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Introduction to Fault-Tolerant Machine Drives

1.1 Background of Fault-Tolerant Machine Drives

Advanced electric drive systems are increasingly being used in a wide range of applications from industrial automation, household appliances, and transportation to oil and gas, mining, and renewable energy industries, where efficient and reliable electric-to-mechanical energy conversion or vice versa is essential. Extensive research activities on electrical drives have been undertaken in both academic and industrial organizations [1]. A typical electric drive is composed of a power converter, a control unit, and an electric motor, generally known as an electric machine, as shown in Fig. 1.1. The power converter contains typically power electronic devices (i.e. Insulate Gate Bipolar Transistor (IGBT), Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET), SiC, and diode), gate drives, and passive components (capacitor and damping resistors, etc.), which are responsible for driving the motor. The control unit consists mainly of microprocessor and its associated electronic circuitry in addition to various sensors. The electric motor delivers controllable torque to a mechanical payload by converting electrical power into mechanical power or vice versa.

As advances emerge fast in the areas of materials, electric machine design and manufacturing, power electronics, microprocessors, and sensing, electrical drives are capable of delivering desirable features such as high-power density, high efficiency, low emission, and good controllability, compared to other counterparts, namely, mechanical, hydraulic, or pneumatic drive/actuation systems [2]. Aircraft employing electrical actuators, electrical propulsion, and power generation in the form of more electric, hybrid, and full-electric aircraft can leverage the merits of weight saving, economical fuel consumption, low CO_2 emission, increased functionality, and less maintenance [3]. Another emerging example is the electric vehicle (EV) replacing traditional internal combustion engine (ICE) for low CO_2 and low harmful pollutant emissions [4, 5]. However, high reliability

Multiple 3-Phase Fault Tolerant Permanent Magnet Machine Drives: Design and Control, First Edition.
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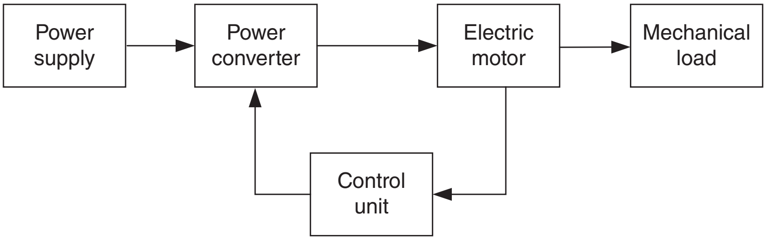


Figure 1.1 Illustration of a typical electric drive system.

is also an essential requirement for these safety critical applications, which should be addressed at the system design stage [6].

In the aforementioned safety critical applications, the electrical drives are expected to continue operation if a fault occurs, or at least being fail-safe without catastrophic damage [7]. Otherwise, the unexpected fault may cause casualties and huge economic losses [8]. Thus, fault tolerance should be considered to attain the reliability requirement for the targeted applications.

Fault tolerance means that the system is capable of performing at a satisfactory level of operation in the presence of fault. It is a common requirement that has been investigated in various areas, such as fault-tolerant computing systems [9], distributed power systems [10], and high availability internet servers. In the scope of electrical drives, the fault tolerance mainly means it is capable of maintaining the original or an acceptable output torque or power level after a fault. The acceptable level defines the minimum output, which should be considered at the primary design stage of such systems.

1.2 Frequent Faults in Electric Drives

An electrical drive is a complex electromechanical system composed of an electronic controller, a power converter, an electric motor, and sensors. These components are exposed to electrical, thermal, mechanical, and environmental stresses as well as chemical corrosion. Fault may occur in each of these components. Studies in [11, 12] have been carried out to investigate the failure distribution of electric machines. The results of the survey show the bearing faults account for the majority of the failures, as much as 51%, followed by stator winding faults, up to 25%. Other faults such as rotor bars and end rings in induction machines, shafts, and other unidentified failures take up the remaining percentage in Fig. 1.2(a). The investigation data in [13] also illustrates that electrical winding failures amount to a failure rate of 1.4×10^{-7} failures per hour in military-grade machines and 1.0×10^{-6} in industrial machines. Since these surveys are mainly focused on induction machines, permanent magnet (PM) failure in permanent magnet synchronous machines (PMSMs) is not included.

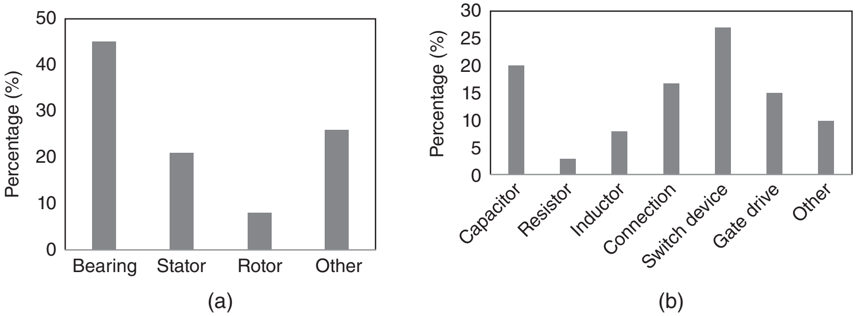


Figure 1.2 Fault distribution in electrical drives: (a) machine side and (b) converter side.

In fact, partial demagnetization is a frequent fault for PM machines due to a strong armature reaction field, overheating, and excessive mechanical stress and vibration [14].

A similar industry survey was conducted on failures in converters in [15]. The survey indicates that the most vulnerable component is the switching devices, followed by capacitors and gate drive circuitry. Open circuit in one phase due to device and connection failures is also a frequent fault. Failures associated with resistors and inductors are quite rare and only observed in a few applications, as shown in Fig. 1.2(b). The survey result shows most IGBT/MOSFET device failures result from thermal and power cycling, with a typical failure rate of 2.78×10^{-6} failures per hour. Additionally, the controller and sensors may also experience faults during operation. Nevertheless, it should be noted that the probability of the microcontroller and sensor faults is much lower.

As mentioned above, many potential faults may occur in the system. In this chapter, the principal device and electromagnetic faults under consideration that may occur within an electric drive are shown in Table 1.1.

On the machine side, the winding insulation degrades gradually due to electrical, thermal, and mechanical stresses and finally develops into open-circuit or short-circuit failure. The short-circuit failure can be classified as interphase and

Table 1.1 Potential faults occurring in an electric drive.

