. But with the model mismatched due to component degradation and other deterioration, the model accuracy is significantly compromised.

In the model-based method, to create MMC mathematical models, state observers [53], sliding mode observers [54], and Kalman filters [55, 56] they are often used. There are problems with IGBTs by comparing the estimated and actual measurements. These methods don't need any extra hardware circuits or training samples. There, it can't directly use the residual signal to find problems.

A hypothesis testing-based fault location method is presented in [57], where these methods are not affected by MMC operating circumstances, but the diagnosis time is still long. Furthermore, compared to the single-fault situation, the multiple-fault scenario is even worse for the MMC system. Nevertheless, the majority of research only considered the circumstances of a single switch's open-circuit failure. Therefore, the method proposed in [58] allows for the quick and simultaneous identification of faults in a large number of IGBT failures; however, it is limited to a certain voltage range. Thus, a Kalman filter-based diagnostic approach is used, which makes use of capacitor voltages. It is also possible to handle numerous IGBT faults using this method.

Noise in the measurements and errors in the parameters can also impact the outcomes of model-based methods for diagnosis and detection. Existing methods improved the algorithm's robustness by using an error compensation mechanism, adjusting the model's hyperparameters, or establishing suitable thresholds [59, 60]. On the other hand, serious disturbances like arm inductor short-circuit and current sensor faults cause residual values to differ from real measurements. The differences

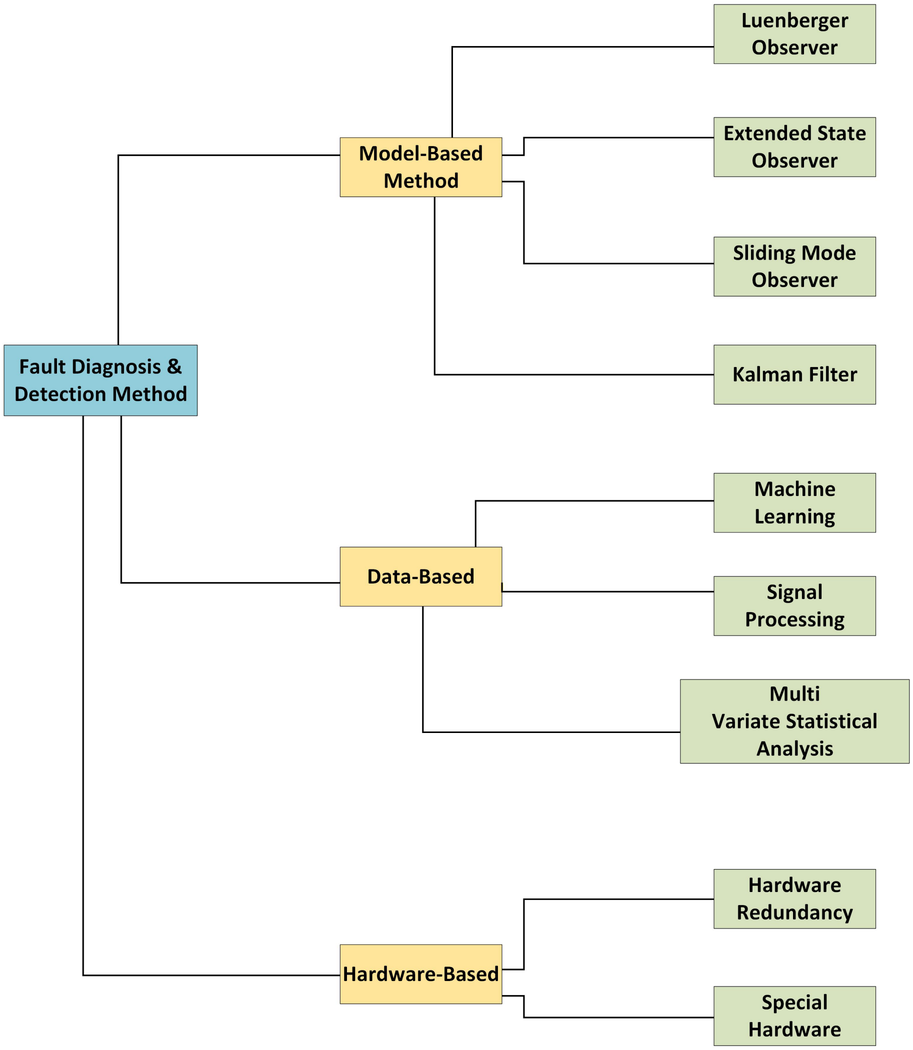

FIGURE 4 | Classification of fault diagnosis and detection techniques.

are so great that they outstrip the residual signals caused by open-circuit IGBTs. As a result, other faults will be misunderstood by the diagnostic method that solely considers one kind of problem.

In reality, model-based techniques, the residual signal consists of enough fault information that can be used to effectively detect the fault in the system. But conventional approaches can only inspect the residual amplitude for defects; they don't take other factors into account. In two-level inverters, the damaged leg can be located using the residual sign [61]. Integrating line and phase voltage variations also allows for effective identification of IGBT and current sensor faults [62, 63]. To differentiate between problems with the power switch and current sensors, three-level inverters use three-phase currents. When it comes to solar energy conversion units, the direction of the residual vector is seen as a hallmark of the defect. On the contrary, it is difficult to directly apply the previously mentioned approaches to MMCs due to the variances in operating principles. Nevertheless, these approaches fail to consider how substantial variations in model parameters (such as problems with arm inductor short-circuits) might impact diagnostic outcomes [64]. Figure 4 depicts the different fault diagnosis techniques.

