Modelling, Simulation and Implementation of a Fault Tolerant Permanent Magnet AC Motor Drive with Redundancy

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Abstract

Fault tolerant motor drives are becoming more important in safety critical applications. Although a single motor module fault tolerant drive may be sufficient in some applications, this motor drive only offers limited redundancy. This thesis investigated the dual motor module fault tolerant drive system in which two motor modules were connected electrically in phase and on a common shaft provide redundancy and to increase the reliability of the entire drive system.

A general phase current mathematical model to produce the desired output torque was developed to minimize copper loss and torque ripple in the motor drive, which is applicable to both sinusoidal and trapezoidal brushless permanent magnet motor types. A detailed fault effect investigation was performed in this thesis and it is concluded that switch short-circuit fault is the most serious fault since it reduces the electromagnetic torque output significantly and generates larger torque ripple in the motor drive due to the presence of large drag torque. Three fault remedial strategies were proposed to compensate the torque loss and to reduce the torque ripple under different faulty conditions. It is concluded from the analytical results that fault remedial strategy 3 is the tradeoff algorithm in which the zero torque ripple factor can be achieved with only a modest increase in copper loss comparing with the minimum possible value.

Two practical dual motor module fault tolerant brushless permanent magnet drive test arrangements with different motor structures were developed in this thesis. The computer simulation studies using the MATLAB Simulink were performed to verify the effectiveness of the proposed fault remedial strategies. The efficiency of the motor drive was predicted based on torque loss measurements and the results were verified in the simulation study. The effect of faults on the drive efficiency was investigated as well.

The entire fault tolerant motor drive control system was also developed to verify the analytical and simulation results. A fault detection and identification method to detect switch open-circuit faults, switch short-circuit faults, and the winding short-circuit faults was also proposed. Its advantages are the simplicity of the implementation and reduction of the cost of the drive system. The experimental results demonstrated that the proposed fault remedial strategies can be implemented in real time motor control and are effective to compensate the torque loss and reduce the torque ripple.
Declaration

The work in this thesis is based on research carried out at School of Electrical and Electronic Engineering, The University of Adelaide, Australia. This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

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Jingwei Zhu

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<td>(B)</td>
<td>Damping coefficient</td>
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<tr>
<td>(e_{1,2,3,4,5,6})</td>
<td>Phase back-EMF voltages</td>
</tr>
<tr>
<td>(e_{1,2,3,4,5,6}(\theta_e))</td>
<td>Phase back-EMF functions</td>
</tr>
<tr>
<td>(E_m)</td>
<td>Amplitude of back-EMF voltage</td>
</tr>
<tr>
<td>(I_{in})</td>
<td>Input phase current of current sensor</td>
</tr>
<tr>
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<tr>
<td>(I_{m0})</td>
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<tr>
<td>(i_{measured})</td>
<td>Measured current</td>
</tr>
<tr>
<td>(I_{mRS})</td>
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<tr>
<td>(I_R)</td>
<td>Current in the rheostat</td>
</tr>
<tr>
<td>(i_{reference})</td>
<td>Reference current</td>
</tr>
<tr>
<td>(I_{SCm})</td>
<td>Peak value of short-circuit current</td>
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\( L_{11}, L_{22}, L_{33} \)  
Self-inductances in phases 1, 2, and 3

\( L_{pu} \)  
Per unit the inductance

\( m \)  
The number of phase with open-circuit fault

\( M_{12}, M_{23}, M_{31} \)  
Mutual inductances between phases 1, 2, and 3

\( n \)  
Total number of phase in the motor drive

\( N_p \)  
Number of pole pairs

\( P_{ave} \)  
Average copper loss in a dual module motor drive

\( P_{cu} \)  
Instantaneous copper loss of a dual motor module

\( P_{cu0} \)  
Instantaneous copper loss of a single motor module

\( P_{cu\text{relative}0} \)  
Relative copper loss in a single motor module drive

\( P_{cu\text{relative}} \)  
Relative copper loss in a dual motor module drive

\( P_{cu\text{RS}} \)  
Copper loss of a dual motor module under a fault remedial strategy

\( P_{cu\text{SC}} \)  
Copper loss in a short-circuit winding

\( P_{cu\text{SC}_{pu}} \)  
Per unit copper loss in a short-circuit winding

\( P_{in0} \)  
Total input power of a single module motor drive

\( P_{in} \)  
Total input power of a dual module motor drive

\( P_{mech0} \)  
Mechanical power of a single module motor drive

\( P_{openloss} \)  
Open-circuit power loss in a dual motor module drive

\( P_{out} \)  
Output power of a dual motor module drive

\( R \)  
Equivalent winding resistance

\( R_{pu} \)  
Per unit winding resistance

\( T_0 \)  
Electromagnetic torque of a single module motor drive

\( T \)  
Electromagnetic torque of a dual module motor drive

\( T_{ave} \)  
Average torque in a dual module motor drive

\( T_{\text{avedrag}} \)  
Average drag torque in a short-circuit winding

\( T_{\text{avedrag}_{pu}} \)  
Per unit average drag torque
$T_{F0}$  Output torque of a single module motor drive under faulty condition

$T_F$  Output torque of a dual module motor drive under faulty condition

$T_{L0}$  Load torque of a single module motor drive

$T_L$  Load torque of a dual module motor drive

$T_{\text{max}}, T_{\text{min}}$  Maximum and minimum total instantaneous torque values

$T_{\text{openloss0}}$  Open-circuit torque loss in a single motor module drive

$T_{\text{openloss}}$  Open-circuit torque loss in a dual motor module drive

$T_{\text{ripple}}$  Torque ripple factor

$T_{\text{RS0}}$  Output torque of a single module motor drive under a fault remedial strategy

$T_{\text{RS}}$  Output torque of a dual module motor drive under a fault remedial strategy

$v_{1, 2, 3, 4, 5, 6}$  Instantaneous values of phase voltages

$V_{DC1, 2}$  DC link voltage

$V_{in}$  Current sensor output voltage

$V_{out}$  Amplifier output voltage of phase current measurement

$V_{\text{phase}}$  Phase voltage for Hysteresis current control

$V_R$  Voltage of the rheostat

$\Delta h$  Bandwidth of the hysteresis current control

$\Delta i$  Current error between the reference current and measured current

$\Delta T$  Integration time

$\eta$  Efficiency of the motor drive

$\psi_{pm1, pm2, pm3}$  Three phase flux linkages of the rotor permanent magnets

$\theta_e$  Electrical rotor position

$\theta_r$  Mechanical rotor position

$\omega_m$  Mechanical angular speed
\( \omega_{pu} \) \hspace{1em} \text{Per unit value of the mechanical angular speed}

\( \omega_r \) \hspace{1em} \text{Electrical angular speed}

\( \omega_e \) \hspace{1em} \text{Electrical angular speed}

\( \phi \) \hspace{1em} \text{The phase difference between the back-EMF voltage and the short-circuit current}

\( \psi_{1, 2, 3, 4, 5, 6} \) \hspace{1em} \text{Total values of the phase flux linkages}

F \hspace{1em} \text{Fault}

OC \hspace{1em} \text{Open-circuit fault}

RS \hspace{1em} \text{Remedial strategy}

SC \hspace{1em} \text{Short-circuit fault}

* \hspace{1em} \text{Superscript denoting reference values}
Chapter 1

Introduction

1.1 Project Motivation

Electric propulsion systems have many advantages over conventional propulsion system such as greater flexibility in design and placement, higher efficiency and lower air polluting effects. Therefore, there has been a growing trend towards the use of electric propulsion systems in cars, ships and aircrafts. For example, various programs have already considered replacing conventional aircraft subsystems with electric motor drives and moving towards what is called more-electric or all-electric aircraft [1, 2].

In addition, since the cost of electric drive systems can be reduced in comparison to hydraulic and some mechanical systems, more and more electric drive systems are also accommodated in vehicles. Some of the key applications include active suspensions, damping and stabilization actuators, power steering, electromechanical brakes, clutch and shift actuators, air conditioning and ventilation systems, starter–generators and traction drives [3].

