POWER ELECTRONIC SYSTEMS RELIABILITY SURVEY

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Abstract: With wide-spread application of power electronic systems across many different industries, their reliability is being studied extensively. This paper presents a comprehensive review of reliability assessment and improvement of power electronic systems from three levels: 1) metrics and methodologies of reliability assessment of existing system; 2) reliability improvement of existing system by means of algorithmic solutions without change of the hardware; and 3) reliability-oriented design solutions that are based on fault-tolerant operation of the overall systems. The intent of this review is to provide a clear picture of the landscape of reliability research in power electronics. The limitations of the current research have been identified and the direction for future research is suggested.

***Index Terms*—Fault diagnosis, fault-tolerant operation, power electronic systems, reliability.**

I. INTRODUCTION

Power electronic systems play an increasingly important role in adjustable-speed drives, unified power quality correction, utility interfaces with renewable energy resources, energy storage systems, and electric or hybrid electric vehicles (HEVs). The power electronic techniques provide compact and high-efficient solutions to power conversion. However, introduction of power electronic techniques into these application fields challenges reliability of the overall systems. One of the concerns related to reliability lies in the power semiconductor devices and electrolytic capacitors that are the most vulnerable links. Most of power electronic converters are not equipped with redundancy. Therefore, any fault that occurs to the components or subsystems of the system will lead to shutdown of the system. These unscheduled interruptions not only cast significant safety concerns, but also increases system operation cost and partially offsets the benefits of introducing power electronic systems. For instance, in HEVs, faults of electric propulsion systems will impair fuel economy and lengthen cost recovery period [1]. For a photovoltaic (PV) generation system, the cost of failure is equal to the value of the energy that would be generated while the system is down plus the cost of repairing and replacing parts [2]. Over the past several decades, much attention has been directed to the reliability of power electronic systems. In [3]–[6], various metrics of evaluating system reliability are defined. In order to analyze the reliability of power electronic systems, mathematical estimation of reliability is necessary. Component-level failure models are studied extensively [3], [7]–[13], and several quantitative methodologies are presented to build system-level reliability models, both of which combine to give an accurate reliability prediction [5], [14], [15], [16], [17]. In many cases, the classic design cannot meet reliability requirement of specifications. Numerous solutions are proposed to improve the reliability. Active online monitoring, management of faults, and extending fault-tolerant operation by reconfiguring control strategies are among the commonly adopted methods to enhance reliability [18]–[29]. Since redundant design is an effective solution to maintain postfault operation and to thus reduce the number of unexpected breakdown of systems, various power converter topologies equipped with redundant capability are proposed [30]–[48]. In view of the importance of reliability and much research carried out into it, it is considered a timely attempt to present a systematic perspective on the status of the power electronic reliability for engineering design and future research. This paper presents a comprehensive overview of the reliability of power electronic systems. The composition of the review is based on three different scenarios. First, for any given system the reliability assessment or benchmarking is necessary before any reliability improvement effort is attempted. Second, if any reliability improvement of the system is deemed necessary, the algorithmic change may be preferred over significant hardware alternation. Third, the reliability assurance can be implemented in the design stage if the system is yet to be built.

II. RELIABILITY PREDICTION METRICS

The first step in evaluating and improving system reliability is to determine what metrics to analyze. Because metrics always reflect the design goals, any information that is utilized to determine the metrics shall be based on requirements from customers and careful consideration of intended applications. The commonly adopted metrics for the evaluation of power electronic systems encompass reliability, failure rate.

Reliability is defined as the probability that an item (component, subsystem, or system) performs required functions for an intended period of time under given environmental and operational conditions [2]. The reliability function $R(t)$ represents the probability that the system will operate without failures over a time interval $[0,t]$. The reliability of a system is dependent on the time in consideration. The reliability typically decreases as the time in consideration progresses. For commercial products, the time should cover the warranty time. B. Failure Rate The failure rate of an item is an indication of the "proneness to failure" of the item after time t has elapsed. Fig. 1 shows a typical failure rate curve as a function of time, which is commonly known as the bathtub curve.