Machine side	Drive side
Winding open circuit	Switch device open circuit
Winding interphase short circuit	Switch device short circuit
Winding intraphase short circuit	DC-link capacitor failure
Demagnetization	Controller/sensor failure
Uncontrolled generation failure at high speed	

intraphase short circuit, which occur between phases or within a single phase, respectively. The intraphase fault is usually caused by turn-to-turn insulation failure. In particular, an intraphase fault involving a few turns, also known as a turn fault, is reported as the worst-fault scenario since only a few turns are short circuited. The resultant fault current is massive and the excessive hotspot temperature may lead to catastrophic failure. Partial demagnetization is another common fault in PM machines due to the excessive armature reaction field, overheating, and a high level of mechanical stress and vibration. It may cause torque reduction and increased torque ripple, etc.

On the drive side, the switch device is also subjected to open-circuit and short-circuit failure due to electric and thermal–mechanical stress during repeated switching on and off operations. DC-link capacitor is exposed to combined electrical and thermal stress during inverter operation and hence contributes to a considerable failure rate in electric drives [16]. Gate drive failure gives rise to similar consequences of switching device failures and may be incorporated into the switch device fault mechanism.

Besides, another possible fault is the uncontrolled generation, particularly for PM machines. If the power converter fails when the machine is rotating at high speed, the electromotive force (emf) may be much higher than the DC-link voltage and consequently cause uncontrolled rectification via the freewheeling diodes in the power converter. This may damage the DC-link components if the generated power is excessive and cannot be absorbed [17, 18].

So far, most of the fault-tolerant electrical drives focus on the faults described above [8, 13], since the most frequent bearing failure can be significantly reduced by regular maintenance, online monitoring, and replacement, whereas the controller and sensor faults are less likely.

1.3 Design Requirements of Fault-Tolerant Machine Drives

The requirements for the fault-tolerant systems in distributed power systems have been investigated in [10]. The methodology for fault-tolerant electrical drives follows relatively similar principles. The principal guideline is one fault in the system should be isolated in a subunit and has limited effect on the remaining healthy part, which can be in place to maintain uninterrupted operation. As extensively discussed in literature, four design criteria for fault-tolerant electrical drives are summarized.

A) **Partitioning and Redundancy:** A fundamental specification for fault-tolerant system is that a single fault would not disrupt the whole system.

Therefore, the fault must be confined to a relatively independent subsystem. This implies the system should be partitioned into several subunits. A fault would only disable the fault module, which would not cause malfunction of the whole system. Then, the remaining healthy modules could continue operation to meet the output requirement in the faulty condition. The trade-off between the redundancy number and cost is often debated at the design stage [3].

B) **Fault Isolation:** Partitioning alone is not enough to prevent the system breakdown from a faulty module, since certain types of fault may affect the remaining healthy subunits or even propagate to the whole system. It may lead to more severe consequences. Thus, many measures are employed to achieve fault isolation. Specifically, magnetic, electrical, thermal, and physical isolations are required for ideal fault-tolerant electrical drives to accommodate fault [19].

C) **Fault Detection:** On one hand, fault detection can help the electrical drive to isolate fault by taking appropriate fault mitigation action while on the other hand, continued operation needs information on fault type and location to perform appropriate postfault control. Fault must be detected before severe consequences occur. Indeed, fault detections are core techniques for fault-tolerant machine drives and require extensive and in-depth investigations.

D) **Postfault Control:** After a fault, the machine drive changes its physical behaviors and the control law under healthy conditions may lose its effectiveness. For example, new voltage harmonics and excessive fault current may arise, and consequently, the current tracking quality with conventional control techniques deteriorates significantly, resulting in excessive torque pulsation, etc. Thus, a new postfault control strategy should be in place to protect the system and maintain its operation for continued functionality.

In summary, the above four requirements should be taken into consideration to design an integrated fault-tolerant electric machine drive system. However, current research on the fault-tolerant machine drive is quite fragmented, and most literatures only focus on one of them.

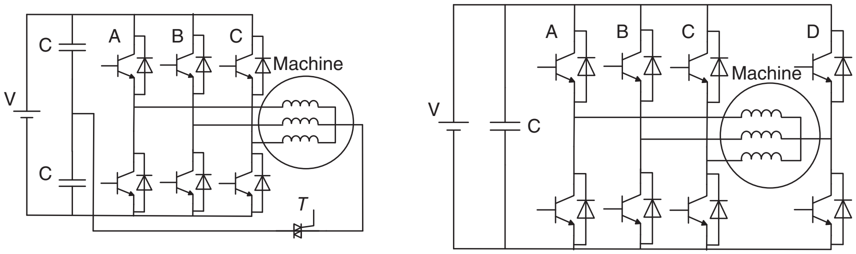
1.4 Current State-of-the-Art Techniques of Fault-Tolerant Machine Drives

To achieve an integrated fault-tolerant machine drive, a number of effective techniques have been developed, which include fault-tolerant machine drive topology, fault modeling, fault detection, and postfault control. These techniques are essential to accommodate various failures by transferring the machine drive from healthy operation to postfault operation in a reliable manner. The fault-tolerant machine drive topology enables the fault isolation and postfault operation while the fault modeling technique assesses machine performance in both healthy and faulty conditions and also aids in fault detection. Fault detection can identify and classify the faults and consequently trigger appropriate mitigation actions. After the fault, the previous control law becomes invalid since the machine has changed its physical behaviors. It requires a new postfault control strategy to accommodate the fault and suppress excessive and undesirable fault current if present. Subsequently, these key techniques are reviewed and the main challenges are highlighted.