It should also be emphasized here that the requirement for electric drive varies in different applications. For example, in an aircraft application, the efficiency of a drive system is highly critical to decrease the weight and space of the system. In a submarine application, the mechanical and electrical noise is critical which can be minimized by reducing the torque ripple in the drive. However, the reliable electric drives are essential in all safety critical applications such as aerospace, transportation, medical and military applications, and nuclear power plants. In these applications the reliability of the electric drive systems must be ensured, as in such systems, any failure in motor drives may result in loss of property and human life. Therefore, it is very desirable and absolutely necessary for the motor drives utilized in safety critical applications to have the fault tolerant capability and to be able to produce a satisfactory output torque even in the
presence of fault.

Although a number of definitions can be given for “fault tolerant system”. But the simplest definition is that it is a system where a fault in a component or subsystem does not cause the overall system to malfunction. The fault tolerance of a given system can be quantified in terms of reliability and availability. Generally, reliability means an attribute of components and systems that will not need to be repaired and is often measured in terms of mean time to failure (MTTF). Availability is simply measured in terms of the expected proportion of time that the system will be available for use [4]. Fault tolerant control (FTC) is an emerging key area in automatic control [5]. The principal aim of the FTC is to avoid the development of local fault into failures that can cause safety hazards. The function of fault tolerance can be obtained through reconfiguring control system or taking remedial strategies using information from fault detection and identification.

In addition to the reliability, the fault tolerant motor drive mainly concerns the ability to operate (availability) in a satisfactory status after sustaining a fault. The term “satisfactory” implies a minimum level of performance once being faulted. For example, the aircraft can continue to fly and land safely after a fault occurs. Currently, despite its cost, redundant design is widely adopted to improve the robustness and reliability of the motor drive against faults.

The various types of electric machinery can offer application specific characteristics. The two main types of fault tolerant motors are Switched Reluctance Motor (SRM) and Permanent Magnet (PM) motor. Although the SRMs have inherent fault tolerant capabilities, they have limited applications due to their higher torque ripple, higher acoustic noise and lower power density. Therefore, PM machines are considered as the future of fault tolerant motors.

Brushless PM motors are an important category of electric machines, in which the rotor magnetization is created by permanent magnets attached to the rotor. Presence of PMs in such motors eliminates the need of using field windings and external energy source, which can improve the motor efficiency significantly [6]. In addition, due to the absence of the rotor windings, this arrangement allows excellent heat dissipation in the motor.
Furthermore, the use of higher magnetic flux density PM materials makes it possible to develop higher power density machines. Combining high efficiency with high power density makes such motors widely appealing in many applications, including fault tolerant motors [7].

As it is well known, brushless PM motors commonly have wye connection and use electronic switching converters to perform the similar function of the mechanical commutators that exist in the conventional brush DC motors. Although the earlier developments of switching converters and controllers were complex and expensive, with the development of power electronics, microprocessor and motor control technologies, brushless PM motor control is becoming much easier and inexpensive and is opening a wide range of applications where such motor drives are utilized.

A limited number of papers have been published on the topic of fault tolerant motor drives. These earlier studies were related to the design of fault tolerant motors, the topologies of the inverter, fault detection and identification methods and fault remedial strategies. However, it was observed in the previous studies, knowledge of fault tolerant motor drives was not complete to develop a higher reliable electric drive system for safety critical applications. Therefore this study aims to continue to investigate fault tolerant motor drives to be able to address various practical issues for safety critical applications. The following section will present the literature review to identify specific research gaps on the fault tolerant motor drives.

1.2 Literature Review

1.2.1 Fundamental aspects and fault modes in electric motor drives

The structure diagram of a fault tolerant motor drive and the potential faults which may occur in this system are illustrated in Figure 1.1. To prevent catastrophic failures and inspire confidence, the motor, inverter circuit, sensors and controller system (including hardware and software) should be individually fault-tolerant, robust and reliable, and should have a degree of redundancy.

The general fault modes can be summarized as follows [8, 9]:

- Motor winding open-circuit;
- Motor winding short-circuit (including partial turn-to-turn or complete);
- Inverter switch open-circuit;
- Inverter switch short-circuit (including reverse diode open-circuit and short-circuit fault);
- Power supply failure;
- Rotor position sensor failure, current sensor failure;
- Controller failure and combination faults.

Therefore, it is important to detect the above listed faults in the drive and then adopt a suitable fault remedial strategy. It can be concluded that the research in the area of fault tolerant motor drives is related to the fault tolerant design both in the motor and inverter topologies, the detection and identification of faults, and implementation of fault remedial strategies to compensate the torque loss due to a fault or faults.

1.2.2 Fault tolerant motor design

In order to make a motor drive fault tolerant, the motor itself must have the features of fault tolerance, and in the literature a number of studies have been undertaken to investigate the fault tolerant capability of different types of motors. The two main types of fault tolerant motors are Switched Reluctance Motor (SRM) and Permanent Magnet (PM) motor.

The SRMs have inherent fault tolerant capability [10, 11]. In SRMs, since the stator has
concentrated windings around separate poles, the magnetic, electrical and thermal interference between each phase is small, thus they can continue to operate when one of the phases fails. However, SRMs are not preferred in applications which require high efficiency and accurate control. In addition, they produce acoustic noise and vibration that are higher than their counterparts.

Conventional three-phase brushless PM machines have higher torque density and efficiencies than SRMs, however, they have no fault tolerant capabilities due to the strong electrical and magnetic interactions between the delta connected stator windings. In [12-16], a fault tolerant PM motor which combined the advantages of SRMs and PM motors was proposed and investigated in detail. It was stated that similar fault tolerant features as the SRM can be achieved by adopting a special design for the PM motor. If the electrical, magnetic and thermal interaction between phases in this motor is minimized, the failure in one phase of the motor does not affect the operation of healthy phases. In addition, when the phase windings are driven by separate single-phase H-bridge circuits, the electrical isolation between the phases is also guaranteed. In this approach, the magnetic and thermal interaction is also minimized since in the entire motor drive, each phase windings are located in different slots and each winding is wound around a single tooth. Moreover, machines are designed with a per-unit inductance can effectively limit the short-circuit current of the machines in its rated value under a phase short-circuit fault condition. Although such design approach reduces the torque density slightly, the experimental results had shown that the PM machine with fault tolerant design can provide a greater torque density than the SRM.

From the control point of view, the brushless PM motors can be classified into two principal classes: sinusoidal current excited and rectangular current excited motors. The second type of motor is also known as the brushless DC (BLDC) motor. In order to reduce the overrating of each phase, more than three phases are used which can further increase the level of fault tolerance. Moreover, the amplitude of torque pulsation can be reduced by using multiphase in brushless PM motors [17-21].

In [22], the multiphase motor design concept was incorporated into BLDC motors to enhance their fault tolerant capability. Three BLDC motors with 3, 4 and 5 phases were designed in order to compare their torque outputs under healthy operation and under a
single phase fault. It was suggested that increasing the number of phases could increase the fault tolerance of the BLDC motors. However, as the number of devices and gate drives increases, the possibility of a fault as well as the cost also increase. Therefore, it was concluded that the BLDC motor with 5 phases is the optimum number of phases for fault tolerance.

### 1.2.3 Inverter circuit fault analysis and possible topologies

As it is mentioned previously, any brushless PM motor control, the inverter circuit is necessary as it is used to perform the similar function of the mechanical commutators in the conventional DC machines. Inverter faults include switch open-circuit and short-circuit. It was observed that reliability prediction of inverters in motor drives is still an area of active research.

In [23], the types of faults and their effects on currents, voltages and torque in a particular Interior Permanent Magnet (IPM) machine during flux-weakening operation were investigated by computer simulation study only.

How the inverter circuit responds to different types of inverter faults is the important factor that determines the fault tolerant capability of the inverter circuit. In [24-26], the short circuit characteristics of IPM synchronous machines under both three-phase symmetrical and single-phase asymmetrical fault conditions were studied. For the case of symmetrical fault, closed-form equations were derived to describe the machine’s response. Asymmetrical single-phase fault was analyzed using a dynamic simulation technique. These studies have contributed to the design of effective system protection and fault tolerant control.

Although the standard three-phase motor drive inverter is not fault tolerant, the need for fault tolerant systems has inspired much research in analysis, modeling and simulation of various inverter topologies. In [10] and [27], a fault tolerant power electronic circuit topology to improve the reliability of the motors was studied.