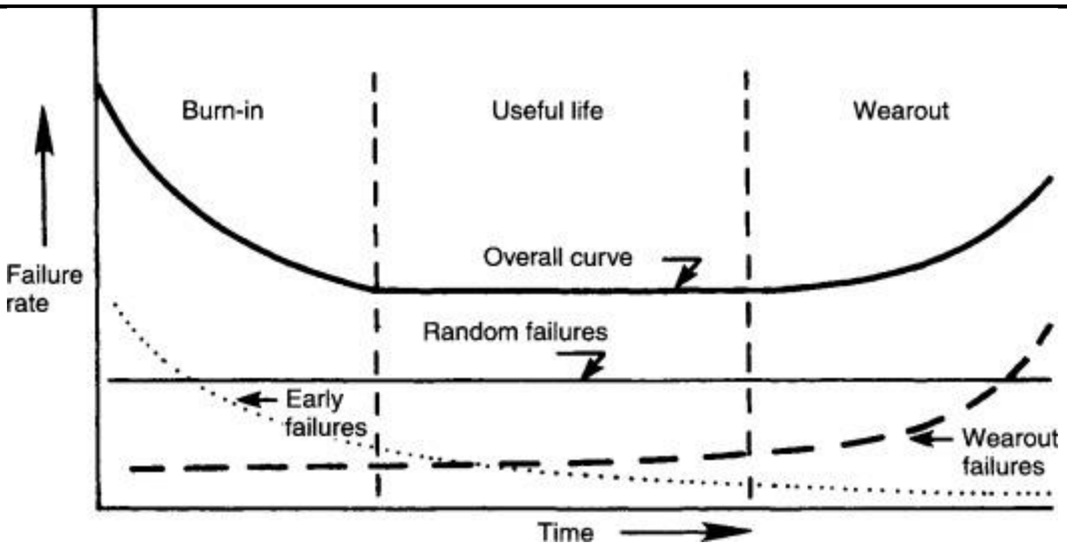

Fig. 1 shows failure rate curve (bathtub curve)

The shape of the bathtub curve in Fig. 1 suggests that the life cycle of an item can be divided into three different periods: the burn-in period, the useful life period, and the wear-out period. Although an item is subjected to quite extensive test procedure and much of the infant mortality is removed before they are put into use, undiscovered defects in an item during the process of design or production lead to the high failure rate in the burn-in period. When the item survives in the initial burn-in period, the failure rate tends to stabilize at a level where it remains relatively constant for a certain period of time before the item begins to wear out. While in wear-out period, systems have finished their required missions. Therefore, the failure rate in useful life time is important to carry out reliability analysis. The failure rate $\lambda(t)$ is related to the reliability function $R(t)$ by $\lambda(t) = \lim \Delta t \to 0\ R(t) - R(t + \Delta t)\ R(t)\Delta t = -\ 1\ R(t)\ dR(t)\ dt$ (1) where Δt is a time interval with $\Delta t > 0$. The reliability $R(t)$ is determined from the failure rate $\lambda(t)$ with the consideration of $R(0) = 1$, i.e., the item is fully functional at the initial state $R(t) = e - t\ 0\ \lambda(\tau)d\tau$. (2) In many reliability models, the failure rates of components and subsystems are assumed independent of time, although this assumption has limitations [4], [49]. With the assumption of $\lambda(t) = \lambda$, (2) is simplified to $R(t) = e{-}\lambda t$. (3) The failure rate is then estimated from the mean number of failures per unit time, which is expressed in failures in time (FIT) 1 FIT = $10{-}9$ failure/hour. (4) C. Mean Time to Failure The MTTF is the expected time before a failure occurs. Unlike reliability, MTTF does not depend on a particular period of time. It gives the average time in which an item operates without failing. MTTF is a widely quoted performance metric for comparison of various system designs. This indicator reflects life distribution of an item. Nonetheless, it does not convey the information that a longer MTTF than the mission time means that the system is highly reliable within mission time. When the failure rate $\lambda(t)$ is constant λ, the expression for MTTF is simplified to MTTF = $1\ \lambda$. (6) D. Mean Time to Repair The (MTTR) is the mean repair time that it takes to eliminate a failure and to restore the system to a specified state. The repair time depends on maintainability, such as effective diagnosis of faults, replaceable components at hand, and so on. E. Availability and Average Availability The availability is the probability that a system will be functioning at a given time. The average availability denotes the mean portion of the time the system is operating over a given period of time. For a repairable system, if it is repaired to an "as good as new" condition every time it fails, the average availability is Aavg = MTTF MTTF + MTTR. (7) Therefore, availability improvement entails increasing MTTF and decreasing MTTR. The main limitation associated with the metric of average availability lies in the fact that it cannot reflect frequency of failures or maintenances required. Hence, it is only utilized to assess the repairable systems where the primary concern is availability rather than reliability.