3.2 | Data-Based Fault Diagnosis Method

There are different approaches to data-based fault diagnosis methods, which are given below:

3.2.1 | Signal/Feature-Based Approach

The fast Fourier transform (FFT) method is a suitable way to calculate the discrete Fourier transform (DFT) and its inverse transform. When working with enormous datasets, it works better than the DFT. The FFT algorithm's time complexity goes from $O(n^2)$ to O when the DFT is broken down into it [65]. The result speeds up processing a lot. This method could help many different fields, such as communication systems, pattern recognition, and signal processing [66].

This study primarily used the FFT algorithm to examine the frequency domain of the MMC SM open-circuit failure signal. The FFT transform can be used to turn the fault signal into one in the frequency domain. This transformation makes it easier to find and get the frequency properties that are related to the faults. Faults usually cause noticeable changes in the frequency range, so this change makes it possible to find out what went wrong [67].

Time-frequency analysis techniques may assist in early fault identification by monitoring the system's frequency response during a failure, particularly when harmonic components are amplified. By carefully looking at the fault features mentioned above, you can build a more complete fault diagnosis model. This will make it easier and faster to find open-circuit fault SMs [68]. These features can help with fault recovery and maintenance by giving you important reference data. They can also help you find the fault. To make the technology more adaptable and reliable, it is important to carefully look at the features of open-circuit failure in MMC SMs.

Signal analysis and machine learning are the two main ways to find problems with SMs currently. Signal-analysis methods that keep an eye on changes in voltage and current waveforms are what fault detection systems use [69]. But these technologies can't always tell the difference between different kinds of failure, and they are easily affected by noise in the background. Machine learning techniques can be used to train models to sort problems, but these methods need a lot of labeled data and have trouble with complicated nonlinear signals. Also, the methods that are already in use still need to be better at real-time performance and resilience. A lot of work has been done lately to find ways to find faults in MMC SMs [70, 71].

Signal analysis methods look at the waveforms of changes in voltage and current to find mistakes. Wavelet transformations can be used on the high-frequency parts of SM voltages to find open-circuit problems. To attain precise fault localization [72], introduced an intriguing technique employing the Hilbert-Huang transform (HHT) to derive the time-frequency characteristics of signals. However, these methods yield noisy and inferior outcomes when addressing complex nonlinear signals.

This paper [73] examines the current sensors' approach to fault diagnosis in MMC. After looking into how the current sensors failed and getting the SM capacitor voltage characteristics for different types of faults using the mathematical model and operating principle of MMC, a fault diagnosis strategy for MMC current sensors based on recognizing fault features was first suggested [74, 75].

This technique identifies and pinpoints faults using output current sensors and arm current sensors by observing the voltage of SM capacitors, eliminating the necessity for additional hardware circuits. Also, the method may still be able to quickly find problems even when there is a load disturbance and an MMC parameter mismatch [76].

In paper [72], an open circuit fault detection system is created using evidence fusion theory (EFT) and weighted amplitude permutation entropy (WAPE). The experimental results indicate that WAPE outperforms SMO in feature extraction performance when the two methods are compared. The main benefit of this strategy is that it is easy to find different faults with SMs.

In paper [77], an event mechanism (ETM) is created to find and fix open circuit failures in MMC SMs. The ETM fault detection system turns on when the voltage and current of the capacitor are added together. The suggested method speeds up the controller's processing time without needing any more hardware.

These feature-based methods, techniques like FFT, HT, and HHT, are effective in fault diagnosis and detection; however, they have certain limitations as well. These techniques are significantly influenced by noise, EMI, and switching harmonics. The transient response is not handled by FFT; therefore, HT and HHT play a critical role in it. However, the HT and HHT have to have a trade-off in time-frequency resolution, mode mixing, and boundary effects. As the application scalability increased, like in large-scale MMC, the computational cost also increased, and it had latency issues as well. The future direction is of a hybrid fault diagnosis framework to effectively diagnose the fault in the system.

3.2.2 | Artificial Intelligence-Based Approach

MMC and the power system are non-linear systems that are noisy, transient, and non-stationary. Techniques like Feature-based models are limited to the fixed threshold, decomposition of signals, and manual tuning, which are not a pragmatic approach in a changing grid environment. However, these limitations push academia to look for more robust handling of fault detection in MMC and power systems [78, 79]. The AI-based algorithms, like CNN, SVM, and LSTM, provide an efficient and robust approach to handling these nonlinear faults in the grid. They can adapt to the different situations and handle them in the most efficient way possible. These methods provide significant advantages like scalability, automation, reliability, and real-time control of power equipment in the grid [80, 81].

Artificial intelligence (AI) fault classification addressed issues of a non-linear system and also resolved issues with a manual threshold. This makes it a flexible way to deal with a non-linear system [82]. HVDC protection systems have used AI algorithms such as support vector machines (SVM) and back-propagation neural networks (BP-NN) [83]. For instance, the MMC-HVDC system was safeguarded by 13 ANN models [84], leading to elevated model precision but significantly increasing the computational overhead. It was suggested that a convolutional neural network (CNN) be used for an MMC-HVDC system with two terminals. However, its performance is greatly influenced by noise and harmonics. Much new research is deploying AI-based models to rapidly detect faults, but these new technologies introduce new challenges for the power system. The conventional deep neural network in MMC fault diagnosis is unable to extract the fault features that significantly chang e over time.