1.4.1 Fault-Tolerant Machine Drive Topologies

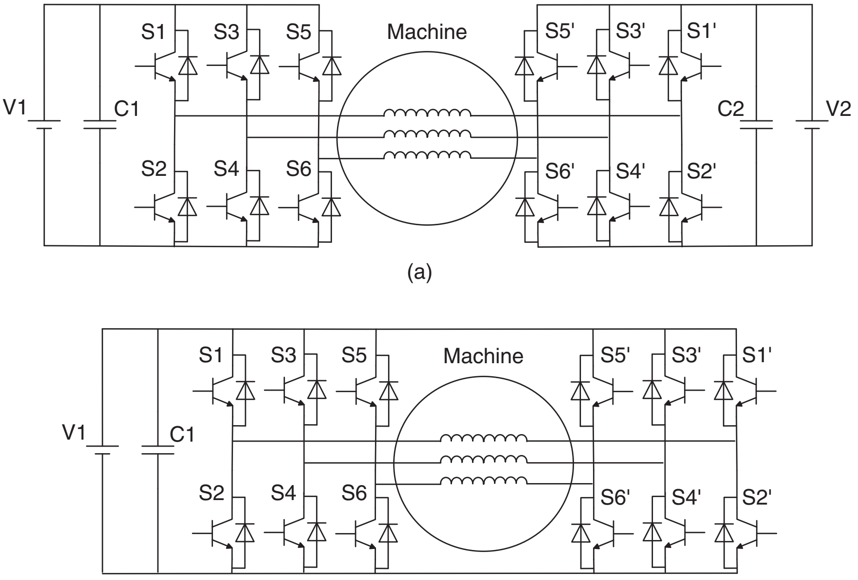
Various fault-tolerant machine topologies have been reported and investigated in literature. The most straightforward approach is to adopt two or more redundant machine drive modules either in series or in parallel [7, 20]. In case of a failure in one module, the fault is isolated and the other module can continue its operation. However, the use of multiple machine modules for redundant operation occupies large space and necessitates additional accessories to guarantee operation, resulting in low power density and bulky size. Therefore, this approach becomes less attractive.

Alternatively, some level of fault tolerance may be achieved on a typical 3-phase machine drive by employing a neutral connection of the 3-phase winding to the midpoint of the DC link or to a fourth inverter leg as shown in Fig. 1.3(a) and (b) [21], respectively. It can cope with an open-circuit fault either in the inverter or in the 3-phase windings. By employing the neutral connection, the two remaining phase currents can be controlled independently. Zero-sequence current is utilized to generate the equivalent rotating magneto-motive force (MMF) in the machine if one phase is open circuited.



(a) (b)

Figure 1.3 3-Phase fault-tolerant machine drive: (a) full bridge with DC midpoint and (b) four-leg inverter.



(a)

(b)

Figure 1.4 3-Phase machine using open-end winding drive (a) with independent power supplies and (b) with single power supply.

Another common fault-tolerant approach for 3-phase machines is to employ open-end winding drives as shown in Fig. 1.4. Both terminals of a 3-phase winding are available (opened) for connections to dual 3-phase inverters. The dual drives can share one DC link or use independent power supplies [22]. In addition to better fault-tolerant capability, they also bring the merits of 3-level voltage output, lower DC-link voltage for a given rated voltage of the machine and high efficiency. In case of a switch failure in one inverter, drive operation can be sustained by appropriate control of the healthy side inverter.

The access to the neutral point in Fig. 1.3 can be eliminated by employing more than three phases in a single machine as shown in Fig. 1.5 [23, 24]. Depending on the number of phases, a multiphase machine is capable of continuous operation when one or more than one phase has failed. Multiphase machine is initially investigated for high-power applications. By dividing the required power between multiple phases, higher power levels can be realized with specific rated power electronic converter modules. It can also reduce torque pulsation and lower DC-link harmonic current. As described above, a neutral point connection is required for a 3-phase machine after one phase is open circuited so that the current in the remaining two phases can be controlled independently. However, it is possible to take advantage of the additional degrees of freedom in a multiphase

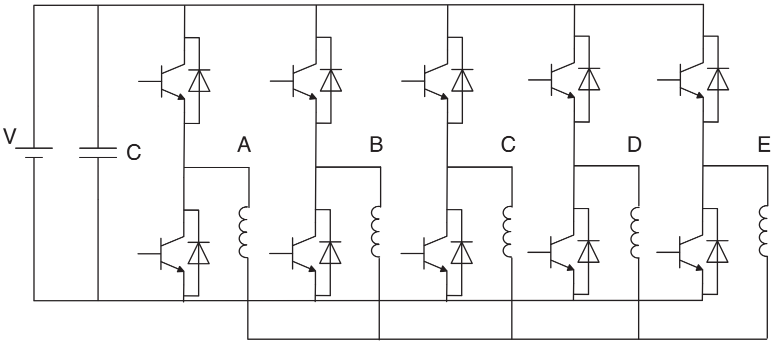
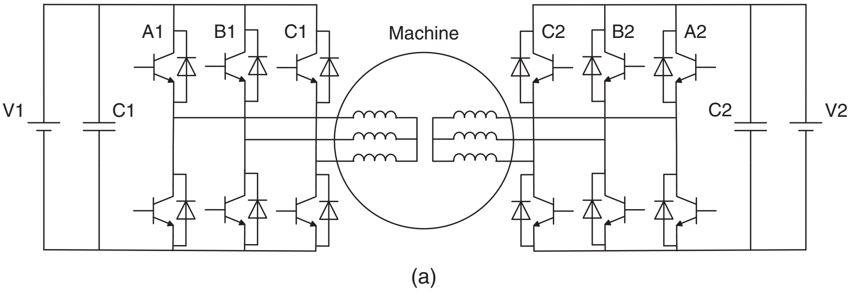


Figure 1.5 Multiphase (5-phase for illustration) fault-tolerant machine drive.

machine where the number of phases is greater than 3. With appropriate control of the power converter, a multiphase machine can continue its operation in case of an open-circuit fault without connecting the neutral point. Five-phase, six-phase, and seven-phase machines are most extensively investigated for both induction machines and PM machines [25–27]. Additionally, various control algorithms have been proposed to achieve the maximum attainable torque or minimum torque ripple [28–31] under fault conditions.

One common disadvantage of the 3-phase and multiphase fault-tolerant machine mentioned above is the complex postfault control since the machine no longer operates in a balanced manner after a fault. To alleviate this problem, the machine windings can be configured as multiple 3-phase windings with each driven by an independent inverter [32] as shown in Fig. 1.6. If a fault occurs in one set of 3-phase winding, the whole set will be taken out of service. The remaining sets can continue their balanced operation. The benefits of such fault-tolerant drives are that the postfault control strategy can be much simpler as the operation of the remaining balanced 3-phase windings can be easily maintained. It should be noted, however, that the strong and undesirable magnetic coupling may still exist in different 3-phase winding sets. Consequently, the short-circuit current may still be excessive and torque ripple may increase due to the mutual coupling. This concept has been realized in both induction machines, synchronous machines, and PM machines [25, 26, 33–35]. However, the majority of the above solutions cannot cope with excessive current in the event of short-circuit fault.