II. RELIABILITY ASSESSMENT OF POWER ELECTRONIC SYSTEMS

Reliability evaluation is important for design and operation management of the systems. Quantitative assessment of reliability for power electronic converters is essential in determining whether a particular design meets certain specifications. It also serves as a criterion to compare different topologies, control strategies, and components. Moreover, the accurate reliability prediction gives a valuable guidance to management of the system operation and maintenance. All reliability analysis involves some forms of models, which are either at the component level or at the system level. A. Component-Level Reliability Models For power electronic systems, reliability research at the component level has been mainly focused on failure rate models for the key components in power circuits, such as power semiconductors, capacitors, and magnetic devices. Field experiences have demonstrated that electrolytic capacitors and power switching devices such as insulated gate bipolar transistors (IGBTs) and metal–oxide field-effect transistors (MOSFETs) are the most vulnerable components. Magnetic components are much more reliable and feature failure rates that are more than one order of magnitude lower than those of other power devices [2], [51]. There are numerous reliability models available for these electronic components. Empirical-based models, which typically rely on observed failure data to quantify model variables, are most widely employed to analyze the reliability of components. The premise is that the valid failure-rate data are readily available either from field applications or from laboratory tests. There are many empirical-based reliability models of electronic devices, but the military handbook for the reliability prediction of electronic equipment (Military-Handbook-217) is well known and widely accepted in both military and industrial applications [7]. Another important data source of empirical-based failure rate models is RDF 2000, which considers dormant modes and effects of the temperature cycles, and includes data of IGBTs [52]. RDF2000 is a preferred reference in a complex analysis since it takes into account all types of stress. The failure rates of IGBTs, diodes, and capacitors are estimated and compared in [5] from two data sources and also Coffin–Manson and Arrhenius Equations. It turns out that each approach has its disadvantages. Thermal failure mechanisms of IGBTs have become a focal area in the component-level reliability research of power electronics. The methodology considers electrical and mechanical stresses, temperature changes, and spatial temperature gradients. It tries to explore each root cause of component failures. The physics-of-failure method can model potential failure mechanics, predict wear-out conditions, and integrate reliability into design process. However, building this type of models is complex and costly, and requires substantial knowledge about materials, process, and failure mechanism [13]. B. System or Subsystem-Level Reliability Models for Non fault Tolerant or Fault-Tolerant Systems A system-level reliability model presents a clear picture of functional interdependences and provides a framework for developing quantitative reliability estimates of systems to guide the design tradeoff process. Several methodologies to quantify the reliability metrics of power electronic converters have been introduced. They can be categorized into three types of reliability models: part-count methods, combinatorial models, and state-space models.

1) Part-Count Models: The following have been assumed in the part-count model: 1) any fault that occurs to each of the components or subsystems will cause the overall systems to fail; 2) at components level, the failure rates of individual components are assumed constant during useful life time; 3) the system is treated as a series structure of all components or subsystems. The MTTF of the inverter is estimated as $MTTF = 1\ \lambda(t) = 1\ \lambda C + 6\lambda T + 6\lambda D$ (9) where λC , λT , and λD are the failure rate of the capacitor, the IGBT, and the diode, respectively.

2) Combinatorial Models: Combinatorial models are extensions to part-count models and include fault trees, success trees, and reliability blocks diagrams. These methods can be used to analyze reliability of simple redundant systems with perfect coverage. Fault tree has been used to analyze reliability of electric drive systems as illustrated by Fig. 4 [17].

3) Markov Model: Markov model is based on graphical representation of system states that correspond to system configurations, which are reached after a unique sequence of component failures and transitions among these states.

