Survey on Reliability of Power Electronic Systems

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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 and analyzed. 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. Based on these three scenarios, the organization of the subsequent text is as follows. Section II introduces fundamental theory of reliability that is relevant to this study. Several common reliability models are presented and compared in Section III. Section IV summarizes the existing methods that are commonly employed to enhance reliability of systems without fundamental change to the systems' architectures. Such methods include active thermal and fault management and degraded operation under faulted situations. Section V introduces concepts of redundancy and modified power electronic systems that are equipped with redundant functionalities. The concluding remarks and discussion are summarized in Section VI.

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, mean

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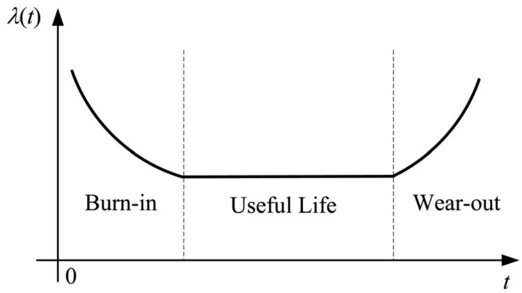

Fig. 1. Typical failure rate curve as a function of time.

time to failure (MTTF), mean time to repair (MTTR), and availability.

A. Reliability

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*. 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

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{R(t) - R(t+\Delta t)}{R(t)\Delta t} = -\frac{1}{R(t)}\frac{dR(t)}{dt} \quad (1)$$

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

$$R(t) = e^{-\int_0^t \lambda(\tau) d\tau}. \quad (2)$$

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

$$R(t) = e^{-\lambda t}. \quad (3)$$

The failure rate is then estimated from the mean number of failures per unit time, which is expressed in *failures in time (FIT)*

$$1 \text{ FIT} = 10^{-9} \text{ failure/hour}. \quad (4)$$

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.

The relationship between MTTF and reliability function is described by

$$\text{MTTF} = \int_0^{+\infty} R(t)dt \quad (5)$$

where $R(t)$ is the reliability function. When the failure rate $\lambda(t)$ is constant λ, the expression for MTTF is simplified to

$$\text{MTTF} = \frac{1}{\lambda}. \quad (6)$$

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

$$A_{\text{avg}} = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}}. \quad (7)$$

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.

III. 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 [1], [5], [14], [15], [16], [50]. 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]. MIL-217 provides an extensive database for many different types of parts. It is intended to provide a uniform database for reliability prediction without substantial reliability experience of a particular component. However, the reliability handbook is criticized for several limitations [8]. One of the limitations is that the models in MIL-217 assume constant failure rate for components over their lifetime [3]. Another main limitation is that the reliability results derived from these models are often pessimistic and cause costly conservative design. Furthermore, MIL-217 neither contains data to determine the influence of dormant modes on components, nor contains the data that reflect the effects of thermal cycles, which are all of significant importance for practical application of power electronics. The failure rate model of some commonly used components such as IGBT is not covered by the handbook. Therefore, the reference values of MOSFETs are often chosen for analysis of failure rate of IGBTs.

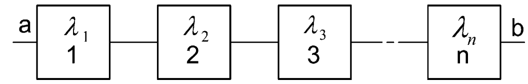

Fig. 2. Illustration of a series configuration with n subsystems.

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.

Since the empirical models of electronic devices are based on previously observed data, reliability prediction results from these models are inaccurate for applications with different design, and operational and environmental conditions. The physics-of-failure model is researched extensively for analyzing reliability of electronic devices, which specifically include power semiconductor devices and electrolytic capacitors [9]–[12]. 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 Nonfault-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.

For a series structure with n subsystems as shown in Fig. 2, the ith subsystem has failure rate λ_i; the failure rate λ of the overall system is determined by

$$\lambda = \sum_{i=1}^{n} \lambda_i. \tag{8}$$

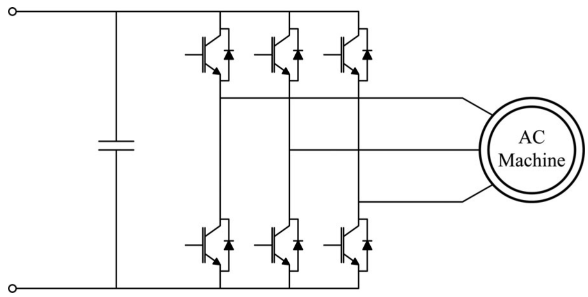

Fig. 3. Schematic of a typical three-phase voltage-source inverter for HEV.

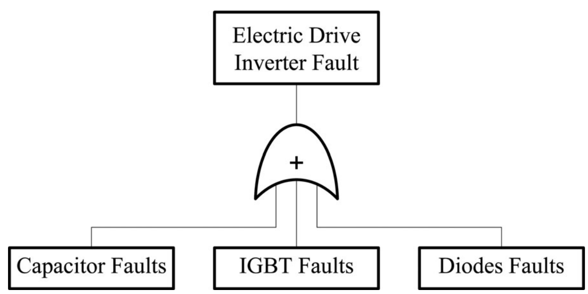

Fig. 4. Fault tree of a typical three-phase voltage-source inverter for HEV.