The work [80] offers a hybrid technique that uses the Harris Hawks optimization algorithm to distinguish MMC-HVDC fault types using current and voltage data from fault and non-fault signals. ANN can predict whether training and experimental data are similar, making it a powerful error classifier. The ANN algorithm predicts component behavior using DC line voltage and current information [81]. It selects the best features from this study's voltage and current data set using Harris Hawks optimization. The Harris Hawks optimization approach employs voltage and current signals to uncover distinguishing features for better identification and faster ANN calculations.

This added feature reacts differently to mistakes. Harris Hawks' optimization method reduces training data, improves training, and eliminates divergence. Benchmark compares several possibilities. That function knows right from wrong. However, this study only considered the single line-to-ground fault, leaving other fault types. The result was only validated in simulation with a normalized frequency and fixed sampling frequency, not incorporating the real-world scenario.

A number of benefits, such as speed and nonlinear pattern classification, make the neural network an effective tool for defect diagnostics [85, 86]. A new method for diagnosing open-circuit faults in IGBTs using data is described in reference [87]. This approach trains the dataset and generates an initial diagnostic model using an extreme learning machine (ELM). The difference between the expected and actual capacitor voltages is employed as a diagnostic threshold, according to reference [88]. On the other hand, this approach has several drawbacks, such as a slow and inaccurate diagnosis.

In order to diagnose the non-linear system, this paper [89] proposes a new data-driven approach based on predictive current. It uses a single trained model of the original system. The major benefits of this method include improved accuracy, implementation of a data-driven Elman model, and the tuning of the Elman model parameters using the MCS technique. However, this paper has a limitation in that the scope is limited to IGBT open circuit fault, only simulation-based results, no detailed fault location, and dependency on data quality.

In this paper [90], the capacitor voltage of the MMC is estimated using an SMO-based BN neural network. It tracks the voltage of the capacitor when the SM is working in a healthy condition and also tracks the voltage under faulty conditions. However, in the conventional method [91, 92], the sliding mode gain has to be adjusted manually, which leads to inefficient and inaccurate working of the model-based technique. However, this sliding mode gain is automatically adjusted by the BN neural network, which results in better accuracy and noise robustness. However, this approach does not discuss the scalability and computational cost of a large MMC system.

However, while AI-based models offer real-time control and automation, they also have limitations [93, 94]. One of the most significant drawbacks of data-driven models is their reliance on high-quality data, which has a direct impact on their decisions. The computational expense, particularly when training neural networks, is a significant barrier to applying it in power systems. The data-driven model is also constrained by the generalization issue in the entire system, which means that one model cannot be employed in multiple topologies because the working context varies [95].

3.3 | Hardware-Based Approach

Hardware-based methods are fault-detection approaches that utilize extra physical hardware, like a physical sensor, to measure the signal directly from the MMC circuits. The benefit of this method is that it directly measures the signal inside from each component of MMC, like SM capacitor voltage, IGBT current, and arm voltage, etc. The real-time data from different electrical components is directly processed, and it will detect the fault in a very short time, which will help to locate and diagnose the problem in a more robust way [96, 97].

In the paper [98], a robust fault-detection method is proposed based on the arm inductor voltage with the help of an extra rectifier bridge and an FPGA. In this topology, two transformers are utilized, where the primary side of the transformer is connected to the arm inductor voltage and the secondary side is connected to the rectifier bridge. When the threshold voltage is exceeded by the arm inductor voltage, then the FPGA is activated, which detects the fault within 23 us [99].

In [99], the MMC's predictive model and control variables are employed to estimate the arm voltages. Identifying the open-circuit switch failure and the defective arm involves a straightforward comparison of the estimated values against the measured arm voltages. Furthermore, as mentioned in papers [100, 101], we can predict the total and differential arm voltages in both the upper and lower arms.

When mathematical models are unavailable, hardware-based methods might be used for critical systems or processes. Important hardware components' redundancy is used by these strategies. To create a residual, the inputs to the redundant hardware are repeated, and the outputs are measured and compared. The residuals should be near zero under typical circumstances; if they aren't, it should be possible to identify the faulty hardware component [100]. With hardware redundancy in place, the next step is to apply a voting algorithm that is typically based on decision-making approaches like fault trees, expert systems, Bayesian networks, or distributed systems. This algorithm will analyze the residual, detect the fault, and initiate the correct reconfiguration [6, 102]. Fast and reliable FDD can be achieved via hardware-based techniques, which provide a compelling alternative to MMCCs [103, 104].

In the paper [105], multiple additional voltage sensors are added in the circuit to measure the cell output voltages. These output voltage measurements are used to compare with the capacitor voltage in OCF to check the instantaneous output voltage and predict the fault in the OCF. Similarly, this method is also applied to the MMMC in DSCC topology, and it illustrates that a defect is detected within 5 us.

Finally, hardware-based FDD methods usually deploy redundant devices and additional measuring hardware equipment to allow for quicker comparisons of measured values with computed estimates as well as references. This can get precise results fast with these strategies, and they are also straightforward to use. The primary issues with MMCCs, meanwhile, are the additional space and cost of equipment demand, as well as their weight. Instead of using individual floating capacitor voltage cells, several contributions [106, 107] employ cluster voltage readings as a control mechanism for MMCCs. As usual, excellent performance control of MMCCs relies on voltage readings in each cell, making this a unique and separate case. Table 4

TABLE 4 | Summary of MMC fault diagnosis methods.