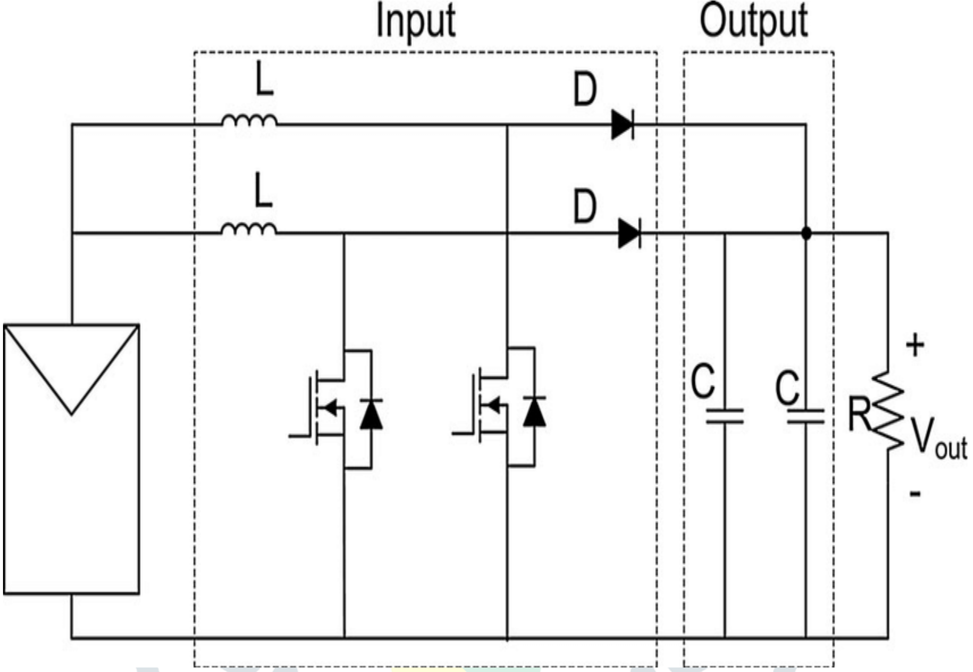

Fig. 2. Schematic of a two-phase boost converter

The system is said in Fig. 2. Schematic of a two-phase boost converter. One important property of Markov process is that the transition probability from one state to another does not depend on the previous states but only on the present state. Hence, the Markov model cannot be used to evaluate the system reliability when components have time-varying failure rates. Another shortcoming is that state space grows exponentially with the number of components. For large system, it is difficult to generate the Markov model from the system functional description and components failure analysis.

III. IMPROVEMENT OF THE SYSTEM RELIABILITY

When reliability of systems designed cannot meet requirements, it is necessary to improve it. Many solutions are proposed to enhance reliability of the power electronic systems from the perspectives of design and active management of operation. The former is effective at the beginning phase of system design and results in higher cost, which is explained in the next section. The latter is based on the existing hardware and realized by modified or augmented control. This section is devoted to management of operation. The solutions found in literature can be classified into three groups: thermal management, diagnostic, and prognostic. A. Active Thermal Management In power electronic systems, the key components, such as electrolytic capacitors and power semiconductor devices, are sensitive to temperature and/or temperature variations. The most contributing stress factor to failure rates of MOSFETs and capacitors are related to temperature [53]. The most common failures of IGBTs are related to thermal-over-temperature- or thermal-cycling-induced failures [18]. Active thermal management techniques are proposed to regulate steady state and transient thermal-mechanical stress in power electronic modules [18], [53]. Central to the concept of active thermal control is that the junction temperature of devices depends on power loss and can be controlled by regulation of power loss of devices. In [53], the junction temperatures of IGBTs and diodes are estimated based on the instantaneous temperature of the heat sink and a dynamic thermal model of the inverter for motor drives. Then switching frequency and load current are then regulated according to the maximum junction temperature to guarantee junction temperatures of all devices below a critical value. Many methods of fault diagnosis in power electronic systems have been reported in the literature. These methods are mainly classified into two categories:

1) the methods based on information of input or output current or voltage at converter terminals; and

2) the methods based on current or voltage information of devices.

1) Diagnostic Techniques Based on Converter Terminal Quantities: The basic idea is that characteristics of the input or output voltage or current of the converters under normal conditions are different from the ones under faulted conditions.

These electrical variables are sensed and compared with predefined performance metrics to determine whether a fault has happened and identify faulted components and types of faults.