The main advantage of part-count method lies in its simplicity. A part-count model can provide an adequate reliability estimation for small systems. It is also an effective approach to reliability comparison among different power electronic system architectures at the beginning of design stage. However, for the systems that can tolerate some failures or that can be repaired, the approach lead to over conservative results. For power electronic converters that are not equipped with fault-tolerant capability, this part-count method is often adopted [1], [4], [5], [14]. For example, part-count method in [5] is employed to estimate the reliability of a three-phase voltage-source inverter for HEVs as shown in Fig. 3. Any fault of capacitor, IGBTs, and diodes will lead the system to fail. The MTTF of the inverter is estimated based on this model

$$\mathrm{MTTF} = \frac{1}{\lambda(t)} = \frac{1}{\lambda_C + 6\lambda_T + 6\lambda_D} \tag{9}$$

where λ_C, λ_T, and λ_D 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]. Unfortunately, combinatorial models cannot reflect the details of fault-tolerant systems, such as repair process, imperfect coverage, state-dependent failure rates, order of component failures, and reconfiguration.

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. The system is said in *failure-free* state when all components are nonfaulted. The system can evolve from the failure-free state to other states when faults occur to the components. There are two types of states in Markov models: 1) absorbing states that are associated with failed system configurations; and 2) nonabsorbing states that correspond to configurations in which the system can deliver full or partial functionalities.

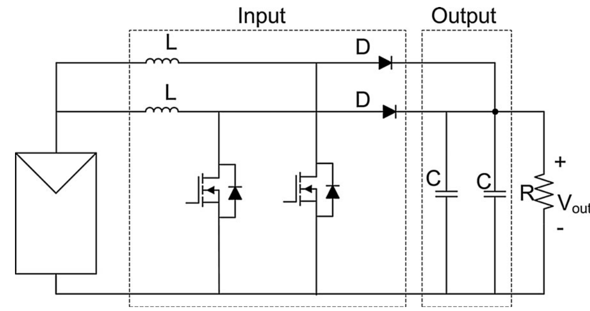

Fig. 5. Schematic of a two-phase boost converter.

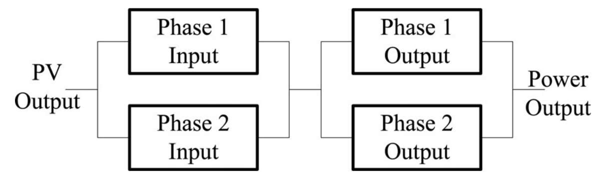

Fig. 6. Functional block diagram.

The Markov reliability model is used to analyze a two-phase interleaved boost converter for PV application [15]. The fault-tolerant system in [15] can operate with reduced phases and depleted output capacitor bank. Each phase is divided into two subsystems: input unit consisting of diode, switch, and inductor, and output unit including output capacitor. Only when all input units, output units, or both in two phases are faulted, will the whole system fail. Since inductors' failure rates are much lower than those of semiconductors and electrolytic capacitors, their failures are not considered. It is assumed that the system is nonrepairable, and that the controller is capable of fault detection, isolation, and reconfiguration, i.e., the system has perfect coverage.

The schematic, functional block diagram and state-transition diagram of the converter are shown in Figs. 5, 6, and 7. The nodes of the state-transition diagram in Fig. 7 represent the states of each system configuration. The edges in Fig. 7 represent transitions between configurations triggered by components failures. The state k^{mn} $(k = 1, 2, \ldots, 7;\ m = 1, 2;\ n = 1, 2)$ denotes the system state with m failed input stages and n failed output stages. λ_{Tm} and λ_{Dm} denote the failure rate of IGBT or diode under the condition of m failed input stages. λ_{Cmn} represents the failure rate of capacitors with m failed input stages and n failed output stages.

Evaluation of the model through simulation or mathematical algorithms would yield the probability of the system being in one of the states. The Chapman–Kolmogorov equation is used to analyze the Markov reliability model. For instance, the Chapman–Kolmogorov equations for states 0^{00} and 3^{11} are

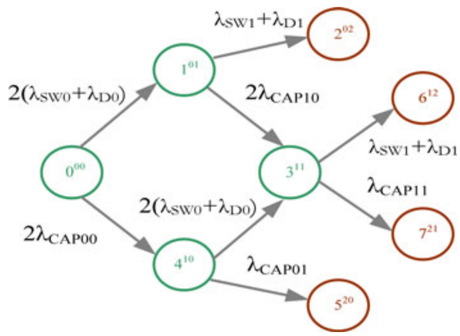

Fig. 7. State-transition diagram.

given by

$$\begin{aligned}\frac{dp_0(t)}{dt} &= -\left[2(\lambda_{T0}+\lambda_{D0})+2\lambda_{C00}\right]p_0(t)\\ \frac{dp_3(t)}{dt} &= 2\lambda_{C10}p_1(t)+2(\lambda_{T0}+\lambda_{D0})p_4(t)\\ &\quad -\left[(\lambda_{T1}+\lambda_{D1})+\lambda_{C11}\right]p_3(t)\end{aligned} \tag{10}$$

where $p_k(t)$ is the probability of the system being in state k^{mn} at time t. Since the system has four nonabsorbing states, the system reliability at time t can be expressed as

$$R(t) = p_0(t) + p_1(t) + p_2(t) + p_3(t). \tag{11}$$

Once reliability $R(t)$ is obtained, MTTF can be readily estimated based on (5).

Markov chain is a very effective approach to quantify the reliability of fault-tolerant systems. This approach can cover many features of fault-tolerant systems, such as sequence of failures, failure coverage, and state-dependent failure rates. One can estimate different reliability metrics from the Markov model, such as MTTF, reliability, availability, and so on.

There are some limitations associated with Markov model. 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.