To accommodate short-circuit fault in power electronic switches or phase windings, alternative fault-tolerant drives are developed. Owing to its rugged, magnet-free rotor structure and concentrated windings, the switched reluctance machine (SRM) is inherently fault tolerant as shown in Fig. 1.7 [36, 37]. Each phase winding can be magnetically, thermally, and electrically isolated. Due to low mutual coupling between phases, the short-circuit current can be limited in a



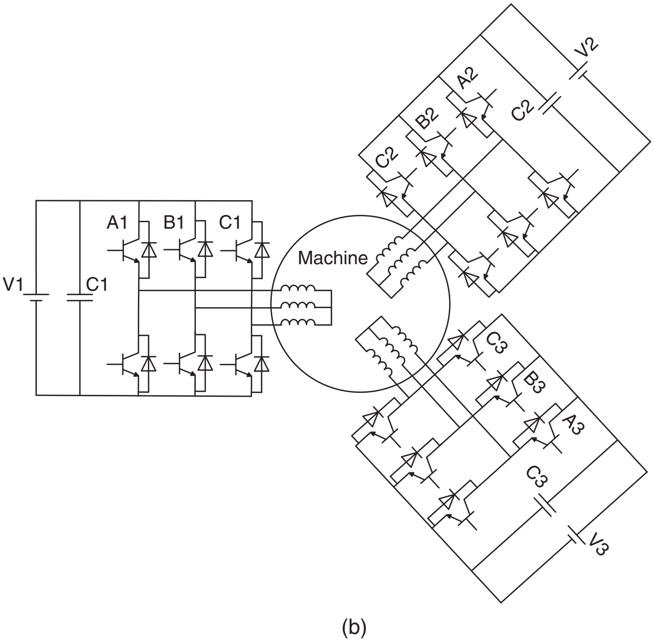


Figure 1.6 Multiple 3-phase fault-tolerant machine drive: (a) dual 3-phase and (b) triple 3-phase.

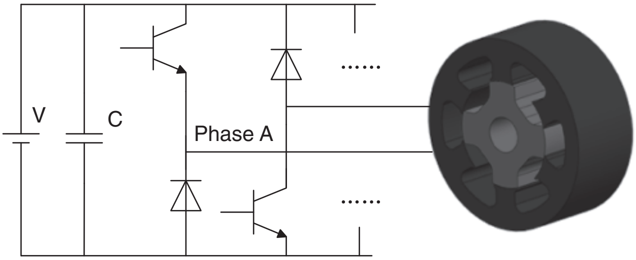


Figure 1.7 SRM machine drive.

safe region [38]. The electric isolation is also carried out in the inverter, and each phase is excited by an independent asymmetrical H-bridge. Thus, a failure in one phase either in the winding or in the bridge would not influence the operation of the remaining healthy phases. The faulty phase can be deactivated simply by disabling the active switches. Additionally, the active switching devices in the bridge are in series with a winding, so in case of switch misfiring, there is a delay in the rise of current that prevents the shoot-through fault of the bridge. However, an SRM drive exhibits high torque ripple, undesirable noise and vibration, and inferior torque density/efficiency. These undesirable attributes are even worse in fault condition. Furthermore, the SRM drive may lose its starting capability due to a phase absence.

To enhance the torque performance of a fault-tolerant drive, a single layer, fractional-slot concentrated winding (FSCW) PM machine is developed as shown in Fig. 1.8 [39], which facilitates electrical, magnetic, thermal, and physical isolations between phases. Each winding is wound on every alternative tooth, so each slot only contains one phase coil, facilitating thermal and physical isolation between phases. With the help of surface-mounted magnet rotor and the unwound stator teeth, the magnetic isolation between phases is also largely realized. The tooth tip and slot opening are specially designed by controlling their depth and width to obtain per-unit self-inductance in each phase in such a way that under a short-circuit fault, the fault current is limited. Further, the modular design philosophy is extended to the inverter with each phase excited by a single-phase H-bridge, as shown in Fig. 1.8; thus, each phase is also electrically isolated. The machine is fault tolerant to both winding open or short circuit and switch open or short circuit. In an event of an interturn short-circuit fault, the short-circuit current can be limited to an acceptable level by applying a terminal short circuit (TSC) on the fault phase via H-bridge control. This methodology has also been extended to switched flux, also known as flux switching, PM machines in [40].

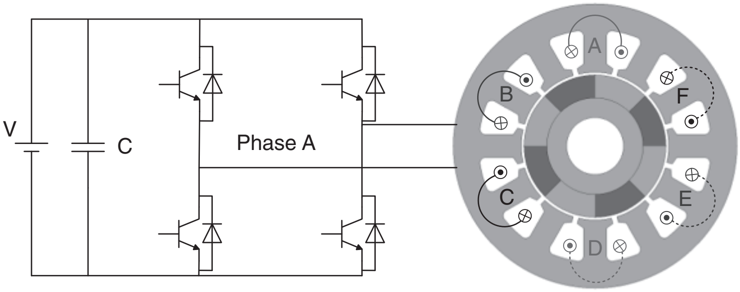


Figure 1.8 Multiphase FSCW fault-tolerant machine drive.

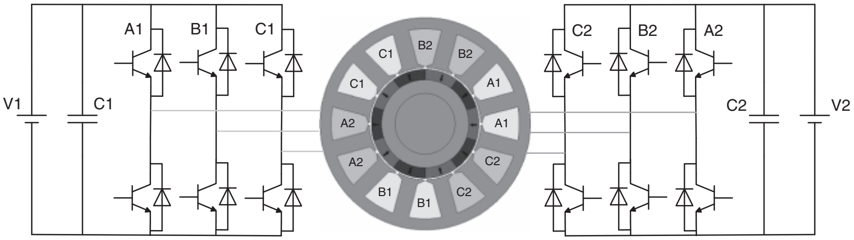


Figure 1.9 Multiple 3-phase FSCW fault-tolerant machine drive.

Similarly, multiple 3-phase configuration can be employed for the FSCW fault-tolerant machine as shown in Fig. 1.9, which facilitates the fast integration of standard 3-phase inverters and simple control [41]. Each 3-phase set winding is driven by an independent 3-phase inverter and can tolerate open-circuit, short circuit, and interturn fault.