In [28], the Fault Power Rating Factor (FPRF) and Silicon Overrating Cost Factor (SOCF) which are used to compare the features such as implementation costs and performance limitations of each of these methods were proposed. In this paper, the
faults under consideration were single inverter switch short-circuit, phase-leg short-circuit, single inverter switch open-circuit and single-phase open-circuit (internal or external to the inverter). The paper classified the inverter topologies into four types: switch-redundant topology, double switch-redundant topology, cascaded inverter topology and four-leg inverter topology. It was shown that in order to add fault tolerant capacity to a standard three-phase inverter of motor drives, fuses and additional power devices should be incorporated into the inverter circuits and there was significant cost associated with providing fault tolerant operation.

The inverter topologies stated in [28] are mainly suitable to the three-phase brushless PM motor drives with the neutral line and cannot be directly used in isolated PM motor structures. In fault tolerant motor drive with isolated phases, H-bridge inverters are widely used to minimize the electrical interface of different phases [12, 22]. It was shown in these studies that when the fault occurs, the control circuit in the motor drive can turn on or turn off the switches to protect the healthy switches and the motor windings. In order to improve inverter reliability, the switches can also be integrated together with the gate drives and additional control circuit (for example fault identification circuit) into power modules [9].

1.2.4 Fault detection and identification

In the case of a fault or faults in the entire motor drive, the motor drive performance can deteriorate significantly unless proper remedial strategies are undertaken. To be able to introduce such strategies in motor drive systems, the hardware and software of the controller must detect the faults first. As it is given previously, the most common electrical fault modes are winding open-circuit, winding short-circuit (including partial turn-to-turn or complete) faults, inverter switch open-circuit and short-circuit faults (including reverse diode open-circuit and short-circuit fault). Since different faults require different fault detection and identification approaches, there were significant research interests in recent years to study suitable approaches.

To detect motor or inverter electrical faults, it is necessary to monitor the phase currents and the switch on-state voltages, which are then compared with the predicted values which are obtained by a detailed analysis of the motor and the inverter.
As indicated earlier, SRMs possess inherent fault tolerant capability therefore one of the earlier fault detection techniques was considered in SRMs. In [29], four fault detection devices to detect winding faults were proposed and verified by experiments. These devices were overcurrent detector, current differential detector, the flux differential detector and the rate-of-rise detector. It was observed from this work that the first detector is very easy to implement, but it is not fast acting. The second device is fast acting, but it can not be used to detect short-circuit faults. The third device can detect almost all types of faults, but it is oversensitive and so it may respond to faults in other phases. The fourth device lacks of sensitivity.

Insulation failure in a motor may lead to turn-to-turn faults, phase to phase faults or phase to frame faults. There is evidence to suggest that breakdown of the stator winding insulation is a major cause of motor failure. For motors with a physical separation between phases, phase to phase faults are extremely unlikely and most phase to frame faults are the result of the continued operation of a machine with an undetected turn-to-turn fault. The analysis of winding turn-to-turn faults in Permanent Magnet Synchronous Motor (PMSM) drives was discussed in [30]. The evident features of turn-to-turn faults are local heating and the considerable current increase. Therefore, the quick detection of a turn-to-turn fault is essential. The turn fault detection method, which employed negative and zero sequence components at the machine terminal voltages as the fault indicators was proposed in [31]. Although the method had the ability to detect a turn fault without being affected by the controller actions, it required additional voltage sensors, which were a critical drawback. Furthermore, the turn fault detection method proposed in [31] only applied to Y-connected stator windings with an accessible floating neutral point.

A simple real-time detection technique for turn-to-turn faults in fault tolerant PM motor drives was developed in [13, 32, 33]. The technique is based on a comparison of the tested phase current and the expected current value that could be predicted in the current controller in advance. Then the turn-to-turn faults were detected in each PWM cycle without the need for any additional sensors. When turn-to-turn faults were detected, a terminal short-circuit in the inverter circuit was applied to the faulty phase, allowing the PM motor drive to continue to operate.
The voltage drop across a conducting switch of an inverter, referred to as the “on-state voltage”, is the function of the current flowing through the device. An on-state voltage sensor can compare this voltage to a pre-determined level, to produce a single digital signal which can indicate whether or not the device is carrying excessive current. This concept was studied in [13, 32, 33]. In these studies, the winding terminal short circuit fault and switch short circuit fault detection schemes were provided which utilized the signals from four on-state voltage sensors in the H-bridge circuit. The drawback of this fault detection schemes is the number of on-state voltage sensors required for effective detection.

In [34], an approach based on knowledge models to detect and isolate faults in a pulse-width-modulation (PWM) inverter driving a PMSM machine was studied. The fault diagnosis system utilized the input variables of the drive only. The method considered the analysis of the current vector trajectory and the instantaneous frequency in a fault mode. In the first approach, the transistor or current sensor fault was considered if the measured current was zero or had a large offset. In the second approach, an inverter fault was diagnosed by comparing the instantaneous frequency and the current fundamental frequency obtained by the rotor position sensor. However, this approach was found to detect switch fault (no turning off or turning on one of the transistor) and current sensor faults only.

In [35], a technique to detect and identify the power switch open-circuit fault in voltage source inverters was proposed. The fault detection techniques in [35] employed a direct comparison of the measured voltages and their reference voltages obtained from the PWM reference signals that was based on an analytical model. The measured voltages were machine phase voltages, or system line voltages, or inverter pole voltages, or machine neutral voltages. The proposed technique can be embedded into the existing AC drive software as a subroutine without an excessive computational effort. The shortcoming of this approach is that the extra voltage sensors are needed to incorporate into the system to finish the fault detection performance.

Knowledge-based fault detection and identification techniques were reported in [36-39]. In [36] and [37], an automatic diagnosis and location method for open-switch fault in brushless DC motor drives was developed. This method was based on adaptive neuro-
fuzzy inference systems (ANFIS) which was implemented to perform an online condition monitoring task. ANFIS based was trained off-line by simulation and experimental results under various healthy and faulty conditions. The neural network based method reported in [36] and [37] demands high computer calculating capacity and is suitable to detect faults that develop gradually. In [38, 39], the fault diagnostic neural network (FDNN) was used to identify the switch faults in the inverter circuit. Although the techniques described in [36-39] can detect the open-circuit switch fault, they are highly complex to implement in real time motor control.

1.2.5 Fault tolerant control and torque ripple minimization

Fault tolerant control (FTC) combines diagnosis with control methods to be able to prevent simple faults developing into serious failure and hence increase the availability of the motor and reduce the risk of hazards. There is wide range of FTC strategies varying from a simple re-tuning to a complex estimation to predict the fully sensor data. In another strategy, a complex reconfiguration or on-line controller design is considered [40, 41].

After faults are detected and identified, the realization of fault tolerant control on motor drives can be made by using suitable fault remedial strategies. There are two primary functions of fault remedial strategies in motor drives. Firstly, the faults should be isolated and reconfigured to avoid catastrophic failures. Secondly, the control parameters should be changed to make the motor drive generate required output torque similar to the healthy operation. Some fault remedial strategies for induction motor drives and SRMs were presented in [10, 29, 42-45].

The fault remedial strategies to deal with switch faults in BLDC motor drives under square-wave operation and with relatively large torque ripple were presented in [46, 47]. The fault tolerant control against inverter faults in PMSM drive was described in [27], which is accomplished by adding an extra inverter leg to the standard three-phase inverter configuration. The midpoint of the additional leg is connected to the neutral point of the PMSM that should have Y-connected windings with neutral point accessible. When an inverter fault is detected, the faulted phase is isolated by disconnection. Post-fault operation is then commenced by activating the additional fourth inverter leg which
is connected to the neutral point of the machine.

In [48] fault remedial strategies for winding short-circuit fault and open-circuit fault in Y-connection PM motor drive was studied. As the excitation of the motor is fixed, it is not sufficient to simply disconnect the machine by turning off the inverter switches due to the existence of the braking torque. In this paper, the controlled balanced short-circuit current on the winding terminals was provided by turning on related switches to limit the short-circuit current and the braking torque.