The challenge of applying Markov models to increasingly complicated systems can be clearly appreciated in a high-power multilevel converter that may have hundreds of components and subsequent failure mode transitions. In a centralized PV generation plant, many individual inverter systems provide power to loads together and interact with each other. It is difficult or laborious to build reliability models for these complex large systems. In order to effectively tackle the aforementioned problem, it is proposed to decompose a large system into several subsystems. Then, one of these reliability models or their combination is used to analyze reliability of each subsystem and the overall system. Decomposition of a large system depends on the specific system and failure modes of components. The PV inverter for generation is decomposed into storage capacitor bank, power semiconductor devices, and cooling subsystems, based on the similar failure rate models [2]. In [17] a motor drive system is broken down into three functional blocks: stators, bearing, and electric drive. Further decomposition can be carried out for subsystems in order to simplify analysis.

IV. 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. In [18], the maximum junction temperature and temperature changes are monitored as shown in Fig. 8. When junction temperatures or temperature changes exceed the safety threshold, switching frequency and current limit are decreased to regulate power loss and thus to prevent overtemperature and power-cycling failure in IGBT modules.

However, the delay between change in junction temperatures and changes in power loss makes it a challenging task to balance effectiveness of thermal management and utilization of power device thermal capacity.

B. Fault Diagnosis

Fault diagnosis, which consists of two stages, i.e., fault detection and identification, is another effective approach to improving reliability of systems. Accurate and timely detection and protection can prevent fault propagation and catastrophic results. The fault-tolerant operation also requires effective

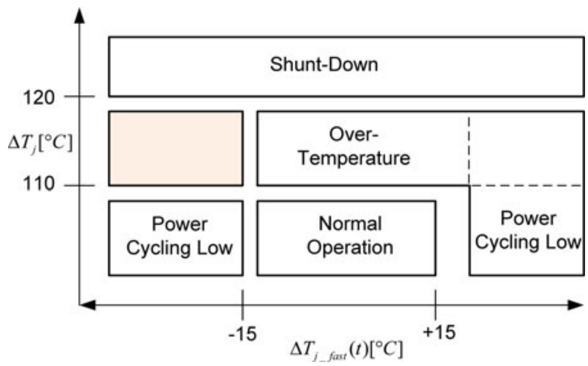

Fig. 8. Regions for an active thermal controller.

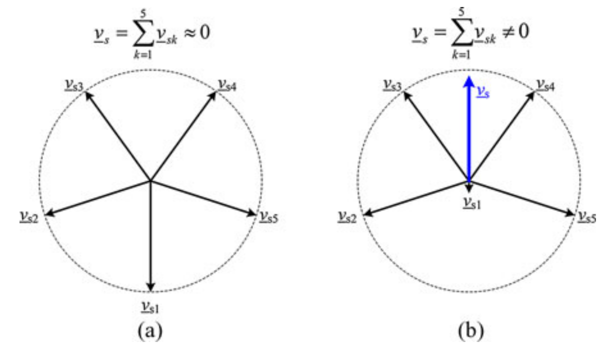

Fig. 9. Diagram of output-voltage phasors at switching frequency for the 11-level H-bridge cascaded inverter in each phase leg. (a) Under the normal condition the output-voltage phasor $\underline{v}_s$ at the switching frequency is approximately zero due to the phase shift of the carriers. (b) Under the faulted condition the switching frequency phasor $\underline{v}_s$ cannot be nullified and the resultant phasor's phase angle is correlated with particular faulted cell.

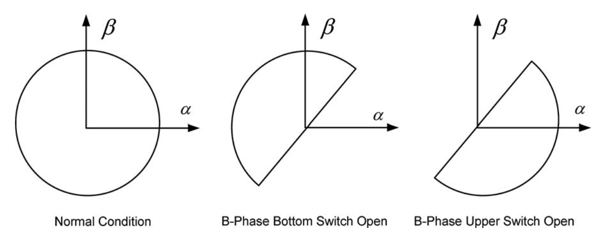

Fig. 10. Trajectories of current vectors under different fault scenarios.

diagnosis of faults. Moreover, diagnosis reduces MTTR and in turn improves average availability of the system.

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.

Lezana *et al*. propose a method to detect a faulted cell in a cascaded multilevel converter as shown in Fig. 9 based on output-voltage frequency analysis [22]. Due to phase shift among PWM carrier signals, the output-voltage phasor $\underline{v}_s$ at switching frequency is zero. If a fault occurs in a cell, the switching-frequency phasor $\underline{v}_s$ of the output phase voltage is nonzero. The phase angle of the phasor $\underline{v}_s$ indicates the location of the faulted cell. The magnitude and phase angle of the phasor $\underline{v}_s$ can be obtained through discrete Fourier transform (DFT) of sampled output phase voltages. The same method is applied to diagnosis of faults in flying capacitor multilevel converters (FCMC) [23], [24]. The method is simple and bears minimal additional cost since only one sensor per phase is necessary regardless the number of converter cells. However, the difficulty is to find a proper phasor amplitude threshold to assert a fault since practical $\underline{v}_s$ is nonzero even under normal conditions. The second challenge is to distinguish normal transients from actual faults.

Smith *et al*. propose a method to detect intermittent misfiring fault of switches in the three-phase H-bridge inverter for motor drives based on motor stator current time-domain response [25]. The principle is explained as follows. When a misfiring fault occurs on one of the switching devices in the inverter, the voltage disturbance will cause an increment to the stator current space vector. The incremental current will be in the direction that is determined distinctively by the failed device. As the inverter recovers from the disturbance, the length of the incremental current vector reduces to zero. The incremental system model can be used to provide compensation to the measured current response, such that the modified incremental current signal will decay in the opposite direction to the initial offset caused by the voltage disturbance. Therefore, the trajectory of the current response can be used to detect the occurrence of the misfiring fault and pinpoint the problematic switching device.