References	Category	Method	Fault type	Validation	Time	Load var.	Hybrid AI
[108]	Model-based	Kalman filter	SM OCF	Sim	25 ms	Yes	No
[47]	Data-based	SVM	Switch OCF	Sim	11 ms	No	Yes
[52]	Model-based	Ext. Kalman filter	SM cap. voltage	Exp	Nr	Yes	No
[55]	Model-based	Pauta criterion	SM OCF, arm inductor	Exp	20 ms	Yes	No
[56]	Model-based	Amended Kalman	IGBT OCF	Exp	20 ms	No	No
[59]	Model-based	Residual + Pauta	IGBT OCF, arm inductor	Exp	21 ms	Yes	No
[73]	Data-based	Threshold proc	Sensor OCF	Exp	9.8 ms	Yes	No
[109]	Model-based	Kalman filter	Switch OCF	Exp	70–150 ms	Yes	No
[110]	Data-based	FFT	Cluster switch OCF	Sim	Nr	No	No
[111]	Data-based	CNN + BiGRU	SM OCF	Sim	Nr	Yes	Yes
[112]	Data-based	PSC + PWM	SM cap. voltage	Sim	60 ms	No	No
[113]	Data-based	DWT + LSTM	HVDC fault	Sim	2-5 ms	Yes	Yes

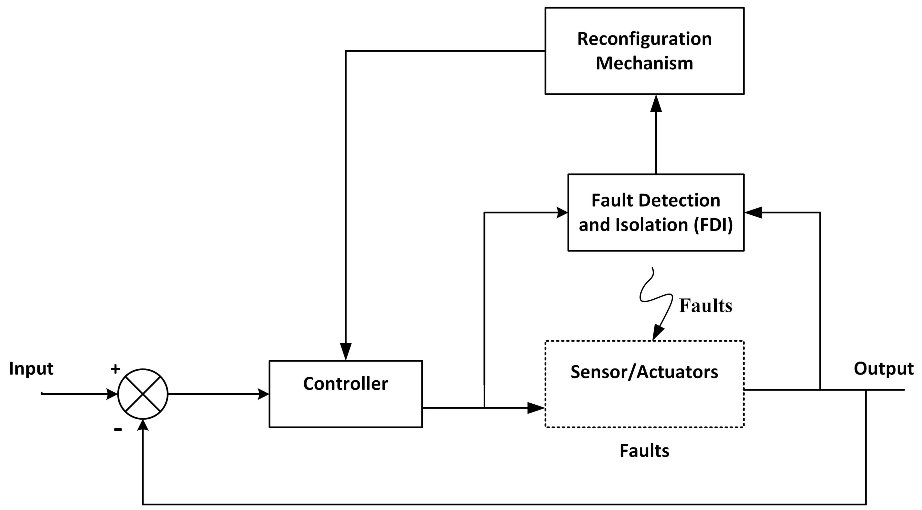

FIGURE 5 | AFTCS topology in MMC.

shows the comparison between different FDD techniques used in MMC.

4 | Fault-Tolerant Control Techniques

Once the fault is detected in the MMC using various techniques, the next step is to overcome these faults in a quick time to protect the overall system stability. The following are the techniques of FTC mentioned in the literature:

4.1 | Active Fault-Tolerant Control System (AFTCS)

The AFTCS is an efficient control technique that consists of a fault detection and isolation unit (FDI) to maintain system stability and performance under faulty conditions. The reconfiguration mechanism allows AFTCS to handle the unexpected faults in an efficient way. It detects faults in real-time and ensures the system reliability and resilience even in faulty conditions [114, 115].

If the MMC sensor or actuator side has a failure, the FDI unit will isolate the issue and reconfigure the system by substituting a healthy value for the problematic one. The figure below shows how a plant uses the sensors to estimate a value, which it then sends to the controller at the same time as the observer-based approach [116, 117]. It is depicted in Figure 5.

When calculating the estimated and real numbers, the controller checks to see if the difference is within allowed limits or if there is a fault within MMC; the difference must be greater than the threshold value [5, 118]. If the problem is located in MMC, the following step is to isolate it by changing the setting that instructs the observer-based mechanism to run in parallel with the system. This will keep the system stable and prevent complete shutdowns. An alarm is activated to inform the operator of the issue and allow them to respond appropriately [119].

In paper [120], the author thoroughly discussed the AFTCS advanced methods to resolve the faults in MMC under SM failure. However, this approach led to the deployment of redundant

SMs, which can increase the size and weight of the system. Therefore, the aforementioned paper uses a non-redundant approach to control the fault [121].

In paper [122], the author uses a discrete linear parameter varying method (LPVM) to resolve the faults of the actuator. Using LPV and linear matrix inequality (LMI), this study proposed a dependable method for fault estimation. In paper [123], it showcases neural networks that employ the backstopping approach. The implementation of the first observer provides estimated values for modules that are malfunctioning. After that, these errors are removed using a back-stepping method [124].