Fault interrupting methods and topologies in IPM motor drives were provided in [26], where the thyristors were incorporated into the standard three phase inverter circuit to interrupt the short-circuit current after winding short-circuit fault occurred. Naturally, the isolation switches increase the on-state losses which results in a reduction in efficiency including healthy operation. Another innovative fault remedial strategy for inverter faults in IPM motor drives were presented in [49]. In this fault remedial strategy the fault related changes in torque and speed are compensated by providing higher currents in the healthy phases.

The fault remedial strategies described above can only be applied in standard three phase motor drive with neutral point accessible. A few of remedial strategies for fault tolerant motor drives with isolated phases were proposed in [12, 13, 22, 50]. As given in these studies, when winding short circuit fault occurs, the upper two switches in the H-bridge inverter were turned on and the lower two switches were turned off. Due to the 1pu per unit inductance of the winding, the phase short circuit current is limited and equals to the full load value. In order to output rated torque as in the healthy operation, the current in healthy phases was increased to compensate the torque loss due to various faults. However, the torque ripple in these studies was higher under the fault remedial strategy. Moreover, in the case of a complete motor failure, or power supply failure, or controller failure, complete drive failure is unavoidable.

In [51], the fault tolerant operation of a five-phase fault tolerant permanent magnet motor drives with sinusoidal and quasi-rectangular currents was studied. In the work reported, under a single phase fault operation, the output torque was kept the same as in the healthy operation by adjusting the current on the healthy phases. However, in the case of two phase fault, the output torque was varied to prevent over current in the
healthy phases.

Torque ripple is a critical concern in many applications where demands low acoustic noise, high efficiency, and friendly human-machine interactions [52]. In steer-by-wire applications, high level of torque ripple free operation is required in addition to the fault tolerance [53]. Some torque ripple minimization techniques in standard three phase PM motor drives were discussed in [54-59]. Moreover, the torque pulsation reduction technique for multi-phase IPM motor drives were presented in [60]. Torque ripple reduction techniques can be classified into two categories: motor design stage and controller stage that usually accommodate modified excitation currents in the motor.

An optimal torque control technique in a fault tolerant PM motor drive with isolated phases was proposed in [61-63] by the same authors. The optimal current control strategy used in the motor drive enabled ripple-free torque operation while minimizing the copper loss under voltage and current constraints. However, the studies were based on computer simulation and not verified by the experimental results.

## 1.3 Gaps and Contributions

### 1.3.1 Gaps and objectives

From the above discussions, one can conclude that a number of studies on the fault tolerant motor design, the inverter circuit fault analysis and topologies, the fault detection and identification techniques, and fault tolerant control strategies have been undertaken. It was concluded that the fault tolerant brushless PM motor configuration with isolated phases is a suitable choice for safety critical applications, which can accommodate isolated H-bridge inverter circuits to eliminate the electrical interaction between the phases.

However, the existing fault analysis and investigations are mainly concentrated on brushless PM motors with three-phase star-connected windings or using a single motor module with multiple (3 to 6) isolated windings. It was considered that a single fault tolerant motor drive can not provide a reliable fault tolerant electric propulsion system for safety critical applications due to the absence of redundancy.
Moreover, although a single motor module fault tolerant drive system (simplified as single fault tolerant motor drive in this thesis) may overcome most of the operational problems in safety critical applications, and the multi-phase fault tolerant motor structure can improve the performance of the motor drive, the complete motor drive failure (for example the power supply failure or motor controller failure) has not been considered. Redundant design is one of the common tools to increase the reliability of a system as it has been utilized in many areas. However, the investigations on multiple fault tolerant brushless PM motor drives on a common shaft for safety critical motor applications have revealed that the method is important to provide redundancy. Therefore, this thesis considers the study of a dual motor module fault tolerant drive (simplified as dual fault tolerant motor drive in this thesis) and associated techniques.

Furthermore, it was concluded that before applying an effective fault remedial strategy, the motor drive control system should detect and identify the faults effectively in advance. The investigations also demonstrated that there is no effective fault detection and identification technique available in fault tolerant motor drive system. Although the reported technique can detect the switch open-circuit and short-circuit fault by using multiple voltage sensors, the cost of this technique is significant. Therefore, this thesis aims to develop practical fault detection and identification methods for the fault tolerant motor drive. In addition, the research on real time fault remedial strategies for fault tolerant motor drives in various faulty operations are found limited. This research also aims to investigate this aspect.

The principal aims of this research can be given as below:

- Designing and developing a dual fault tolerant brushless PM motor configuration for safety critical applications;
- Comprehensive fault analysis and performance test of this dual motor drive system under real time operating conditions;
- Developing practical fault detection and identification methods for various possible faults;
- Developing real time fault tolerant remedial strategies for different faults and demonstration of the operation of the motor drive system under these faults;
Implementation and verification of dual motor module fault tolerant PMAC drives.

1.3.2 Main contributions

Although single motor fault-tolerant drive system may be sufficient in some critical applications; it does not offer any redundancy in the case of a complete motor drive failure. This thesis proposed a dual motor module fault tolerant PM drive configuration on a common shaft to increase the reliability of the entire motor drive system.

The mathematical models for the dual motor module fault tolerant drive were established and comprehensive fault analysis was undertaken. Since the output torque in the motor drive is proportional to the phase current, the reference current have to be calculated for the torque control. Therefore, through the analytical investigations, the general reference current calculation model was developed which can be utilized in both healthy operation and faulty operation and both in sinusoidal and trapezoidal brushless PM motor types. The fault analytical study has shown that if the per-unit inductance of a winding is 1.0, the short-circuit current under winding short-circuit and switch short-circuit fault is limited. However, in rated rotor speed, the average drag torque under switch short-circuit fault condition is found to be greater than the value under winding short-circuit fault condition. Therefore, after the power switch short-circuit fault was detected and identified, the switch in other leg was turned on to transfer the switch short-circuit fault into the winding short-circuit fault. This conclusion also provided a theoretical guidance for the fault tolerant motor design.

After the faults occurred in the motor drive, suitable remedial strategies should be adopted to avoid catastrophic failures while the motor drive operating. In this thesis, three fault remedial strategies were proposed to compensate the loss of torque due to the faults. These fault remedial strategies are increasing the average current on healthy phases (fault remedial strategy 1), doubling the current in the same phase of the second motor module (fault remedial strategy 2), and zero torque ripple with minimum copper loss fault remedial strategy (fault remedial strategy 3). It was concluded that fault remedial strategy 1 can not improve the torque ripple feature although it consumes the minimum copper loss. Fault remedial strategy 3 is the most suitable method as it can generate the same output torque with smallest torque ripple as the healthy operation with only a modest increase in copper loss comparing with the minimum possible value.
However, the implementation of this suitable algorithm in the motor controller is found slightly complicated compared with the other methods.

In order to investigate the features of the fault tolerant motor drive with redundancy, two practical fault tolerant brushless PMAC motor drive setups were designed: 4-pole interior rotor PMAC motor drive and 48-pole exterior rotor PMAC motor drive. In this thesis, the performance investigation of 48-pole motor drive based on measurement was presented and the results were verified by MATLAB based simulation studies. Furthermore, the fault effect on the motor drive efficiency was investigated by the analysis and simulation. It was concluded that the efficiency of the motor drive under phase short-circuit fault condition is much lower than the healthy operation and phase open-circuit fault condition due to the existence of drag torque produced by the winding short-circuit current. In addition, the simulation studies on the dual 48-pole fault tolerant PMAC motor drive setup under healthy and faulty conditions both at lower and higher speeds and light and heavy load were performed in this thesis. The simulation results demonstrated that the proposed fault remedial strategies are effective to the potential faults.

In addition, in order to verify the proposed fault remedial strategies and verify the conclusions obtained in the analytical and simulation study, hardware and software implementation of the entire motor drive was developed. A practical fault detection and identification method to detect switch open-circuit fault, switch short-circuit fault, and the winding short-circuit fault was also developed in the real system. As the fault detection circuit with inverter drive circuit is combined, the additional switch on-state voltage sensors are eliminated. Therefore, the advantages of this fault detection and identification method are the simplicity of the implementation and reduction of the cost of the motor drive system. In addition, in the implementation of fault remedial strategy 3, a reference current calculation method was proposed, which offers a simple solution in real time motor control.