Fig.3. Diagram of output-voltage phasors at switching frequency for the 11-level H-bridge cascaded inverter

Fig.3. Diagram of output-voltage phasors at switching frequency for the 11-level H-bridge cascaded inverter in each phase leg. (a) Under the normal condition the output-voltage phasor vs at the switching frequency is approximately zero due to the phase shift of the carriers. (b) Under the faulted condition the switching frequency phasor vs cannot be nullified and the resultant phasor's phase angle is correlated with particular faulted cell. This method needs only two current sensors. However, this method can detect only open-switch faults, and is only applicable to a three-phase sinusoidal inverter with no neutral current. In [27], the authors proposed a method of fault diagnosis for a three-phase voltage-source inverter of motor drives. The method is based on Concordia stator mean current patterns. Under healthy and ideal conditions, the average stator current pattern is a point. Considering offset current, the average current pattern should be a circle. When a fault occurs, the stator currents are no long symmetric, and a dc component exists in the stator current vector. And correspondingly the average stator current pattern is biased in the direction that depends on which switch is out of order.

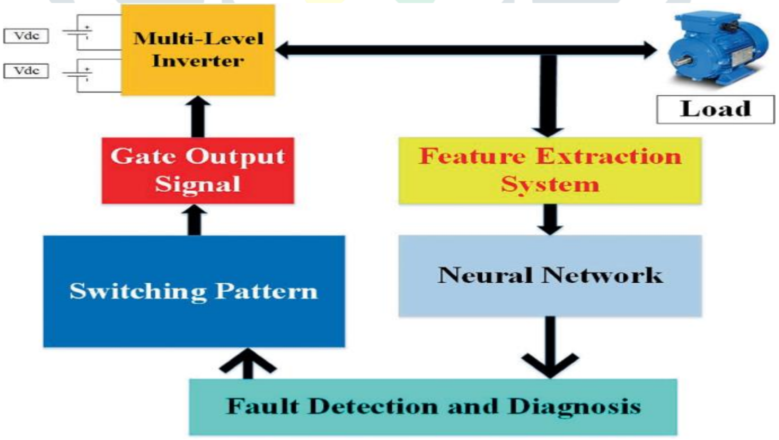

Fig. 4 Fault detection and diagnostics in a cascaded multilevel inverter using Artificial neural network

Artificial intelligence (AI) algorithms have been proposed to detect fault in a cascaded multilevel converter [28]. The proposed scheme is illustrated in Fig. 4. The first step is sampling of output-voltage signals. Then, the mathematical algorithms like fast Fourier transform and correlation are applied to the measured data. This is called feature extraction system (FES), which can reduce the number and size of neural network (NN) and training time. When FES is completed, the NN analyzes the data to detect faults. The behaviors of the NN depend on selection of FES process, its own structure, and the training process. The detection process is computationally intensive and time consuming. Various specific methods of fault diagnosis have been proposed based on input or output currents or voltage information. These methods employ output or input voltages and current information rather than states of power devices. Therefore, they belong to indirect detection schemes and bear relatively low cost. However, these methods need performance criteria built in advance. Accuracy and reliability of diagnosis depend closely on whether these criteria can distinguish all possible healthy states from faulted conditions. 2) Diagnostic Techniques Based on Voltages or Currents of Devices: These methods are based on direct detection of device faults. The principle is that the current and voltage across power switches cannot track command signals (gate driver signals) from the controller when they are open-circuited or shortcircuited. The controller needs to monitor these voltage and current parameters. A diagnosis method for open-circuit fault in three-phase voltage-source inverters without sensors is proposed [29]. The collector–emitter voltage drop of an IGBT follows voltage level changes of the gate driving signal during normal state. When an open-circuited fault occurs to the IGBT, its collector–emitter voltage remains constant at high level. Therefore, the controller can detect a fault by judging the gate command signal and the collector–emitter voltage drop of an IGBT. Hence, the opencircuited faults of six switches in the three-phase inverter can be detected by monitoring of six gating signals and three collector– emitter voltages of the lower switches in three phase legs. The techniques based on device voltage and current information feature high-speed response, accuracy, and reliability, and even can realize cycle-by-cycle diagnosis. However, large numbers of sensors are needed since the controller needs almost all the current and voltage signals of each switch. Therefore, complex hardware and the associated high cost are the main drawbacks although development of an integrated smart driver technique will mitigate this problem. In addition, for large systems with hundreds of power switches, real-time monitoring constitutes a daunting task for the controllers. In summary, these techniques of fault diagnosis are mainly focused on power switches. Most of these methods amount to indirect detection of switch faults based on load currents of the power converter. Their salient characteristics include simple hardware circuit and low cost. However, they typically take more than one fundamental period to detect faults. Such delay may be unacceptable for some applications that require real-time detection. They also need complex algorithms to process measured data. It is difficult to distinguish normal transient process and actual faults. Methods to improve accuracy of detection are proposed by some literature.