In paper [120], an efficient fault-tolerant strategy approach is used, which is a non-redundant control-based approach that requires no extra electrical equipment in the SM of MMC. This approach works by combining three critical elements, which are resilient capacitor voltage control, where working SMs adjust their capacitor voltage to balance arm voltage, arm current reference adjustment, which curbs the circulating current and ensures balanced power, and phase-shifted carrier PWM. However, the remaining SMs are under more stress, and they need a very complex control system for their operation [125, 126].

To achieve acceptable performance in low-frequency and fault-tolerant operating situations, a redesigned SM is positioned in the center of the upper and lower arms in [127]. During typical operation, the SM capacitor voltage fluctuation is reduced because the middle SM can balance the low-frequency power fluctuation between the upper and lower arms. A healthy SM can be reconfigured in the middle SM and used to replace a damaged SM in either the upper or lower arm during post-fault operations [128, 129].

An innovative method for global redundancy is detailed in [130], which involves linking the system to a pair of HB series-connected SMs. The suggested FTC method may help keep the system running continuously with minimal deterioration, reduce the initial cost and volume, and share the redundant SM in one phase using bidirectional switches. Adding more global redundant SMs improves the fault-tolerant operating capacity in each phase of [131, 132].

The MMC primarily has two types of redundancies: hot-reserve redundancy, also known as active redundancy, and cold-reserve redundancy, also known as passive redundancy [133]. The hot-reserve redundant SMs take part in the regular operations; cold-reserve redundant SMs do not. Faster dynamic reactions and higher power losses are typical outcomes of hot-reserve redundancy for the MMC, whereas cold-reserve redundancy is associated with slower dynamic responses and lower power losses [134]. In addition to other comparisons on cost and control complexity, they are also mentioned in the paper [135].

When hot-reserve redundancy-based techniques are utilized, the SM capacitor voltages operate at a lower value, and the redundant SMs work under normal conditions [136]. Reduced voltage and current ripples in the capacitors are the key benefits of hot-reserve redundancy [135, 137]. The broken arm's voltage returns to normal when the SM fails because all of the SM capacitors in the arm increase in voltage [138, 139].

The defective SMs and an equal number of healthy SMs in the opposite arm are avoided when an SM failure happens in [140, 141]. In order to keep the normal output voltage range of the malfunctioning phase, the other healthy SMs' capacitor voltages are activated. The post-fault procedures in [142, 143] involve the remaining healthy SMs, but the defective ones in the defective arm are the only ones that are bypassed. The internal energy balancing control mechanism is further investigated in this asymmetric operation under post-fault operating conditions. Each SM in [144] has its capacitor voltage adjusted to its rated value, the same as the redundant SMs.

Redundancy is a popular strategy for protecting MMC from failures, but unique power circuits with controllers have also been identified as a means of eliminating defects. In [145], the authors assessed the effectiveness of continuous model approaches using a control mechanism based on discrete half-bridge SMs. This method's primary benefits include eliminating fault-induced power oscillations, allowing the voltage to stabilize, and balancing the voltage between the capacitor's upper and lower arms.

In both [146] and [147], the authors balanced the MMC's inner current using the CCSC technique. Since the smaller models do not account for CCSC and second harmonics, the method's main benefit is that it increases the internal current's efficiency in models two and six. The authors used MATLAB Simulink to develop these models and confirm their accuracy in the frequency and time domains.

The use of AFTCS in MMC has the potential benefit of making it easier to eliminate a wide range of mistakes, including those caused by actuators and sensors. However, because of the substantial computations needed for multiple flaw diagnosis, the pace is substandard. Adding a lot of noise to the system could potentially throw off the fault detection judgment. Therefore, intelligent control is necessary for defect identification, which is discussed in papers [148, 149].

4.2 | Passive Fault-Tolerant Control System (PFTCS)

The basic structure and topology of PFTCS are simple and robust compared to AFTCS. The major difference in the working of PFTCS is that there is no FDI (Fault Diagnosis and Isolation) and controller reconfiguration, which allows this FTC to be very fast, quick, and robust. When activated, the PFTCS can quickly identify issues with the system's sensors, actuators, or both. The key benefit of PFTCS is its robust architecture, which allows it to handle faults in non-linear and noisy environments readily [150, 151] as shown in Figure 6.

Due to the time required to discover the problem, the AFTCS in MMC will malfunction if it occurs rapidly and dramatically. Because of its speed and ease of use, a PFTCS is ideal for these kinds of scenarios [152, 153]. To solve the single-point failure, the PFTCS was used as a robust FTC in papers [154, 155]. A single-point failure is a critical fault because it can destabilize the whole system, requiring an immediate FTC system to maintain stability even under such faults. Thus, a fast and robust FTC

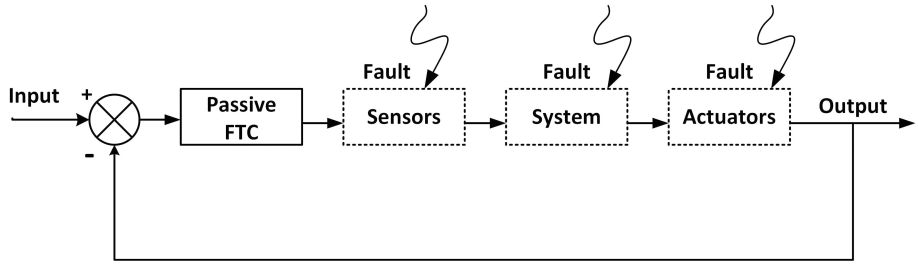

FIGURE 6 | PFTCS topology in MMC.

system is required for the stability of the system, and PFTCS can provide such stability [156, 157].