The experiments performed in this thesis include one phase open-circuit fault test, two different phase open-circuit fault test, two same phase open-circuit fault test, one motor complete fault test (may be caused by power supply failure or control failure), and one phase short-circuit fault test. The experimental results demonstrated that the proposed
fault remedial strategies can be realized in a real time motor control and are effective to compensate the torque loss due to the faults. Moreover, a complete failure of a motor module and associated test results demonstrated that the dual fault tolerant motor drive system offers a redundancy. This offers a higher reliability than single motor drive system because it can continue to provide rated output torque under this serious fault. In addition, the efficiency test results of the motor drive were obtained to verify the simulation studies.

A single phase short-circuit fault experimental results demonstrated that in order to provide rated output torque as in healthy operation, the phase currents in healthy phases have to be increased significantly due to the large drag torque produced by the short-circuit current. It was found that under the above operating state and a heavy load condition, it is impossible for the motor drive to achieve the rotor speed as in the healthy operation. The efficiency of the motor drive was also found very low. For example, the efficiency of the 48-pole dual motor drive under one phase short-circuit fault condition and at 92 rpm rotor speed was 38% while the efficiency in healthy operation under same speed was 67.5%. Therefore, it is necessary to design the motor with 1.0 per-unit inductance to limit the short-circuit current. An alternative is to add back-to-back thyristors in series with the motor windings which can be used to block the short-circuit current associated with inverter faults, and then the remedial strategies for phase open-circuit fault operation can be adopted.

1.4 Outline of the Thesis

The content of this thesis is organized as seven chapters. Chapter 1 covers the general background of the project. This chapter indicates the advantages of fault tolerant PM motor drive, and presents a detailed literature survey on the work accomplished about the fault tolerant motor drives. The main gaps, objectives and main contributions are also summarized in this chapter.

In order to provide a theoretical basis for the research work presented in the thesis, Chapter 2 introduces the operation principle and control methods of the brushless PM motor drive and illustrates the configuration of the fault tolerant brushless PM motor drive. Considering the possibility of the total loss of output torque in the case of a
complete failure of the motor drive, Chapter 2 proposes the dual fault tolerant motor drive structure which consists of two identical motor modules on a common shaft.

In Chapter 3, the fault classification is performed after the analysis of fault modes and the reasons for the occurrences of the faults. The mathematical models for the reference current calculation both in single and dual motor module fault tolerant brushless PMAC drives are also presented in the chapter. In addition, the effects of various faults on output torque, torque ripple and copper loss are studied. At last, three fault remedial strategies for various faults are proposed in this chapter to compensate the torque loss and reduce the torque ripple due to these faults.

In order to investigate dual motor module fault tolerant PMAC drives, two practical motor drive setups are built. Chapter 4 introduces the parameters of the motor drive and provides some efficiency estimation results using the experimental results. In the chapter, MATLAB based simulation studies are presented to verify the efficiency prediction results. The simulation study of designed fault tolerant motor drive is also provided in the chapter to prove the effectiveness of the proposed fault remedial strategies. In addition, the comparison of the simulation results on single and dual motor module fault tolerant drives is made to further demonstrate the advantage of the dual motor module drive.

Chapter 5 provides the implementation details of the dual motor module fault tolerant brushless PMAC drive. The dsPIC30F4011 controllers are used to control the two motor modules. The hardware design and software design are presented in Chapter 5. Since effective fault remedial strategy requires the detection and identification of the faults first, the fault detection and identification method is also developed in this chapter.

Chapter 6 describes the experimental results to verify the analytical and simulation results and demonstrate the flexibility of the proposed remedial strategies. Chapter 7 describes the general conclusions of the entire thesis and proposes ideas for potential future research directions.
Chapter 2

Fundamentals of Fault Tolerant Brushless PM Motor Drives and Control

2.1 Introduction

Permanent magnets (PM) have been used in electrical machines as replacements for the electromagnetic excitation systems almost from the beginning of the development of such machines. However, the low energy densities and high cost of the earlier magnetic materials limited their use to small or brush DC machines. The advent of modern permanent magnets with significant amount of energy density has brought out the evolution of PM machines [64].

As it is well known, PMs in motors generate the air gap magnetic field, which eliminate the use of excitation or field windings as in the conventional brush DC motor. Due to the absence of the field windings and associated copper losses, it is possible to design a motor with much higher efficiency characteristics. Moreover, higher magnetic flux density in the air gap can be achieved by using high performance PM materials. This higher magnetic flux density makes it possible to design the motor with impressively high values of power density. In addition, the absence of the field windings simplifies the construction and maintenance of the PM motors while increasing the flexibility of their usage in special applications, which can also simplify the electrical equipment circuit. At a result of these and combining high efficiency with high power density, PM motors have become more attractive than other motor drives in recent years.

In late 1950s, the availability of static switching power devices led to the development of inverters. This achievement enabled the rotor armature circuit to be constructed on the stator and the replacement of the mechanical commutator with an electronic commutator, which led to the development of brushless PM motors. This new design
enabled better cooling and higher voltages to be achieved. In addition, the absence of commutator and brushes made such motor’s maintenance free and improved their dynamic characteristics due to the elimination of brush friction.

However, the back-EMF voltages induced in the stator windings of such motors are AC when rotor with PMs rotates in a given direction. Hence, in order to produce a constant torque, it is required that the excitation currents fed to stator windings should also be AC. Therefore, in general the brushless PM motors are also known as PMAC motor. The requirement of the AC current in the brushless PMAC motors, however, requires more complicated electronic controller. In addition, to achieve a maximum torque and minimum torque ripple, the excitation currents should be synchronized with the back-EMF voltages, which can be achieved by the rotor position knowledge. Therefore, a rotor position sensor is also required in such motors which can be mounted on the shaft of the motor.

Although the above additional requirements can make the control of these motors slightly complex, with the development of power electronics, microprocessor and motor control technology, brushless PMAC motor control is becoming much easier and inexpensive [65], which can also integrate indirect position sensor technology into the motor drive.

It has been found that after special design and adopting isolated electrical inverter circuit, the brushless PMAC motor drive can be fault tolerant. This chapter aims to provide the theoretical basis of the brushless PMAC motor configuration to be used as a fault tolerant motor drive. Therefore, the main contents of this chapter includes the classification and mathematical models of the brushless PM motor drives; the configuration of the single and dual motor module fault tolerant drives and the current control schemes in these systems.

### 2.2 Conventional Brushless PM Motor Drives

#### 2.2.1 Classification

The classification diagram of the brushless PM motors is shown in Figure 2.1, which is classified in terms of the flux direction, the magnet position in the rotor structure, the
position of the rotor, and the induced back-EMF waveforms. As shown in the figure, based on the direction of the field flux, the PM machines can be widely classified as radial-field, in which the main flux direction is along the radius of the machine; and axial-field, in which the main flux direction is parallel to the rotor shaft. Although the radial-field PM machines are commonly used in industries; the axial-field machines play a significant role in a small number of applications because of their compact shape, smaller axial length, higher power density and higher acceleration [66].

![Classification diagram of the brushless PM motors](image)

**Figure 2.1 Classification diagram of the brushless PM motors**

As shown in Figure 2.2 [6], in brushless PM motors, the magnets can be mounted either on the surface of the rotor (surface mount permanent magnet motors) or can be placed inside the rotor (interior permanent magnet motors). In such motor types, Interior Permanent Magnet (IPM) motors have certain superior characteristics compared to surface mount permanent magnet motors, which is due to some of their inherent characteristics such as higher torque density and extended flux weakening region. The higher torque density in IPMs is due to the presence of reluctance torque. In addition, such construction offers a rugged rotor structure that is desirable in high-speed operation. However, the IPM configuration can produce considerable torque pulsation.

An alternative classification of brushless PM motors can be made on the location of the rotor: interior rotor and exterior rotor as shown in Figure 2.3 [67]. If rapid acceleration and deceleration of the load is required in a specific application, as in the case for servo systems, then the ratio of the torque and inertia of the motor should be as high as possible. Therefore, PM motors with interior rotor and high energy density magnets are desirable. Exterior rotor configuration is usually being used in application requiring
constant speed such as fans, blowers, and spindle motors. The high inertia of the exterior rotor is an advantage in achieving uniform and constant speed. Both interior rotor and exterior rotor PM motors are used in the experimental setups of this research.