However, due to the concentrated windings, very little reluctance torque can be exploited. The output torque of an FSCW PM machine purely relies on the PM field and, consequently, an increase in torque capability leads to higher flux linkage. The presence of a strong PM field poses a safety hazard to the machine as it cannot be turned off in the event of a fault [42]. The back emf may be much higher than the DC-link voltage at high speed and, consequently, uncontrolled rectification via the diodes of a power converter may occur in case of an inverter failure. Excessive regenerative power that flows to the DC-link capacitor may cause catastrophic failure to the drive system. Significant braking torque may also be imposed on the rotor causing excessive stress to the mechanical system or a sudden reduction in speed that may induce an accident. Thus, the maximum back emf should be limited [43]. However, this is in conflict with the requirements for torque production. Further, the use of concentric windings also gives rise to sub- and high-order MMF space harmonics, which produce extra rotor loss. Hence, the magnets need to be segmented axially or circumferentially to avoid excessive rotor temperature [44]. The magnets are also subject to the risk of demagnetization in high temperature and in case of a drive failure [45]. The demagnetization leads to torque reduction and increase in machine currents for closed-loop controlled drive under the same load condition. The vicious cycle may continue, causing further increases in temperature and demagnetization.

According to the foregoing review, it can be concluded that the conventional 3-phase induction machine and PMSM drives are only fault tolerant to open-circuit failure while SRM and FSCW PM machine could tolerate open-circuit, short-circuit, and interturn fault. Multiphase machine drive normally has better postfault torque capability compared to multiple 3-phase counterpart albeit requires more complex postfault control. PM machine has the merits of high efficiency and high torque density; however, the high back emf also poses challenges to the system design. In general, no existing topology could achieve high performance as well as good fault tolerance in a simple and cost-effective manner.

1.4.2 Fault Modeling Techniques

For fault-tolerant machine drive systems, the postfault behavior is notably changed and should be carefully assessed to understand the fault behavior. For example, maximum torque capability and torque ripple in postfault operation should be assessed [46]. New voltage harmonics would appear that pose an extra constraint on voltage if field weakening operation is required [17]. In addition, in order to optimize the output capability in fault condition, accurate fault modeling is necessary to guide machine design and to facilitate postfault control in order to achieve high efficiency and high-power density [7] in both healthy and postfault operations. Especially for interturn fault, which causes excessive fault current and results in local hotspots, its behavior should be captured to facilitate the development of diagnostic techniques and corresponding mitigation action [47]. Thus, various fault modeling techniques are being actively investigated.

Lumped parameter-based modeling is commonly employed to describe the machine in both healthy and fault conditions. Lumped parameters, inductance values in particular may be extracted from analytical derivations [48], finite element (FE) simulations [49], or experimental tests [50]. For example, based on closed-form voltage equations established from this process, the responses of an interior permanent magnet (IPM) machine under single-phase open circuit [51] and symmetrical and asymmetrical short-circuit faults [52] were investigated. An induction machine with one-phase open circuit was modeled and its control behavior was accessed in [53]. The fault modeling technique has been extended to multiphase induction machines by using the inductance matrices [54]. With derived lumped parameters, circuit-oriented method can also be employed to investigate induction machine behavior [55] with faults in both stator and rotor sides, such as broken rotor bar. A five-phase synchronous reluctance machine with open-circuit faults was modeled in the synchronous frame in [56] when the current was controlled in the synchronous frame with zero steady-state error. A novel field reconstruction method was used to analyze the machine performance and vibration [57] for an FSCW PM machine. This method utilizes the fields produced by the current in a single slot and the field from the magnets to reconstruct the field distribution along the air gap with arbitrary current excitation.

It should be noted that most of the modeling methods above consider the machine as a linear system, and hence compromise the model accuracy. The postfault behavior can also be evaluated by FE simulations [58]. However, the FE method is quite time consuming, and not suitable for developing fault detection strategies, control methods and performing comprehensive performance assessment over a wide operation region.

Accurate interturn fault modeling is very important to improve the understanding of fault behavior, which is essential for the development of fault detection algorithms [59]. A survey of stator turn fault modeling techniques was presented in [60]. In [61], a transient model for an induction machine with interturn fault was derived using reference frame transformation theory. In [62], magnetic saturation was considered by using modulation of air gap permeance at twice the fundamental frequency. Stator turn fault in surface-mounted PM machines was discussed in [49, 63–66]. The inductance values were derived by turn ratio (the ratio of partially short-circuited turns to the total number of turns in a coil), permeance network, and FE simulation. In addition, back emf harmonics were considered in [50] to improve the model accuracy. An analytical approach was proposed in [48] to capture the inductance and PM flux. Particularly, variation of slot leakage inductances under interturn fault, which has a significant impact on the turn fault current, was also investigated. It is shown that the leakage inductance is strongly dependent on the position of the fault turns in a slot, which will finally affect the fault current.

An important fact in a turn fault condition is that the winding distributions are no longer symmetrical. To represent the winding distribution, and the resultant MMF in such fault conditions, the winding function proves to be a powerful tool. The inductances for the fault turns, fault phases, and other healthy phases can be obtained by integrating the product of the representative turn function, winding function, and airgap permeance as described in [67, 68], assuming linear magnetic characteristics. The theory has been applied in a salient pole synchronous machine with coils in series and in parallel connections [69, 70]. However, for an IPM machine, the magnetic saturation should be considered since it has a crucial influence on the field distribution. In [59], a semi-analytical model of IPM with turn fault was derived by using the healthy *dq* flux maps to deduce the flux in a fault condition. The magnetic nonlinearity was considered in the healthy flux map. Further, a high-fidelity model was developed in [71] based on the inverse of a four-dimensional (4D) table extracted from FE simulation that exhibits high accuracy. However, it can only deal with the turn fault with fixed turns and fixed position (coil location and slot position). The investigations in [47, 72, 73] show that both the slot location and coil location of a turn faul affect the fault current. This location dependency causes a significant difference in the fault current and consequently affects fault detection and fault-tolerant machine design.

It follows that although various modeling tools are available for fault behavior prediction, the accuracy, flexibility, and computational efficiency are still limited. Particularly for interturn fault, the impact of fault turn location on fault behavior is worth investigation in order to assess the worst-case scenario in terms of fault current and detectability.