The redundant SMs are disabled, and the SM capacitor voltages for cold-reserve redundancy-based techniques run at their rated value when everything is running smoothly. When one SM stops working, the backup SMs step in and contribute. For both the regular and redundant SMs, a smooth bypassing and insertion technique is given in [158]. There is less power loss and fewer SMs needed for cold-reserve redundancy techniques. The reduced number of SMs in operation results in poor harmonic performance and excessive voltage stress [159, 160]. Additionally, the MMC's dynamic performance can be negatively affected when the capacitor voltages in the cold-reserved SMs begin to operate and rise from zero [161, 162].

However, certain drawbacks of PFTCS can significantly compromise the performance of the system in fault situations. The limited fault coverage by PFTCS is a major drawback because there is no FDI to handle unexpected faults in the system [163, 164]. The PFTCS also lacks handling real-time adaptation, has limited efficiency in handling complicated system design, and has limited efficiency in handling multiple faults [165, 166].

4.3 | Hybrid Fault-Tolerant Control System (HFTCS)

The hybrid FTC combines the best advantages of both active and passive FTC. This hybrid approach provides an efficient and robust method for a complicated system. Using HFTCS, the problems with AFTCS time delays and PFTCS multiple fault detection are simply resolved. Research paper [167, 168]. For the purpose of controlling the air-fuel ratio in ICGEs, the authors presented a hybrid FTCS in 1986 that relied on KF and triplex hardware redundancy. To quickly detect a high number of ICGE faults and overcome defects utilizing triplex redundancy, the suggested method employs both active and passive FTCS types [154, 169].

While this method is great for quickly identifying many different types of problems, it becomes problematic for fault estimation when the ICGE is subjected to harmonic distortion. In the paper [170], in order to overcome the above-mentioned faults, a hybrid FTCS is deployed against actuator faults and uncertainties of the model. This model can also provide a reliable solution against the harmonic distortion in the system [169, 171].

In the two FTC systems, the redundant SMs are configured according to two criteria: optimal dynamic performance and perfect electrical stress. The arms of [172, 173] are equipped with both hot-reserve and cold-reserve redundant SMs. If one SM fails, the hot-reserved SMs can still offer smooth FTC. By moving from cold-reserve redundant SMs to hot-reserve SMs, FTC is maintained with minimal power losses.

In most cases, the dc-link voltage remains constant in traditional MMC power transmission systems. The dc-link voltage must be equal to the sum of the voltages in each arm's capacitors in order to regulate the internal energy and circulating current effectively. Nevertheless, the dc-link voltage is modifiable in certain cases. For the motor drive based on MMC, an FTC method is suggested in [174] using FF-ZSV injection and dc-link voltage adjustment.

In [175, 176], a similar concept is further investigated for multiphase SM failures using this foundation, allowing for the guarantee of sophisticated fault-tolerant operation in MMC-based motor drives [177, 178]. Because the dc-link voltage of the MMC-based STATCOM is also floating, it is possible to boost all capacitor voltages to improve fault-tolerant performance in the event of a catastrophic SM failure [179–181].

When there are more redundant SMs than faulty SMs, the defective arm can achieve a lower capacitor voltage increment, and the MMC-based STATCOM can keep working correctly within a certain operational zone even when there are more faultier SMs than redundant SMs. The Table 5 shows the comparison of different FTC techniques used in MMC.

5 | Comparison With Existing Literature

While prior reviews have significantly contributed to the different aspects of faults that occur in MMC, there are certain constraints. The existing literature clearly illustrates the multi-faceted benefits of the MMC in high-voltage power systems; however, the modular design requires advanced FTC and FDD techniques to ensure resilience and reliability in real-time. The review papers [190] and [191] discuss the switch faults, SM faults, and voltage imbalances in MMC during the event of the faults. Furthermore, the papers [5] and [192] shift the focus toward hardware redundancy integrated with software-based modulation to enhance the performance of the system under faults.

The review papers [4, 193] categorize the FTC methods on the basis of their efficiency and harmonic performance under a fault scenario. There is still a significant gap in the theoretical and practical implementation of the FTC-based method. The old research was more focused on theoretical validation

TABLE 5 | Comparison of different FTC techniques in literature.