A method to detect faults of switches in a three-wire three-phase voltage-source inverter is proposed in [26]. The solution is based on the analysis of the current vector trajectory in the Concordia frame. It can be observed that the current trajectories take a half cycle, rather than a cycle under faulted conditions as shown in Fig. 10. Therefore, the faulty leg in the inverter can be located based on the knowledge of the current trajectory. The faulty transistor is isolated by determining the current polarity in the faulty phase. 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. Seven patterns are formed with the mean stator

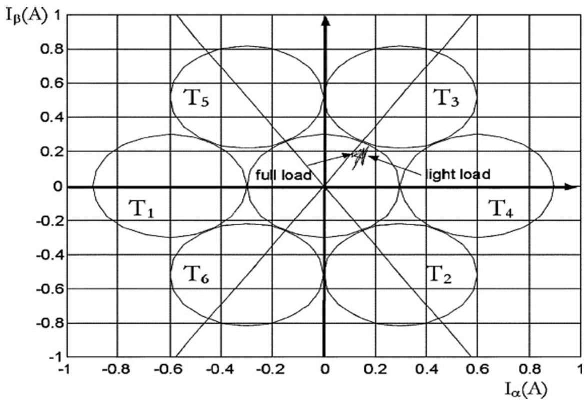

Fig. 11. Concordia average current vectors.

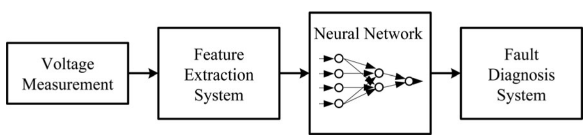

Fig. 12. Fault-detection scheme based on the AI algorithm.

current vectors. One of these patterns is dedicated to the healthy state while the other six correspond to open-circuited fault of six switches, as shown in Fig. 11. This method only needs two current sensors. However, the boundary design of the pattern that corresponds to healthy state has a significant influence on detection accuracy.

Artificial intelligence (AI) algorithms have been proposed to detect fault in a cascaded multilevel converter [28]. The proposed scheme is illustrated in Fig. 12. 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 short-circuited. 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 open-circuited 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. On the other hand, direct monitoring of voltage and current signals of devices provides a reliable solution to fault diagnosis with the substantial sensing requirement. Smart drivers are studied extensively, which could alleviate the problem as further progresses are made.

C. Prognosis of Failures in Power Devices

Prognosis is the ability to accurately and precisely predict the remaining useful life of a failing component or subsystem [54]. Prognosis can detect potential faults and notify controllers or personnel to take preventive or remedial actions [6]. In comparison to the fault diagnosis, significant challenges associated with prognosis exist since the prediction of fault evolution involves substantial uncertainty. Several prognosis methods reported in the literature are mainly focused on the power semiconductor devices.

Prognostic system based on the saturated collector–emitter voltage V_{CESat} trace of the IGBT module is developed for HEV application [19]. As shown in Fig. 13, V_{CESat} of IGBT modules exhibits a significant degradation trace. V_{CESat} of IGBT remains unchanged until approximately 5×10^5 cycles. Then, it starts decreasing gradually before a sudden drop (more than 17%) at about 6×10^5 cycles, followed by a quick increase of V_{CESat}. The prognosis method is based on the idea that an IGBT will be considered as being seriously degraded if its measured

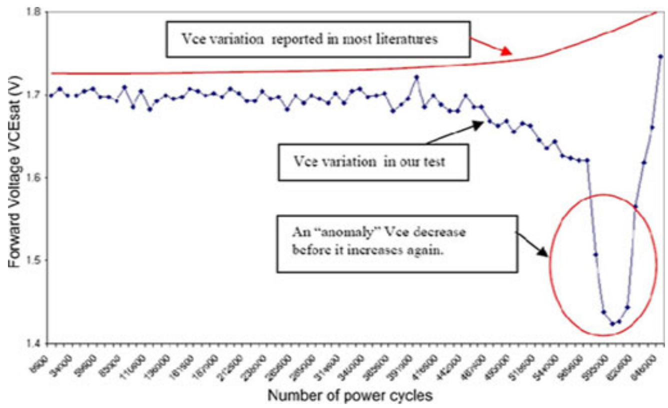

Fig. 13. Variation of V_{CESat} of the IGBT module at 400 A as a function of power cycles.

V_{CESat} deviates by more than $\pm 15\%$ from its normal reference value. A direct comparison is impossible because of wide and fast variation of operating current and temperature during actual vehicle operation. So an adaptive approach is developed. A prognostic subroutine is inserted into the vehicle control system after key-on and/or key-off of each vehicle period. The prognostic algorithm is responsible for building an adaptive reference table and comparing measured V_{CESat} and the reference value with same temperature in the lookup table.

The evaluation of the increase in leakage gate current of power IGBTs or MOSFETs is used for early damage fault prognosis [20]. The principle is that the initial gate current of 100 nA rises to the order of microampere under stressed conditions. When the stressed conditions are suppressed, the gate current remains at values that are several times higher than the initial gate current.

The component of output-voltage ripple at switching frequency in switching power supply is monitored to predict fault of electrolytic capacitors and their remaining life time [21]. The increase of the voltage ripple across capacitors indicates increased equivalent series resistance (ESR), which is one of the best fault signatures for capacitors.

These methods of fault prognosis are all based on failure mechanism of components and need to monitor slight changes in electrical parameters. It is difficult and expensive to detect small signatures which reflect incipient faults of components from large signals.