![Image](a) Surface magnets  (b) Interior magnets

**Figure 2.2 Sample cross sections of PM motors based on magnet position.**

![Image](a) Exterior rotor  (b) Interior rotor

**Figure 2.3 Sample cross sections of PM motors based on rotor position.**

In addition, based on the shape of back-EMF waveforms, brushless PM motors can be classified as brushless trapezoidal permanent magnet (BTPM) motor (also known as brushless DC motor) and brushless sinusoidal permanent magnet (BSPM) motor [66].

The typical back-EMF waveforms of BTPM and BSPM motor are shown in Figure 2.4 for a single phase. In a three phase BTPM motor, rectangular currents in phase with the corresponding back-EMF waveforms are applied to three phases, which are synchronized with the instantaneous rotor position. Sinusoidal currents are applied to the windings of the BSPM motor to produce constant torque. Such motors are also known as sinusoidal PMAC motor. Also, since such motors operate on the principle of a
rotating magnetic field as other synchronous motors, it is simply called permanent magnet synchronous motor (PMSM) [65].

Rectangular or sinusoidal current waveforms are generated with rotor position information. However, the requirement of rotor position sensor for above current waveforms is different. Rectangular current waveform requires the position signals at intervals of 60° electrical angles, while sinusoidal current waveform needs continuous position information. Therefore, BTPM motor drives are simple and have lower cost than BSPM motor drives. However, BSPM motors have a better dynamic performance such as fast response and smooth output torque.

![Figure 2.4 Typical single phase back-EMF waveforms in brushless PM motors.](image)

**2.2.2 Electrical model**

The standard three-phase brushless PM motor normally is connected in star configuration. Figure 2.5 displays the electrical equivalent circuit of a brushless PM motor [66]. It is assumed that the stator windings of the brushless PM motor are identical windings and have 120° phase difference. Each phase consists of a series connected resistor, inductor and induced back-EMF voltage source. In addition, there are mutual inductances between the phase windings.

The general voltage equations in the matrix form for the three-phase brushless PM motor can be expressed as a function of total flux linkages of each phase as

\[
\begin{bmatrix}
  v_1 \\
v_2 \\
v_3 \\
\end{bmatrix} = \begin{bmatrix}
  R & 0 & 0 \\
  0 & R & 0 \\
  0 & 0 & R \\
\end{bmatrix} \begin{bmatrix}
  i_1 \\
i_2 \\
i_3 \\
\end{bmatrix} + \frac{d}{dt} \begin{bmatrix}
  \psi_1 \\
\psi_2 \\
\psi_3 \\
\end{bmatrix} \tag{2.1}
\]
Here \( v_1, v_2, \) and \( v_3 \) are the phase voltages; \( i_1, i_2, \) and \( i_3 \) are the phase currents; \( \psi_1, \psi_2, \) and \( \psi_3 \) are the total flux linkages; and \( R \) is the winding resistances.

![Figure 2.5 Equivalent circuit of the standard three-phase brushless PM motor](image)

The total flux linkages given above include the flux linkages established by PM and the stator currents, and can be expressed in matrix form as:

\[
\begin{bmatrix}
\psi_1 \\
\psi_2 \\
\psi_3
\end{bmatrix} =
\begin{bmatrix}
L_{11} & M_{12} & M_{13} \\
M_{21} & L_{22} & M_{23} \\
M_{31} & M_{32} & L_{33}
\end{bmatrix}
\begin{bmatrix}
i_1 \\
i_2 \\
i_3
\end{bmatrix} +
\begin{bmatrix}
\psi_{pm1} \\
\psi_{pm2} \\
\psi_{pm3}
\end{bmatrix}
\]  

(2.2)

Where \( L_{11}, L_{22}, \) and \( L_{33} \) are the self-inductances of the Phases 1, 2, and 3 respectively; and \( M_{12}, M_{13}, M_{21}, M_{23}, M_{31}, \) and \( M_{32} \) are the mutual inductances between the pairs of the phase windings. Since the three-phase windings are symmetrical, the self-inductance and mutual inductances are also symmetric, that is: \( L_{11} = L_{22} = L_{33} = L_1 \), and \( M_{12} = M_{21} = M_{23} = M_{32} = M_{31} = M_{13} = M_1 \). \( \psi_{pm1}, \psi_{pm2} \) and \( \psi_{pm3} \) are the flux linkages established by rotor permanent magnet as viewed from the stator windings and they are functions of the rotor position. When the rotor rotates, the derivatives of the flux linkages with respect to time are the back-EMF voltages induced in the phase windings that are due to the permanent magnets on the rotor.

For a surface mounted permanent magnet motor, it can be assumed that the self-
inductances and the mutual inductances are constant and independent of the rotor position. Therefore, the voltage equation can be simplified for the surface permanent magnet motors as

\[
\begin{bmatrix}
  v_1 \\
  v_2 \\
  v_3
\end{bmatrix} =
\begin{bmatrix}
  R & 0 & 0 \\
  0 & R & 0 \\
  0 & 0 & R
\end{bmatrix}
\begin{bmatrix}
  i_1 \\
  i_2 \\
  i_3
\end{bmatrix} +
\begin{bmatrix}
  L_1 & M_1 & M_1 \\
  M_1 & L_1 & M_1 \\
  M_1 & M_1 & L_1
\end{bmatrix}
\begin{bmatrix}
  i_1 \\
  i_2 \\
  i_3
\end{bmatrix} +
\frac{d}{dt}
\begin{bmatrix}
  i_1 \\
  i_2 \\
  i_3
\end{bmatrix} +
\begin{bmatrix}
  e_1 \\
  e_2 \\
  e_3
\end{bmatrix}
\]

(2.3)

Where \( e_1 \), \( e_2 \), and \( e_3 \) are the back-EMF voltages induced in each phase winding due to the magnet flux linkage.

In the star connected motor with isolated floating neutral, the sum of the three-phase currents is equal to zero, and then the following equation can be given

\[ M_1 i_1 + M_1 i_2 = -M_1 i_3 \]  

(2.4)

Substituting Equation (2.4) into (2.3), the voltage equation of the surface mounted permanent magnet motor can be simplified as follows:

\[
\begin{bmatrix}
  v_1 \\
  v_2 \\
  v_3
\end{bmatrix} =
\begin{bmatrix}
  R & 0 & 0 \\
  0 & R & 0 \\
  0 & 0 & R
\end{bmatrix}
\begin{bmatrix}
  i_1 \\
  i_2 \\
  i_3
\end{bmatrix} +
\begin{bmatrix}
  L & 0 & 0 \\
  0 & L & 0 \\
  0 & 0 & L
\end{bmatrix}
\begin{bmatrix}
  i_1 \\
  i_2 \\
  i_3
\end{bmatrix} +
\frac{d}{dt}
\begin{bmatrix}
  i_1 \\
  i_2 \\
  i_3
\end{bmatrix} +
\begin{bmatrix}
  e_1 \\
  e_2 \\
  e_3
\end{bmatrix}
\]

(2.5)

Where \( L = L_1 - M_1 \) and is called as the equivalent winding inductance of the surface permanent magnet motor.

As shown in Equation (2.5), the voltage equation has been decoupled by simply introducing the equivalent inductance term \( L \). This makes it easy to study the static and dynamic performance of the brushless PM motor drives.

The induced back-EMF voltage is the function of electrical rotor position \( \theta \). Since the stator windings are symmetrically displaced in three phase motors, the ideal back-EMF waveforms for a sinusoidal brushless PM motor can be expressed as
For a BLDC PM motor, the ideal back-EMF waveform of Phase 1 can be given in piecewise linear form as

\[ e_i = \begin{cases} 
\frac{E_m}{\pi/6} \theta_e & 0 < \theta_e \leq \frac{\pi}{6} \\
E_m & \frac{\pi}{6} < \theta_e \leq \frac{5\pi}{6} \\
-\frac{E_m}{\pi/6} (\theta_e - \pi) & \frac{5\pi}{6} < \theta_e \leq \frac{7\pi}{6} \\
- \frac{E_m}{\pi/6} & \frac{7\pi}{6} < \theta_e \leq \frac{11\pi}{6} \\
\frac{E_m}{\pi/6} (\theta_e - 2\pi) & \frac{11\pi}{6} < \theta_e \leq 2\pi 
\end{cases} \]  

(2.7)

The back-EMF equations of Phase 2 and 3 can be obtained by introducing 120° and 240° electrical phase difference in Equation (2.7) respectively. In addition, the practical back-EMF waveforms always deviate from these ideal assumptions mainly due to the fringing field and manufacturing inaccuracies. If more accurate model of the practical motor is desired, the back-EMF waveforms can be modeled by using a look-up table or multiple harmonic components of the real waveform [66].