IV. FAULT-TOLERANT OPERATION OF POWER ELECTRONIC SYSTEMS BASED ON REDUNDANT DESIGN

Fault-tolerant operation means that a fault in a component or subsystem does not cause the overall system to malfunction [55]. The characteristic of fault tolerance avoids the system from significant loss or unexpected interruptions and improves availability. The research in fault tolerance involves four different aspects: redundancy, fault diagnosis, fault isolation, and online repair. Redundancy can be realized by extra systems or components. Here, just the latter is considered and online repair is unavailable. Fault diagnosis is covered by the last section, and this part focuses on redundant design and fault partitioning. A. Necessity of Fault Tolerance Although reliability such as MTTF or availability can be enhanced by many solutions and failure rates can be minimized as low as possible, failure is inevitable during the mission time of systems. In some critical applications, malfunction is unacceptable or causes serious losses. Therefore, fault tolerance is necessary in many power electronic systems. For electric drives utilized for EVs and HEVs, faults can be critical since an uncontrolled output torque may have an adverse impact on the vehicle stability, which ultimately can risk the passenger safety. Hence, a limping-home function is desirable [30]. According to the performance of postfault operation, there are two types of fault-tolerant operation: the degraded operation and quasi-normal operation, which differ in terms of system cost, performance, and feasibility. B. Degraded Operation Degraded operation under postfault conditions denotes that systems can tolerant faults and continue to perform some key functions with reduced output power or voltage, worsened power quality, or other suboptimal performance metrics. Generally, degraded operation is realized by reconfiguring control strategies to explore inherent redundant capability of the converters with no or few additional devices. Degraded operation of multilevel converters and three-phase voltage-source inverters are investigated extensively in the literature.

V. CONCLUSIONS AND DISCUSSIONS

A comprehensive review of the reliability of power electronic converters has been carried out with the intention to provide a clear picture of the current status of this particular research field. The classification of reliability of power electronics systems is based on three levels. Methods of reliability assessment are first analyzed and compared to provide designers an easy selection of an appropriate reliability model. For existing systems or cost-sensitive systems, several solutions to improve reliability based on active management of operation are introduced, and their advantages and disadvantages are analyzed. For missioncritical applications, fault-tolerant design of power electronic systems serves as a suitable design option. From the analysis of main modified topologies with fault-tolerant capability of multilevel converters, matrix converters, and conventional threephase half-bridge inverters, it is shown that these new topologies with redundancy increase the complexity and cost of systems and even decrease some performance. The more-effective component-level redundant design for power electronic systems should be studied further. The status of the current research and identified limitations are summarized as follows:

1) Study of fault-tolerant operation is mainly focused on multilevel converters with more components and natural redundant switching state combinations. Some studies reported in the literature involve three-phase matrix converters and voltage-source inverters for motor drives where it is possible for the inverters to operate with twophase output.

2) More components are added to the standard power converters to realize fault tolerance, especially for redundant design. In a true redundant design for all components (switches, diodes, and capacitors) and all types of faults (short circuit and open circuit), the total number of power components even hits four times of that of the standard topology [48]. As a result, the cost could even exceed that of system-level redundancy.

3) It appears that the fault tolerance is assumed in certain to improve the reliability of the power electronic systems. Very few quantitative estimation of increase in MTTF or average availability due to redundant design has been reported except that Lenana et al. compare failure rates of semiconductors devices of standard multilevel converters and ones with fault-tolerant design [31].

4) In contrast to the research effort devoted to switch (IGBT)- fault-tolerant capability of systems, very minimal attention has been directed to faults of diodes and capacitors.

5) Since short-circuited faults and open-circuited faults need different isolation and postfault operation strategies, some continuous operations are only feasible for certain types of fault. If systems are designed to handle two types of faults, the number of extra components increases substantially.

6) Due to many redundant switching-state combinations for multilevel converters, effective utilization of these redundant states can optimize and simplify redundant design. It is beneficial to further study redundant states and modulation strategies.

7) Successful detection of faults and transition from faulty state to postfault state are prerequisites. Low-cost and reliable detection techniques and transient processes from occurrence of faults to postfault steady state should be studied further.

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