V. 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]. Wind turbine should not stop under a breakdown of one or more power devices such that electrical energy can be provided to network and costly disconnection time is avoided [45]. In high-power applications, such as high-power motor drives for pipeline pumps in petrochemical industry, for fans in cement industry, for pumps in water pumping stations, and for steel rolling mills in metal industry, reactive power compensation, and grid interface of renewable energy resources, an unexpected shutdown would cause significant production loss [31].

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.

Degraded operation has been studied for cascaded H-bridge multilevel (CHBM) inverter with space-vector modulation applied to motor drives shown in Fig. 14 [32], [33]. In [32], the faulted converter cells are isolated from the system, and redundant switching states are used to generate a neutral voltage shift. Thus, a balanced line-to-line ac output voltage and minimal harmonic distortion result. In comparison to normal operation, the magnitude of output voltage decreases and harmonic distortion increases. Due to unbalance, the load neutral point cannot be directly connected to the neutral point of an inverter output. The main difference of control strategy proposed in [33] is that the faulted cells also participate in operation and contribute two output-voltage levels dependent on specific faulted switches.

Similar to CHBM converters, degraded operation of neutral point clamped (NPC) converters is realized by use of redundant switching states [34]–[37]. Fig. 15 shows the schematic of a conventional three-phase NPC inverter. Li *et al*. present a control scheme to maintain continuous operation of the three-level inverter for a flywheel energy storage system by utilizing the redundancy of voltage vectors [34]. Without the need of extra power devices, this method covers single short-circuited

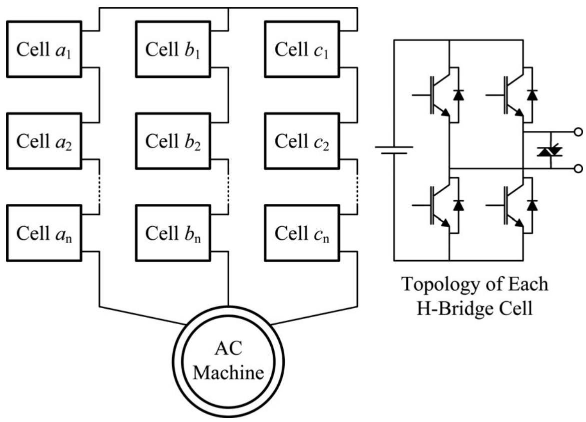

Fig. 14. CHBM inverter as a motor drive.

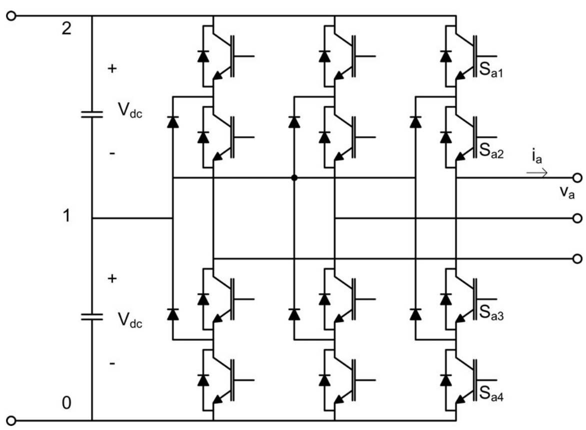

Fig. 15. Schematic of a conventional three-phase neutral point clamped inverter.

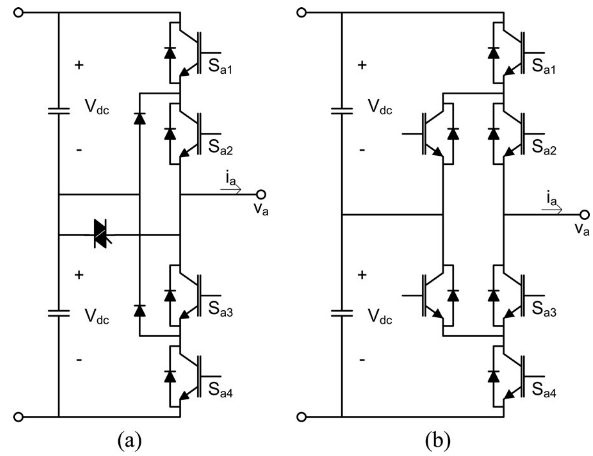

Fig. 16. Schematic of a phase leg of a neutral point-clamped inverter realized with two different fault-tolerant designs.

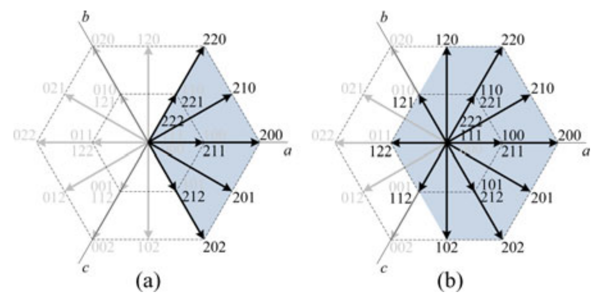

Fig. 17. Vector diagram of an NPC converter when (a) S_{a1} fails in short circuit and (b) S_{a2} fails in short circuit.