In Equations (2.6) and (2.7), \( E_m \) is the amplitude of the back-EMF voltages that is proportional to the motor mechanical angular speed \( \omega_m \) and can be calculated by

\[ E_m = k_e \omega_m \]  

(2.8)

where \( k_e \) is the back-EMF constant. In Equations (2.6) and (2.7), \( \theta_e \) presents the electrical rotor position angle that can be given by

\[ \theta_e = N_p \theta_r = N_p \int \omega_m dt \]  

(2.9)

Where \( \theta_r \) is the mechanical rotor position angle and \( N_p \) is the number of pole pairs of the motor.
2.2.3 Torque model

As other type of machines, brushless PM machines can convert electrical energy into mechanical energy or vice versa. Thus the electromagnetic torque of brushless PM motors can be directly derived from the relationship with its mechanical output power. In a standard three-phase motor, the total input instantaneous power $P_{in}$ is equal to the sum of the instantaneous powers absorbed by the three-phases and can be given by

$$P_{in} = v_1 \cdot i_1 + v_2 \cdot i_2 + v_3 \cdot i_3$$

(2.10)

From Equations (2.5) and (2.10), the instantaneous power $P_{in}$ in the surface mounted permanent magnet motor can be expressed as:

$$P_{in} = R(i_1^2 + i_2^2 + i_3^2) + \frac{L}{2} \left( \frac{di_1^2}{dt} + \frac{di_2^2}{dt} + \frac{di_3^2}{dt} \right) + (e_1i_1 + e_2i_2 + e_3i_3)$$

(2.11)

As seen from the equation above, the input instantaneous power consists of three parts. The first part is the copper losses in the stator winding. The second part represents the change rate of the energy stored in the magnetic field. According to the energy conservation principle, the third part is the power converted into mechanical power and is called mechanical output power.

In the rotating mechanical system, the mechanical power equals to the product of the electromagnetic torque $T_0$ and angular rotor speed $\omega_m$, that is

$$P_{mech} = e_1i_1 + e_2i_2 + e_3i_3 = T_0 \cdot \omega_m$$

(2.12)

Thus, the electromagnetic torque in the surface PM motor can be easily obtained as

$$T_0 = \frac{1}{\omega_m} (e_1i_1 + e_2i_2 + e_3i_3)$$

(2.13)

As seen in Equation (2.13), the electromagnetic torque is inversely proportional with the rotor mechanical angular speed and directly proportional with the sum of the products of the phase current and back-EMF voltage. This torque equation is not suitable to calculate electromagnetic torque for zero speed operation. Since the back-EMF voltages
are also proportional with the rotor angular speed. The general back-EMF voltages can be expressed by

\[
\begin{align*}
    e_1 &= k_e \omega_m e_1(\theta_e) \\
    e_2 &= k_e \omega_m e_2(\theta_e) \\
    e_3 &= k_e \omega_m e_3(\theta_e)
\end{align*}
\]  

(2.14)

Here \(e_1(\theta_e), e_2(\theta_e), \text{ and } e_3(\theta_e)\) are the unit back-EMF voltages and are the functions of the rotor position with a maximum amplitude of \(\pm 1\). For a sinusoidal brushless PM motor, the unit back-EMF functions are the sinusoidal function of the rotor position, while the unit back-EMF functions of a brushless BLDC motor are the trapezoidal function (as in Equation 2.7) of the rotor position.

Then the electromagnetic torque can be conveniently expressed as a function of the unit back-EMF functions

\[
T_0 = k_e [e_1(\theta_e) \cdot i_1 + e_2(\theta_e) \cdot i_2 + e_3(\theta_e) \cdot i_3]
\]  

(2.15)

As in all types of motor drive, the brushless PM motor is normally connected to a mechanical system. Thus the dynamic model of such motor drive system can be given as

\[
T_0 = J \frac{d\omega_m}{dt} + B \omega_m + T_{l,0}
\]  

(2.16)

This relationship is often called the motor motion equation, and here \(T_{l,0}\) is the load torque of a single motor module drive; \(J\) is the inertia of the motor and connected load; \(B\) is the damping coefficient. This equation can be used to describe the dynamic performance of the drive system.

### 2.2.4 Inverter circuit

To produce the required three-phase symmetrical sinusoidal or rectangular excitation currents, the inverter circuit should be connected with the windings of the motor. The most typical inverter circuit for a brushless PM motor is a standard three-phase DC-AC inverter, which consists of a DC link source voltage and six switches and freewheeling diodes as shown in Figure 2.6. The power switches in the inverter are the key elements,
which achieve the regulation of the phase currents in the motor drive.

The inverter has two primary functions for the brushless PM motor control. The first function is position synchronization that requires the inverter to excite the proper phases to maximize the torque output. The second function is the current regulation, taking the advantage of the direct proportionality between the current amplitude and the output torque.

![Three-phase inverter diagram](image)

**Figure 2.6 The topology of a three-phase inverter circuit and the stator windings of a brushless PM motor drive**

### 2.2.5 Control structure

In order to generate required output torque and with minimum torque ripple, the phase current waveforms should be synchronized with the back-EMF waveforms. This function can be performed by the motor drive torque control system which is shown in Figure 2.7. In this closed-loop motor drive torque control system, the three phase reference current generator calculates the reference current according to the torque command and rotor position information. Then, the current controller compares the actual measured phase current with reference current and produces switch control signals to the inverter to keep actual current values close to reference current values. The common current control scheme can be PWM current control or hysteresis current control whose operation principle will be described in section 2.5.1.

The BTPM motors have higher maximum torques than BSPM motors using the same magnetic materials and operating from inverters with the same currents. The reason is that, for the same peak value, the 120° square waveform current has a higher RMS...
value than the corresponding sine waveform current.

Figure 2.7 Three-phase PM motor drive current regulated torque control diagram

2.3 Fault Tolerant Brushless PM Motor Drives

In safety critical applications, the failure of a drive has a serious effect on the operation of the system. In some cases, the failure results in the loss of production whereas in some others it is very dangerous to human safety. Therefore, in safety critical applications it is of major importance to use fault tolerant motor drives which can continue operating safely under a fault.

As mentioned in Chapter 1, although the SRMs have inherent fault tolerant capabilities, the disadvantages of SRMs such as higher torque ripple and acoustic noise and lower power density have limited their applications. Comparing with SRMs, brushless PM motor possesses higher efficiency and higher power density, but it has none of the inherent fault-tolerant capabilities of SRMs. Through special design and using isolated H-bridge inverter circuit, brushless PM motor can provide the same fault tolerant capability as SRMs. Therefore, in this thesis, the fault tolerant brushless PM motor drive are selected and investigated. This section will introduce the winding arrangement and specifications of the fault tolerant brushless PM motor, and the inverter circuit.

2.3.1 Winding arrangement

In order to produce a fault tolerant brushless PM motor, it is important to minimize or eliminate the electrical, magnetic and thermal coupling between the motor windings.
Thus, a failure in one winding will not affect the operation of the remaining windings.

Figure 2.8 shows the winding arrangement of two fault-tolerant brushless PM motors [12]. As can be seen in the figure, each phase winding in both motors occupies two different slots around a single tooth. This physical isolation of phases can prevent the propagation of the fault into the neighbouring phases and increase the magnetic and thermal isolation. In the event of the failure in one of the motor phases, the reduction of the developed average torque can be compensated by overrating the healthy phases of the motor.

The most serious fault in the motor is the winding short-circuit fault which will result in large induced short-circuit current and drag torque in the winding. In order to limit the short-circuit current, higher winding inductance is needed in the motor design. If the winding is designed to have 1.0 per unit inductance, the short-circuit current can be limited at rated current even in the case of a winding short-circuit fault.