1.4.3 Fault Detection Techniques

Fault detection is of key importance for fail-safe and fault-tolerant machine drives in order to take appropriate fault mitigation actions. Timely and reliable detection is essential to avoid false alarms and associated unnecessary downtime. All possible failures in a machine drive, namely, winding or device open-circuit, short-circuit, stator turn fault, etc., should be well detected, classified, and located. Among them, detection of device open-circuit in power converters and interturn short-circuit fault in machine windings is most actively investigated due to their high failure rate. Thus, they are reviewed and will be addressed subsequently in this chapter.

Open-Circuit Fault Detection

Open-circuit faults in motor drives often arise from overloading, overheating, and aging [74–76]. In general, they disrupt current flow in one phase, resulting in a rapid reduction in output torque [77, 78]. Furthermore, postfault actions may lead to increased voltage or current stress on other power switches, thereby posing a substantial safety risk to the motor drives and potentially triggering secondary faults [79]. Thus, it is imperative to explore effective methods for open-circuit fault detection and take appropriate mitigation measures.

Open-circuit faults in machine drive systems can be broadly categorized into two primary types, namely, inverter open-circuit fault and winding open-circuit fault [80], as illustrated in Fig. 1.10(a) and (b), respectively. The detection of winding open-circuit faults is relatively straightforward through current sensors typically used in a drive system. Hence, existing research mainly focuses on the detection of open-circuit fault of a switching device in an inverter (typically, the active switch is open circuited while the diode is normal). Currently, there are two predominant approaches for detecting open-circuit fault, namely, signal-based detection methods and model-based detection methods [81].

Signal-based detection methods typically rely on changes in current or voltage signals following a fault occurrence to identify open-circuit fault. The most apparent characteristics of an open-circuit fault is that the phase current associated with the fault device during the response interval becomes zero. Due to this feature, literature [82] utilizes variations in the current vector slope to achieve open-circuit fault detection and localization. However, current signals are susceptible to disruptions from load variations. To mitigate this challenge,

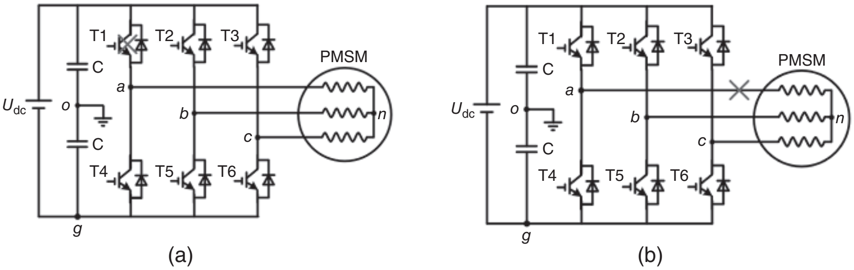


Figure 1.10 Open-circuit fault illustration: (a) switch open-circuit fault and (b) winding open-circuit fault.

Peuget *et al.* [83] introduces the normalization of Park vectors to reduce the impact of load fluctuations in the fault detection. Similarly, literature [84] employs the average of normalized 3-phase currents to detect open-circuit faults. Since the asymmetry of phase currents after the fault can introduce harmonics components, literature [85] employs the harmonic components of phase currents for open-circuit fault detection. Additionally, depending on the installation positions of current sensors, DC-link current [86] is also utilized for open-circuit fault detection. The acquisition of current signals is relatively simple; however, it is prone to load disturbances and long detection cycle.

By contrast, voltage signals normally offer faster detection. Literatures [87–89] analyze open-circuit detection by examining changes in phase voltages, line voltages, neutral point voltages, and the voltage between power device collector and emitter. Reference [90] achieves μs-level detection of open-circuit faults by monitoring the midpoint voltage of 3-phase bridge arm with respect to the ground. Literature [91] uses zero-sequence voltage for single-phase open-circuit detection and discrimination between inverter and winding. However, measuring voltage signals usually requires additional voltage sensors and high sampling rate hardware circuits.

Model-based methods detect the fault by analyzing the difference between model-predicted signals and actual signals [92]. In literature [93–95], the reference current of the motor is calculated using the reference voltage output from the *dq*-axis controller, while the actual current is obtained through physical sensors. During normal operation, the reference current agrees well with the actual signal. However, when an open-circuit fault occurs in a motor drive, a small interval with zero current will result due to the fault. Therefore, a significant difference arises between the reference and actual current, which can be utilized for open-circuit fault detection. Similarly, an approach based on voltage residuals is employed in [96] and [97]. The reference voltage is obtained from the *dq*-axis controller while the actual voltage is calculated from a model with measured

3-phase currents. Hence, by comparing the two signals, the open-circuit fault can be diagnosed. Furthermore, a common mode voltage-based method is developed in [98] for open-circuit diagnosis, which can also achieve quick detection and localization. Model-based fault detection methods can mitigate the influence of controller parameters and transient processes on fault detection, as both reference and actual signals are affected by these factors. However, it is worth noting that this approach requires more knowledge of motor parameters, which may be subjected to variations due to changes in operation conditions.

Interturn Short-Circuit Fault Detection

Interturn short-circuit fault, denoted as turn fault for short notation, as a result of turn-to-turn insulation failure, is known as severer fault while it is more challenging to detect. It usually only involves a few turns in a machine winding, resulting in a benign fault signature as seen from machine terminals and consequently low signal-to-noise ratio for detection. However, excessive fault current flows in the fault turns, which requires fast detection and mitigation action. This necessitates a rapid and computationally efficient detection within a few tens of milliseconds before developing into a catastrophic failure.

In terms of turn fault monitoring, a few standard offline methods including the insulation resistance measurement, direct current test, alternating current test, surge comparison test, and partial discharge test have been discussed in [99, 100]. Online detecting schemes would be more preferred since they provide continuous stator insulation monitoring and enable appropriate mitigation actions. Benefiting from the features of noninvasive and no additional sensors, most of the online turn fault detection techniques are based on motor current signal analysis (MCSA) by inspecting the stator current spectrum to spot the degradation [101]. In [99, 102], the induction machine insulation failure was detected by tracking the negative sequence current and impedance, which was insensitive to the machine slip. In fact, the methods in [103, 104] based on Park's Vector Approach were also employed to monitor the negative sequence current. However, it was shown in [61] that the negative sequence component was not a reliable fault indicator since it does not change in a predictable manner when exposed to the existing asymmetry or supply unbalance. Hence, a more robust fault indicator was developed by making use of the off-diagonal term of the sequence component in the impedance matrix [105, 106]. The disadvantage of this method was that it is required to store two sets of test data under different voltage unbalance conditions. An alternative way was introduced in [107] by exploiting feedforward neural network to compensate for the arbitrary supply voltage and nonidealities in the machine or instrumentation.