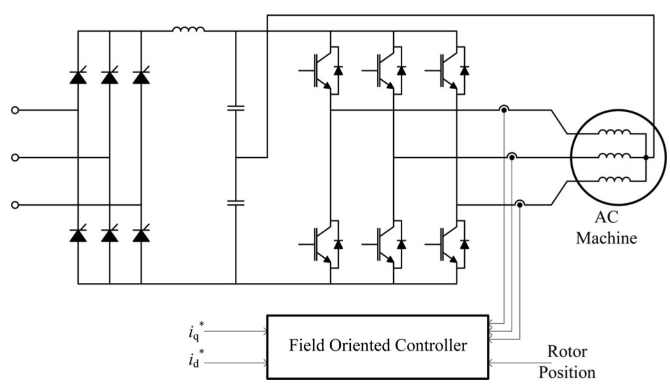

Fig. 18. Three-phase voltage-source inverter for motor drive.

failure of switches or clamping diodes. However, the switches have to withstand the full dc-link voltage. Therefore, overrating of these switches is necessary. Fig. 16 shows two solutions to achieving fault tolerance without device oversizing. The solution shown in Fig. 16(a) is studied in [35]–[37]. Three pairs of thyristors are added to conventional NPC inverter structure to provide balanced three-phase output voltages for short-circuited or open-circuited failures in switches or clamped diodes. Under the normal condition, the SCRs are in off-state. When S_{a2} or S_{a3} fails to turn on, the SCRs are activated to connect load to neutral point and thus maintain continuous operation. The solution shown in Fig. 16(b) features the same control scheme with the previous method to realize degraded operation of NPC converters [38]. The advantage of these two solutions is that it is not necessary to oversize voltage ratings of the power semiconductors. Common to these two solutions is that the maximum modulation index is reduced because of loss of some critical switching states as shown in Fig. 17. Therefore, the attainable magnitudes of output voltages decrease.

Fig. 18 shows a three-phase voltage-source inverter for a motor drive system with open-phase fault-tolerant capability [39]. The principle of the proposed strategy is that motor can work normally as a three-phase or two-phase machine by proper regulation of the phase angles and magnitudes of stator current to keep electromechanical torque unchanged as the system transitions from three-phase to two-phase input power supply. When one phase fails in open circuit and the other two phase legs of the inverter function properly, the output currents increase to $\sqrt{3}$ times of the original value and the phase angle between them is regulated to 60°. Under such condition, the torque generated by motor remains constant. It is worth mentioning that there are several limitations associated with this strategy: 1) it is only applicable for motor drives; 2) only open-circuit faults of diodes and switches can be handled; and 3) oversized dc-link capacitors are needed to handle substantially increased ripple current under the faulted condition.

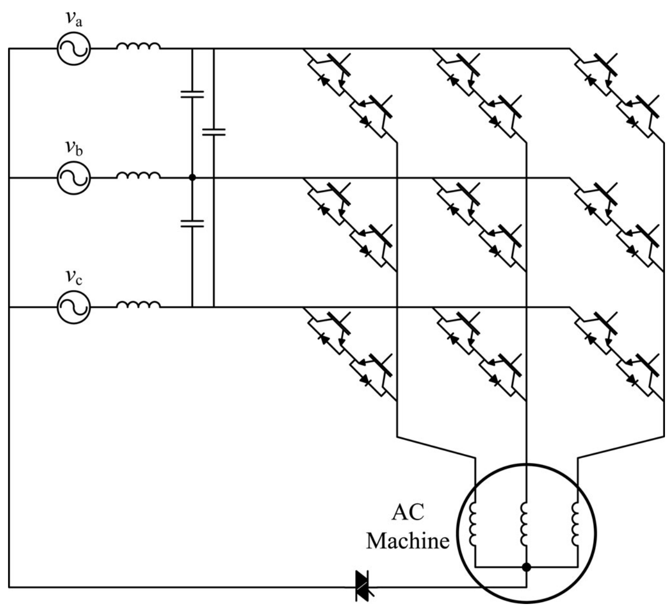

Fig. 19. Three-phase matrix converter for motor drives with fault-tolerant capability.

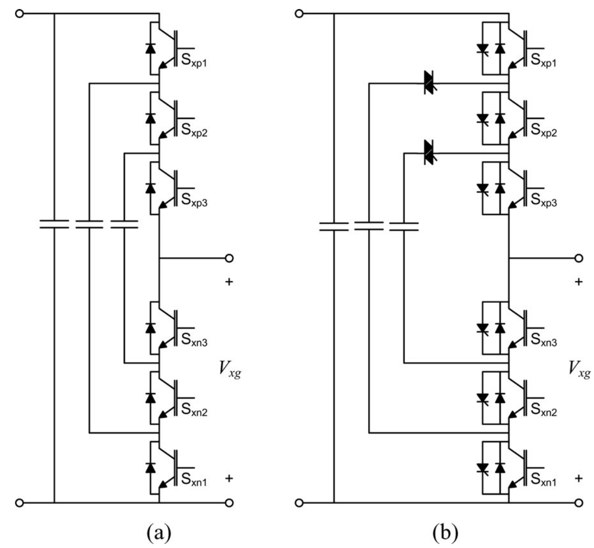

Fig. 20. One phase of (a) a conventional three-cell FCMC; and (b) a fault-tolerant three-cell FCMC.

The similar principle is applied to a matrix converter for motor control shown in Fig. 19. Likewise, only open-circuited faults can be handled.

Degraded operation of power electronic systems can be realized mainly by taking use of systems' natural redundancies. Since minimum additional components are need, simple and low-cost solutions result. However, there are some significant limitations.

1) Application is narrow band. Because of degraded performances, such as reduced output voltage, reduced power, and compromised harmonics distortion, it is only feasible for applications that can tolerate the degraded performance. For some applications, the degraded performance may be unacceptable. For instance, power converters with reduced output voltages under faulty conditions are not suitable well to utility applications. The converters in Fig. 18 and 19 are fault tolerant just for motor drives.
2) Faulted components and fault types that can be covered are limited.
3) Degraded operation is used for multilevel converters due to the fact that they have complex structures and therefore many redundant switching states in combinations.