References	Strategy	FTC category	Control system	Objective	Achievements	Limitations
[171]	N + 1 SM redundancy	Passive	Moderate	– Symmetry restoration under SM faults – Minimizing voltage stress on SM	– Circulating current suppression: 40 to 0.71 A – DC voltage deviation: 0% – AC voltage deviation: 1.05 pu	– Validated only in Simulink – Focused mainly on SM faults – No explicit metrics for computational delays
[161]	Cold reserve redundancy	Passive	Moderate	– Seamless SM transition during faults – Uninterrupted MMC operations	– Balanced capacitor voltage: 125 V – Inrush current: 0 A – No output current distortion	– Transition time of 90 ms – Switching harmonics during a transient – Low power prototype
[182]	MMC + electrode return path	Passive	Moderate	– Ensure fault-tolerant operation under faults	– Fault duration handling: 100 ms – Fault isolation speed: 10 ms – Maintain 50% operation under faults – Ensure operational continuity	– High current faults: 7 kA – Second harmonics oscillation under AC faults – No experimental validations
[181]	N+1 SM	Passive	Moderate	– Maintain stable MMC operation under SM faults – Low output current distortion	Fault recovery time: 100 ms SM overvoltage < 15% Filter size reduction: 12.5%	– 12.5% energy reduction – 0.75 MW increased energy demand – Poor scalability under multiple faults
[183]	SHE–PWM, MPC	Active	Complex	– Maintain voltage magnitude – Better harmonic performance	Fault transition time: 76.43 ms Settling time: 50 ms – Fault condition ripple: 3.85%	– 33% increase in capacitor voltage stress – 248 A current overshoot
[184]	Online DMD–Kalman filter	Active	Moderate	– Ensure accurate fault detection – Continuous MMC operation under sensor faults	– Fault detection: 1 ms – Reconfiguration time: 0.401 s – Detect three types of faults – Model-free FTC	– Only simulation validation – High computational complexity – Limited to sensor faults
[185]	Deep learning + ZSV Inj.	Active	Complex	– Detect and locate MMC faults – Maintains voltage balance – Suppress circulating current harmonics	– Integrate ZVS injection for voltage compensation – Suppress circulating current harmonics – Multi-fault classification	– No quantitative metrics – High Computational Cost – Simulation-only validations
[173]	Unified active–passive FTC	Hybrid	Complex	– Maintain stability after fault occurrence – Ensure the performance of the system in the event of faults	– 50% actuator fault loss – Stable response until 20 s – Better disturbance attenuation – FDD estimation error: 0.55	– No quantitative metrics – High Computational cost – No real-time implementation
[186]	Carrier-based PWM	Active	Moderate	– Improve capacitor balancing – Reduce computational complexity	– Recovery time: 17.34 ms – Performance gain 51% better – Stable output voltage	– Validated on the small system – No circulating current suppression – No quantitative metrics
[187]	SSP + VDA	Active	Moderate	– Maintain uninterrupted operation of MMC – Ensure voltage balancing and grid current quality	– Recovery time: 12 ms – Reconfiguration time: 1 ms – DC-bus voltage maintained: 14.4 kV	– Simulation only validation – PVSM recovery delay – Hardware complexity
[188]	MPC-based FTC	Active	Moderate	– Ensure stable HVDC operation under faults in MMC – Early detection and control reconfiguration	– Maintain stable HVDC output voltage in the event of fault – Fast dynamic response using MPC – Improve stability and robustness	– Simulation-based validation only – No quantitative results – No comparison with other FTC methods
[189]	Sorting + redundant SM	Active	Moderate	– Replace faulty SM while avoiding inrush current – Handle circulating current in HMMC	– Detection time: 10 ms – Capacitor voltage: 2.2 kV – Effective circulating current suppression – Arm voltage restoration	– Slow dynamic response – No performance metrics reported – Single fault scenario tested
[190]	RNN-based FTC	Active	Complex	– Achieve high fault-detection – Maintain voltage balancing	– Computational time: 1.1 ms – Fault-detection time: 2.5 ms – Anti-noise capability: 40 dB SNR – Low sampling requirement	– Depend on dataset quality – No hardware validations – Black-box modelling

of the FTC-based technique, which focuses on the CHBI system; therefore, the advanced power system requires fast and reliable FTC methods to improve the system stability in the event of faults.

There is a significant gap between the advanced FTC algorithm to handle the MMC system with high SM, which significantly increases the complexity of the system and requires high computational resources to implement the FTC in real time. The review papers [194] and [195] provide different FTC and FDD techniques for MLI topologies and focus on open circuit and switch faults. However, most of these systems focus on only limited faults and specific MMC topologies as shown in Table 6.

This review discusses the MMC architecture and application also focuses on its advancements and challenges. This paper

TABLE 6 | Comparison of different MMC based papers.

References	Focus area	Key contributions	Limitations
[191]	Fault diagnosis and tolerance in MMC	Summarized fault diagnosis and control technique for MMC under fault conditions	– Limited DC fault analysis
[5]	FTC and FDD techniques for MMC – Submodule faults	– Detailed survey of MMC faults – Comparative analysis of FTC strategies	– Simulation-oriented – Focused mainly on switch faults and voltage imbalance
[194]	DC fault blocking SM and MMC configuration	Address different losses for SMs and resilient control techniques for MMC in fault scenarios	– Dynamic fault analysis excluded. – STATCOM operation focused
[195]	FTC methods for cascaded H-bridge inverters (CHBI) under faults events	– Classified hardware and software methods – Provided analytical description of CHBI on the basis of VL-L, THD, unbalance ratio	– Scope restricted to CHBI only – High common-mode voltage requirement – Simulation-only validation
[193]	– Single-phase fault-tolerant multilevel inverter (FT MLI) topologies. – Emphasis on switch faults (OC/SC)	– Classification of FT solutions for MLIs. – Novel comparative factors (FTF, CFTF) – Simulation and experimental validation	– Restricted to single-phase MLIs – Focused mainly on switch faults – Experimental validation narrow
[192]	– FTC and FDD for multilevel inverters	– Classification of FD approaches – Evaluation of modulation schemes – Comparative study of soft computing FD techniques	– Scope limited to general MLIs – Focused mainly on switch faults and modulation issues – Simulation-oriented
[4]	– FTC, FDD, and system reconfiguration for MMCCs.	– Comprehensive survey of FDD methods – Comparison of detection speed, accuracy – Discussion of reconfiguration strategies	– Experimental validation missing – Limited scope of faults – Transition control gap
[140]	FTC and FDD for MMC under SMs failure	– Categorization and comparison of FD methods – Evaluation of FTC strategies:	– Scope restricted to SM faults – FTC strategies evaluated mainly on THD and efficiency

[196, 197] has focused limited attention on fault scenario handling in a real-time environment [198, 199]. Moreover, the paper in [175] mentioned the FTC control for various open circuit faults, but it lacks research on the FDD techniques [200]. However, this review covers this gap and provides a comprehensive review of different fault diagnosis and detection (FDD) methods and Fault-Tolerant Control (FTC) for MMC in various applications.