Alternatively, model-based approaches were also investigated in [108–111] for interturn fault by monitoring the estimation errors. It mainly follows the same approach as the open-circuit fault detection by comparing the measured signals and predicted values. This method required an accurate online model, which was usually achieved by adaptive state observer or online learning. In [112], the interturn short-circuit fault was alarmed by tracking the back emf estimator for a PMSM. The temperature influence on the winding resistance was compensated by a transient thermal model; however, the influence on the PM flux variation was not considered, which may compromise detection accuracy.

The feasibility of turn fault detection by injecting high-frequency signal was analyzed in [113, 114] by measuring the high-frequency negative sequence current and further investigated in [115] by monitoring the incremental inductances. It should be noticed that high-frequency injection introduces additional noise in the current and may reduce voltage operating range at high speed. As a result, an advanced method was proposed in [116] by comparing the inherent high-frequency PWM current ripple between different phases, where the switching inverter was exploited as a natural source of high-frequency signal injection into the motor. Therefore, there is no need to inject additional high-frequency component, avoiding the undesirable effects.

It should be noted that for the fault detection techniques reviewed above, the respective fault indicators vary with speed and load and this variation should be compensated in order to improve sensitivity and robustness of the detection. On the other hand, the speed and load transients usually cause false alarm in harmonic-based fault detection techniques. It is important that such false alarm or false positive is eliminated. Last but not least, the classification and location identification of different faults are of paramount importance in order to apply appropriate mitigation action.

1.4.4 Postfault Control Strategies

After a fault, the internal physical behavior of a machine drive is significantly changed. Hence, the original control law is no longer applicable. Further, once a fault has been detected and classified, some forms of reconfiguration in the power converter and its connection to the motor may be required in order to limit fault propagation and facilitate postfault operation. Therefore, it becomes essential to adopt fault-tolerant control strategy to achieve reliable operation. According to different objectives and fault-tolerant schemes employed, the existing fault-tolerant control strategies can be mainly divided into three categories, namely, output torque control, postfault current tracking, and short-circuit current suppression.

At present, output torque control is most extensively investigated. The basic approach is to control the healthy phase currents to maintain a constant rotating MMF after an open-circuit fault. Fu and Lipo [26] proposed a general current calculation method for multiphase machines under open-circuit fault condition [26] and presented a reduced-order fault-tolerant control with decoupling in [117], which maintains the MMF on the fundamental plane by compensating the asymmetry caused by the fault. It is realized by controlling the special harmonic components in the stator currents. However, the reduced order decoupling matrix introduces asymmetric synchronous rotation voltage, which requires feedforward compensation. An optimal torque control is proposed in [28] for five-phase PM machines. The objective function is constructed for torque demand as a constraint with the minimum power consumption, and the optimal currents for postfault operation are obtained by the Lagrange algorithm. However, the current commands contain high-order harmonic components, which pose difficulties for current tracking at high speed. Parsa and Toliyat [33] introduced a fault-tolerant operation strategy based on instantaneous power theory for five-phase PM machine with third harmonic in back emf. Wang *et al.* [118] studied a 15-phase induction motor with nonsinusoidal power supply for integrated power system (IPS) in ship propulsion. The stator windings are composed of three sets of five-phase windings. In such designs, the utilization of the stator MMF can be enhanced by injecting the third harmonic and hence the torque density is increased. The fault-tolerant control strategy is studied in [119] under symmetric and asymmetric open-circuited phase operation. Direct torque control of multiphase motor under fault condition is also investigated in [120].

It should be pointed out that during postfault operation, voltage harmonics will appear due to the presence of fault and asymmetric operation. The voltage harmonics will deteriorate current tracking performance and lead to current distortion. At high-speed operation, voltage harmonics will further reduce the available voltage margin and affect the stability of the system operation. Therefore, it is necessary to study the control algorithm of current tracking in postfault operation. The current commands generated from a fault-tolerant control algorithm can be tracked by the well-known hysteresis control for its fast response speed and strong robustness. However, this method has the disadvantage of variable switching frequency. The work reported in [121] proposed a fault-tolerant control technique for a seven-phase motor under open-circuit fault, and the current tracking errors were reduced by multiple PI controllers operating in the synchronous rotating coordinate system of different harmonic spaces, as shown in Fig. 1.11. However, due to the presence of the voltage harmonics and limited bandwidth of the PI controller, the tracking performance for the AC current commands may not be satisfactory. The authors in [24] studied model predictive control for the postfault operation of a multiphase induction motor, and the switching state is selected for minimum current error based on a model predictive algorithm. However, the model predictive control heavily relies on accurate mathematical model and requires intensive online computation for the optimal solution, which increases the cost and complexity of the digital processing

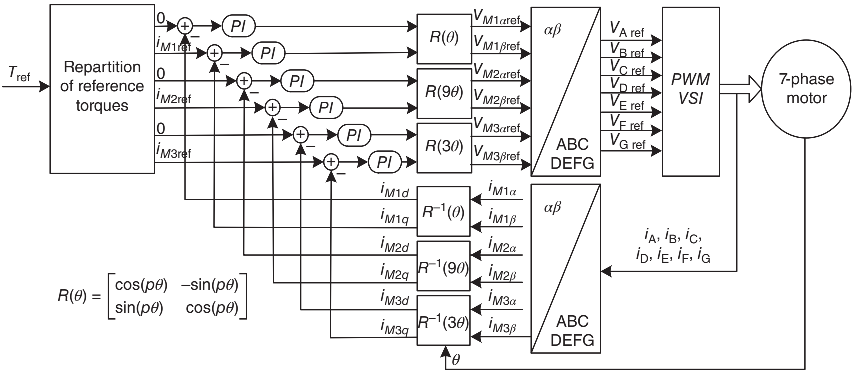


Figure 1.11 Fault-tolerant control diagram of seven-phase motor. Source: Tao *et al.* [122]/Proceedings of the Chinese Society of Electrical Engineering.

units. In addition, field weakening control algorithms are rarely investigated for postfault operation of machine drives at high speed.