C. Quasi-Normal Postfault Operation

Because of many limitations relying on inherent fault-tolerant ability of systems, redundant design is studied and reported extensively to provide quasi-normal operation of power converters under fault situations.

Due to high modularity, cascaded multilevel converters as shown in Fig. 14 can provide approximately similar performances to normal operation by simple redundant design. Song *et al.* present a fault-tolerant control for a static synchronous compensator (STATCOM) based on a cascaded H-bridge inverter [40]. During normal state, the inverters operate with $N+1$ cascaded converter cells in each phase and $2N+3$ output-voltage levels. When a fault occurs to a switch, the faulted cell is bypassed, and the number of output-voltage levels decreases to $2N+1$. The phase-shift angles are regulated to generate a balanced output voltage. At the same time, the dc-link voltages of those cells in the faulted phases also need to increase in order to keep voltage magnitudes unchanged. The same redundant design is proposed for a direct-drive wind turbine application [41]. The main disadvantage is associated with the large number of extra components that are used by bypass switches and backup converter cells. Power semiconductor devices and dc-link capacitors need to be oversized to withstand the elevated dc-link voltage under faulty situations.

Maharjan *et al.* propose an improved control scheme for a cascaded inverter with star configuration which is applied to a battery-energy-storage system [56]. The method makes all $3N-1$ healthy converters in the three phases rather than only converter cells in the phase with faults sharing the increased voltage burden equally by introducing a neutral shift. As a result, the modulation indices for all remaining cells increase slightly. The solution can be used for other applications, and can mitigate the pressure of overdesigning power devices. However, the neutral shift is realized by injecting a fundamental-frequency zero-sequence voltage to each cell. Therefore, the neutral point of the load cannot be directly connected to the neutral point of the inverter output.

FCMC as shown in Fig. 20(a) provide inherent series redundancy if the ratings of devices can withstand increased voltage stress. An open-switch or short-switch fault-tolerant design for three-cell four-level FCMC as shown in Fig. 20(b) is proposed and its control strategy is presented in [42]. According to modulation rules, there are $2m$ switching state combinations in each phase leg of an m-cell. However, based on previous clamped capacitor voltages, only $m+1$ states are effective and are utilized to generate $m+1$ output-voltage levels while other states are

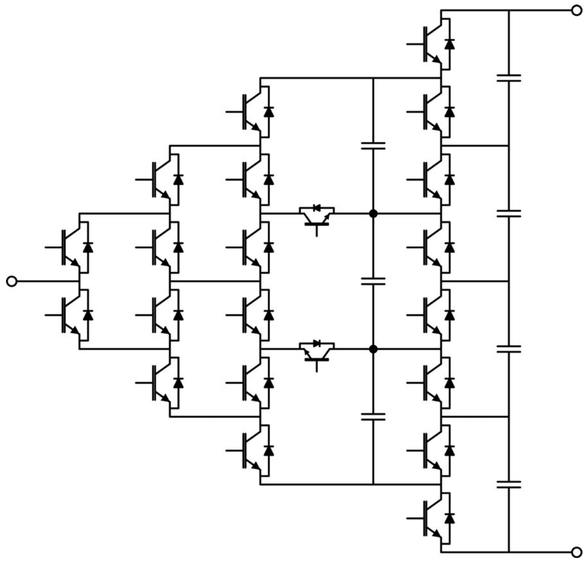

Fig. 21. Modified general multilevel converter with fault-tolerant capability.

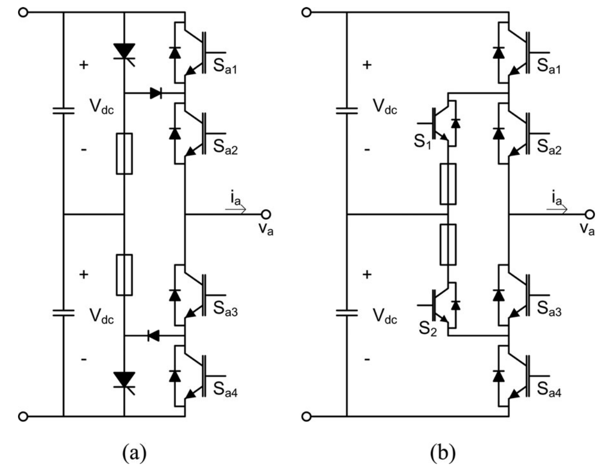

Fig. 22. One leg of NPC three-level converters with two different redundant realizations.

redundant. The presented method in [42] optimizes the switching states by maximizing the number of output-voltage level. For the three-cell converter, the output phase voltage V_{xg} has four levels under normal operation. When a single-switch fault in one phase occurs, the faulted switch and its counterpart are bypassed. The corresponding capacitor is isolated from the system or connected in parallel to the one in a healthy cell. The remaining capacitor voltages are regulated appropriately, and accordingly the inverter still can provide four line-to-ground levels. The disadvantages mainly lie in: 1) under faulty conditions, some switches need to withstand full dc-link voltage, which necessitates oversized design; and 2) large number of extra devices are commanded.

Fig. 21 shows a modified general multilevel converter that is proposed by Chen *et al*. This converter can tolerate short-switch or open-switch faults without loss of any output-voltage level [43]. At least one redundant switching state combination is obtained for any output-voltage level by the change of the circuit configuration. The modified topology achieves redundancy at the price of higher power loss and higher cost compared to the original five-level architecture. Even during normal operation, some output voltage levels have to be realized by five conducted semiconductor devices, while only four devices are in a conduction path for any voltage level for conventional topology. In open-switch or short-switch fault conditions, six devices have to conduct to provide a current path. Increased number of conduction devices will lead to higher conduction losses. On the other hand, the original architecture features good symmetry, where only eight main switches conduct load current and other clamping switches only balance the capacitor voltages. Therefore, the clamping switches only need low current rating.