- *Unified diagnosis–control perspective*: This review paper provides a systematically integrated framework for intelligent fault diagnosis and fault-tolerant control strategies for MMC to enhance its performance in critical applications.
- *Structured multi-dimensional classification*: This paper provides a comprehensive classification scheme, which relates fault types, detection techniques, and advanced control frameworks, which provide easy system understanding and design implementation.
- *Critical and quantitative comparative analysis*: The work incorporates quantitative and critical comparison of existing FTC techniques with their achievements and limitations in the real-time scenario.
- *Emphasis on practical implementation constraints*: This work provides a thorough analysis of the real-world implementation challenges, including hardware limitations,

scalability, and complex control systems for FTC and bridges the gap between theoretical research and practical deployment.

- *Discussion of different faults in MMC architecture*: This paper thoroughly discussed the different faults that occur in MMC in various environments and mentioned different methods to resolve these issues.

In contrast, the present review contributes by bridging these gaps: it jointly addresses both fault diagnosis and fault-tolerant control, provides a structured comparison across multiple performance parameters (accuracy, complexity, cost, response speed, application suitability), and incorporates the latest advances, including AI-driven, hybrid, and low-cost real-time solutions.

6 | Future Research Directions

The next phase of research should focus on the development of hybrid approaches, like the integration of model-based methods with advanced data-driven techniques, particularly AI, to enable real-time fault diagnosis and tolerance with greater accuracy and resilience.

1. *Integration of data-driven control in MMC system*: The future power system must integrate the data-driven FDD techniques with real-time control to enhance the system resilience and reliability in the event of faults.
2. *Physics-informed and hybrid learning models*: The recent hybrid and physics-informed learning model provides an efficient real-time control for the data-efficient FDD for the MMC system, incorporating the physical constraints in this learning model for better performance in real time.
3. *Digital twin-based predictive fault management*: The disruptive technology, like digital twins, provides real-time monitoring and predictive maintenance. However, their complexity and synchronization are critical aspects to consider for future directions.
4. *Cyber-physical security for futuristic MMC system*: The future MMC system will be highly vulnerable to cyber-attacks; therefore, future research direction must incorporate an intelligent system to address the cyber anomalies introduced in the system.
5. *Real-time implementation and HIL validations*: Most of the existing research algorithms are simulation-based; therefore, the future research direction should focus on the real-time implementation, such as HIL validations and FPGA in the loop testing to enhance the performance of the MMC in real-time systems.

These future directions must put a greater emphasis on the real-time implementation and design of efficient algorithms for real-time deployment, and hardware in the loop (HIL) validation to ensure the practical effectiveness of these strategies under realistic grid operating conditions. With continuous development in power electronics, control systems, and AI, the next generation of MMC FDD and FTC is essential for the modernization of the power system.

7 | Conclusion

In conclusion, the MMC stands out as a next-generation technology in modern power systems. It offers significant benefits like modular design, scalability, and reduced harmonic suppression; however, its performance is heavily impacted by potential faults such as SM breakdown and arm voltage issues. To address these faults in MMCs, various fault diagnosis and detection (FDD) and fault-tolerant techniques have been developed, each with its own advantages and disadvantages. Model-based techniques include Kalman filters and sliding mode observers that provide quick responses, but they suffer from computational complexity and parameter variation due to noise. Conversely, data-driven models incorporate machine learning methods such as CNN and LSTM, as well as hybrid neural deep learning techniques, to offer adaptability and faster fault detection in real-time applications.

Although passive FTC is simple and reliable, comparative studies of FTC strategies show that it has limited adaptability because it cannot actively reconfigure during a fault condition. Active FTC methods, like PWM-based, MPC, and zero-sequence voltage injection, provide superior performance and faster responses due to the fault detection and isolation (FDI) block. Moreover, hybrid FTC approaches that combine active reconfiguration and passive redundancy offer an effective balance between robustness, efficiency, and cost. These methods not only strengthen system resilience but also provide practical solutions for effective fault detection in complex systems. They pave the way for real-time resilience in MMC-based applications. Therefore, future research should focus on developing hybrid systems that integrate AI with data-driven models.

Author Contributions

Muhammad Haris Saleem: conceptualization, investigation, writing – original draft, visualization, validation, methodology, writing – review and editing, formal analysis, data curation. **Arslan Ahmed Amin:** funding acquisition, investigation, validation, writing – review and editing, project administration, formal analysis, software, supervision, resources. **Zuhair A. Alqarni:** funding acquisition, visualization, validation, project administration, formal analysis, resources, supervision. **Umair Shahzad:** funding acquisition, investigation, writing – review and editing, methodology, visualization, formal analysis, project administration, resources.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Peer Review

For transparency, the peer review documents associated with this article are available at https://doi.org/10.1002/eng2.70824.

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