In case of a short-circuit fault, especially interturn short-circuit fault, it is essential to adopt timely control to suppress the excessive fault current and avoid further failures. TSC realized via the inverter is usually applied to the whole phase winding where the fault turns are located to reduce the fault current. However, its effectiveness in limiting the fault current is dependent on the location of the short-circuit turns in the winding. Therefore, literature [123] studies a short-circuit current suppression method based on current injection into the healthy part of the winding, which cancels the flux linkage of the faulty turns and consequently reduce the short-circuit current. However, this method requires accurate information on the fault condition, such as the number of short-circuited turns and their physical position in the winding, which is practically impossible to determine. For the 3-phase machine with open winding drive as shown in Fig. 1.4, the flux linkage of the short-circuit turns can be actively reduced by controlling the currents in the healthy phases as described in [124]. As a result, the fault current is effectively reduced. Jiang *et al.* [125] proposed a technique for interturn short-circuit current suppression for PM starter/generator in motoring and generating modes, respectively. With this scheme, however, the torque capability of the drive is significantly reduced.

In summary, although technical issues pertinent to design and operation of fault-tolerant drive systems, such as fault-tolerant machine drive topologies, fault modeling, fault detection, fault mitigation, and postfault operation, have been extensively investigated in literature, some key problems are still remaining and worth further study. Further, the techniques for addressing these issues should be considered at the system level and well integrated to establish a complete machine drive system capable of fault-tolerant operation.

1.5 Scope and Outline of This Book

1.5.1 Scope of this Book

This book is devoted to presenting a systematic and integrated approach to the design and control of fault-tolerant machine drives, including fault-tolerant machine topologies, design optimization, fault modeling, fault detection, fault mitigation, and postfault control algorithm. For each of these topics, the recent advances and current state-of-the-art will be reviewed and the needs for further research in order to develop the technology to sufficient level of maturity will be discussed. The development of advanced fault-tolerant machine drive topologies is a key step to provide a desired level of fault tolerance without significant compromise on the machine drive performance in healthy conditions. Appropriate machine design optimization should be taken to ensure that the machine drive can meet the requirement for performance targets in both healthy and postfault operating conditions. This will be facilitated by a generic and comprehensive fault modeling technique for predicting the machine fault behavior in a computationally efficient manner. The advanced fault modeling technique will also provide a useful tool for the development of fault detection techniques and postfault control strategies. Effective and reliable fault detection techniques are indispensable for monitoring the machine drive operations and for undertaking appropriate mitigation measures when a fault occurs. Suitable postfault control strategy will finally realize the fault-tolerant operation after a fault. Thus, all these technical issues should be addressed, and suitable solutions developed and implemented in order to realize an effective fault-tolerant machine drive system.

In this book, the process of design, control, and development of high reliability/availability fault-tolerant machine drives is described through a specific example by incorporating all the above technical aspects for safety critical applications. Generally, different fault-tolerant machine drive topologies may be preferred for diversified applications. Depending on the machine drive topology employed, the design optimization, modeling, detection, and postfault control techniques may vary accordingly. However, the general process and internal logic are the same for different types of fault-tolerant machine drives. This book offers a generic methodology and systematic approach to the design and control of a typical fault-tolerant machine drive. It also intends to stimulate further developments of the core technologies pertinent to fault-tolerant machine drives.

1.5.2 Outline of this Book

This book is arranged with seven chapters. Each chapter is briefly introduced as follows:

Chapter 1 introduces the background knowledge and recent advances of fault-tolerant machine drives. The frequent failure modes in electrical drives are explained, and the measures and requirements to accommodate these faults as well as to facilitate postfault operations are discussed. Current state-of-the-art techniques for machine topology, fault modeling, fault detection, fault mitigation, and postfault control are reviewed to provide a comprehensive understanding and insight into the fault-tolerant machine drive technology.

To establish an integrated fault-tolerant machine drive, a novel multiple 3-phase PM machine with segregated windings is introduced in **Chapter 2**. The key merits of the fault-tolerant drive topology are assessed against other key state-of-the-art candidates. In particular, its performance is compared against the conventional 3-phase drives in healthy operations, and its ability to tolerate various faults is evaluated and discussed. The machine fault behavior and mutual coupling mechanism are explained from the viewpoint of MMF distribution.

Based on the proposed machine topology in Chapter 2, the design optimization process of a 40 kW machine is described as a case study in **Chapter 3**. An integrated design procedure is developed to consider both the healthy and fault modes of operation while satisfying electrical, thermal, and mechanical constraints. The optimized machine is prototyped and extensively tested for different operation modes in healthy and under fault conditions.

A general modeling technique is developed in **Chapter 4** considering the healthy operation, open-circuit, short-circuit, and unbalanced operation conditions. The model can also be adapted for turn fault with varying numbers of faulted turns and fault location. The accuracy of the model is verified by FE prediction and experimental tests.

Fast and reliable detection techniques are developed in **Chapter 5** for the most common faults, including device open-circuit and winding interturn short-circuit fault. The open-circuit fault is detected by using the relative β-axis residual voltage signals of the three phases. The second harmonics in the instantaneous active power and reactive power are employed as fault indicators for turn fault detection. The effectiveness of the detection methods is evaluated with the proposed general modeling technique and on prototype tests.

Chapter 6 describes optimal torque control strategy for fault tolerant multiphase FSCW PM machines and develops a turn fault mitigation strategy to minimize the fault current for the multiple 3-phase PMA-SynRM drive. Optimal current control strategy is employed to deliver smooth output torque during post fault operation for both constant torque and constant power operating region. By making use of the additional degree of freedom from the multiple 3-phase windings, appropriate phase currents are injected to the fault 3-phase set to reduce the residual flux of the fault turns, leading to a much lower turn fault current and enhanced fault tolerance.

Winding configuration has a dominant impact on the machine performance and its ability to tolerate faults. To further suppress potentially excessive turn fault current, four new segregated winding configurations, namely, delta-connected winding, star-delta-connected winding, mixed-pitch winding, and concentric winding, are proposed in **Chapter 7** to reduce the residual flux linkage of the fault turns. With appropriate mitigation actions, the fault current is reduced by changing the winding connection or modifying the winding layout leading to more cost-effective solutions.

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