Two solutions to maintain short-switch fault-tolerant operation of three-phase NPC converters are presented in [44]. For solution I shown in Fig. 22(a), the upper or lower fast fuse is cleared by turning on the SCR when S_{a2} or S_{a3} fails to open. The faulted phase leg operates with two voltage levels, the high level and low level with the absence of the middle level. Likewise, for short-circuited faults of S_{a1} and S_{a4}, high and low voltage levels remain while fuses and transistors are not actuated. In view of loss of middle voltage level, solution II shown in Fig. 22(b) is proposed. For any single short-circuited fault in one phase, the converter still provides three output-voltage levels, which is similar to normal operation. These two solutions can maintain normal output voltage under conditions of no more than one faulted switch in each phase leg. However, some of the switches have to withstand the total dc-link voltage under faulty states. Therefore, oversizing of the component ratings is necessary.

Although the two solutions aforementioned maintain similar-to-normal operation of the NPC converters under faulted conditions, necessary oversized voltage ratings of semiconductors will lead to loss of the most significant advantage of multilevel converter, that is, voltage stress of devices is the half of dc-link voltage. The oversized design results in high cost and low efficiency even under the normal condition. A redundant phase leg is added to the original topology to overcome these limitations [45], [46]. Fig. 23 depicts the overall structure. When a fault occurs to phase leg x with $x \in \{a, b, c\}$, fuses F_x and F_n are cleared. Thus, the faulted leg is isolated from the system. In addition, the bidirectional switch T_x, S_5, and S_6 are activated such that the redundant phase leg replaces the faulted one. The system is reconfigured into a standard NPC converter. The main disadvantage is due to the large number of additional components and therefore higher cost.

Kwak *et al*. present a matrix converter with a redundant phase leg for heavy electric vehicles as shown in Fig. 24 [47]. The main idea is that the fourth leg replaces the faulted leg by a bidirectional switch and thus normal operation of the system is maintained. The limitation lies in the fact that the topology with redundant capability can cover only the open-circuited fault of switches or freewheeling diodes.

There are some other modified topologies with quasi-normal operation capability. The aforementioned solutions include the power electronic converters for which fault-tolerant operation

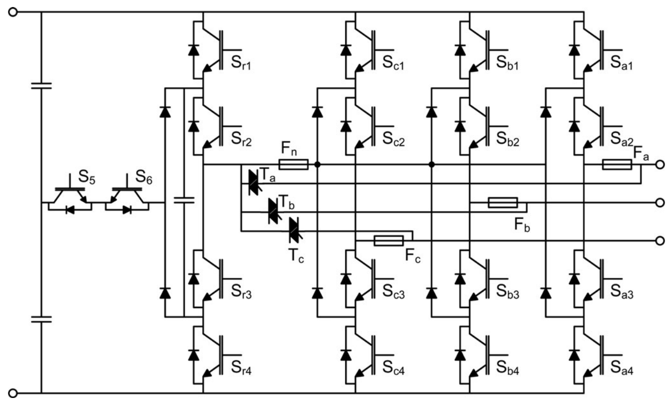

Fig. 23. Three-level converters with a redundant phase leg.

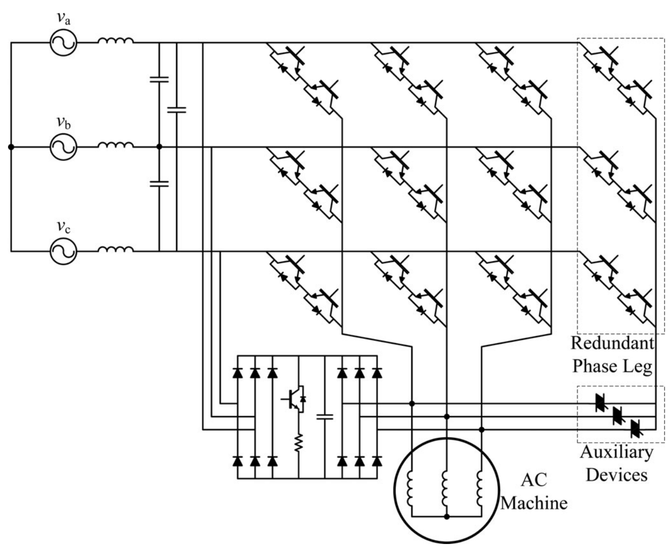

Fig. 24. Matrix converter for motor drives with a redundant phase leg.

is of importance due to their high part-count property and their application with high requirement of reliability.

In comparison to the degraded fault-tolerant operation, the systems with full redundant capability feature augmented number of additional auxiliary components, which increases the initial cost of the system. Furthermore, some redundant design compromises performance such as efficiency under fault-free state, which is undesirable or even unacceptable for some applications that demand very tight efficiency or thermal requirements.

VI. 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 mission-critical 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 three-phase 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 two-phase 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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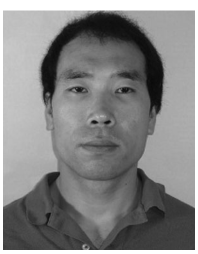

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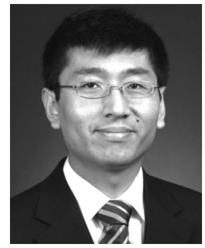

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