![Winding arrangement of fault tolerant brushless PM motors. (a) 4-pole three-phase motor, (b) 8-pole six-phase motor](image)

**Figure 2.8** Winding arrangement of fault tolerant brushless PM motors. (a) 4-pole three-phase motor, (b) 8-pole six-phase motor

### 2.3.2 Inverter circuit

As in other brushless PM motor drive, the inverter circuit is also needed in fault tolerant brushless PM motor drives for current commutation and regulation according to the rotor position. The distinguishing feature of the inverter in the fault tolerant motor drive is that it should accommodate the electrical isolation of the motor phases. Therefore, separate H-bridge inverter circuits are utilized to drive the phases of the motor. Figure 2.9 shows the three-phase windings and the inverter circuit of a fault tolerant brushless
PM motor drive.

Comparing to the standard three-phase inverter circuit, this inverter circuit doubles the number of power electronic devices. However, the device voltage ratings are reduced since the devices withstand the phase voltage rather than the line voltage. As a result of this, the switching losses of the inverter will be reduced, which in turn reduces the heat sink requirements [12]. The circuit topology given here also requires additional drive circuits for the switching devices. However, in some cases, the fault detection and switch protection circuits are combined into inverter circuits which will be described in the fault detection and identification section of this thesis.

![Figure 2.9 Three-phase windings and inverter circuits of a fault tolerant brushless PM motor drive. (S: switch; D: freewheeling diode).](image)

### 2.4 Fault Tolerant PM Motor Drives with Redundancy

As it is mentioned in Chapter 1, although a fault tolerant system with a single motor module drive may overcome most of the problems in safety critical applications and the multi-phase fault tolerant motor structure can improve the performance of motor drives, the complete motor drive failure (for example the power supply failure or motor controller failure) will result in the total loss of the drive function. Redundant design is one of the common tools to increase the reliability of a system and has been utilized in many areas. Ideally, multiple fault tolerant systems should mirror all operations; that is,
every operation should be performed on two or more duplicated systems, so if one fails the other can take over. Therefore, redundancy within a critical system is an essential aspect in design. For modular systems with redundancy, the structure of the system is usually a mixture of series and parallel modules.

In this research, a dual fault tolerant motor drive configuration as shown in Figure 2.10 is proposed to overcome the disadvantage of the single motor module fault tolerant drive. The inverter circuits of this motor drive are provided in Figure 2.11. As can be seen in the figures, two identical three-phase motor modules are connected on the common shaft. A single encoder connected to the same shaft is used to measure the rotor position. Moreover, in order to increase the reliability, each motor module has its own separate motor controller and the DC link power supply.

It is well known that the direct position sensor is prone to failure. Therefore, there is a need for redundancy of the position sensing. In the fault tolerant motor drive research, the position sensor redundancy is achieved by the estimated rotor position which is obtained separately from an indirect rotor position algorithm in [68]. Hence, it will not be discussed here.

**Figure 2.10 Principal diagram of the dual fault tolerant interior rotor brushless PM motor module drive configuration**

As it can be observed in the figure, this topology is analogous to a six phase motor. Although the complexity and the cost of the dual three-phase fault tolerant motor drive may be higher than the single six-phase fault tolerant motor drive, the dual motor module three-phase drive has more flexible fault remedial strategies to various faults as will be discussed later in the thesis. This circuit topology also introduces redundancy for the power supply. Furthermore, if one of the motor drive segments is partially or completely out of order, the remaining motor drive can continue to operate and may
provide sufficient output torque to the critical load by controlling currents in the second motor module. In addition, the maintenance and replacement of the redundant modules is much easier in this approach.

Figure 2.11 The inverter circuits of a dual motor module three-phase fault tolerant drive without freewheeling diodes

2.5 Fault Tolerant Brushless PM Motor Drive Control

2.5.1 Current control scheme

The purpose of current control scheme in fault tolerant PM motor drives is to force the phase currents to track the reference currents which are the function of rotor position. Therefore, as in the conventional PM motor drive, the closed-loop current control scheme in a three-phase fault tolerant motor drive also requires three current sensors for the current control. Although several different schemes have been proposed in the literature to implement current regulation, only two basic schemes, hysteresis and PWM current control, will be discussed below [6, 66].

a) Hysteresis Current Control

Figure 2.12 (a) shows the block diagram of one phase of the hysteresis current controller. Three of these controllers are required for a three-phase fault tolerant motor drive. In this diagram, a current sensor is used to feedback the actual instantaneous phase current signal to the controller. The measured current signal is compared with the reference
current signal. As discussed earlier, rectangular or sinusoidal reference current waveforms are produced using the current command and the rotor position information. Then the current error signal is used to generate switching signals for the power switches of the inverter, so that the current error can be minimized.

![Figure 2.12 Principles of a hysteresis current control scheme for a single motor phase. (a) block diagram, (b) current waveforms](image)

Figure 2.12 (b) illustrates the typical phase current waveform produced by a simple hysteresis current controller for a sinusoidal reference current. As shown in the figure, if the actual current is more positive than the reference current value, switches T₁, T₂ are turned off and switches T₃, T₄ are turned on causing the actual motor current to decrease by applying a negative DC link voltage to the related phase. Conversely, when the actual current is more negative than the reference current value, switches T₁, T₂ are turned on and switches T₃, T₄ are turned off causing the motor current to increase by applying a positive voltage. The hysteresis comparator has a bandwidth that determines the permitted deviation of the actual phase current from the reference value before a switching is initiated. Thus, the actual current can track the reference value within an acceptable error. Although setting a small hysteresis bandwidth, a nearly sinusoidal or rectangular phase current with small current ripple can be obtained, this produces very high switching frequency in the inverter causing high switching losses.
The hysteresis current control scheme is simple to implement and has high dynamic performance. However, there are some inherent drawbacks. One of the drawbacks is that the switching frequency is not constant. This is because the switching frequency not only depends on the hysteresis bandwidth but also the back-EMF voltage and inductance of the motor at a given speed and position respectively. For a given DC link voltage, when the back-EMF of the motor is low, the switching frequency may rise excessively.

b) PWM Current Control

Figure 2.13 (a) shows the block diagram of one phase of a PWM current controller. Similar to the hysteresis current control, a current sensor is required to feedback the actual instantaneous phase current signal. In this method, the error between the reference current and actual current is regulated by a proportional integral (PI) controller to derive the reference signals $u^*$ for the pulse width modulator (PWM). The output of PWM is used to drive the inverter power switches, so that the actual current is forced to track the reference current.

The switching procedure for a PWM current controller is illustrated in Figure 2.13 (b). As shown in the figure, if the reference current is more positive than the actual current, the PWM reference signal $u^*$ derived from PI controller may be positive. The reference signal is compared with triangular carrier signal $u_{cr}$ generated by the carrier generator. If the reference signal $u^*$ is more positive than the carrier signal $u_{cr}$, switches T1, T2 are turned on and switches T3, T4 are turned off, so that positive voltage is applied to the related phase. Alternatively, if the reference signal $u^*$ is more negative than the carrier signal $u_{cr}$, switches T1, T2 are turned off and T3, T4 are turned on causing negative voltage power applied to the related phase.

Since the reference is positive, the interval of applying positive voltage will be longer than that of applying negative voltage within one PWM cycle. This will reduce the current error and force the actual current to track the reference current. Conversely, if the reference current is more negative than actual current, the PWM reference signal $u^*$ may be negative, so that the interval of applying negative voltage will be longer than
that of applying positive voltage within a PWM cycle. This also forces to reduce the current error and make the actual current to track the reference current closely.

The switching frequency in the PWM controller is defined by the triangular carrier signal. It is preset and therefore will ensure the inverter switching capability not exceeded. The tracking error can be kept low by choosing a high gain of the PI controller. On the other hand, the gain is limited as it also amplifies the harmonic currents. In order not to impair the proper operation of PWM control, the slope of the current error signal must be always less than the slope of the triangular carrier signal.

### 2.5.2 Torque control and torque ripple

In a dual three-phase fault tolerant PM motor drive configuration, the phase differences within one motor module are 120°, and two motor modules are arranged in phase. Therefore, similar to the standard three phase PM motor drive torque equation, the total electromagnetic torque in the dual fault tolerant three-phase PM motor drive can be
expressed by

\[ T = k_{e1} \sum_{j=1}^{3} e_j(\theta_e) \cdot i_j + k_{e2} \sum_{j=4}^{6} e_j(\theta_e) \cdot i_j \]  

(2.17)

Here \( k_{e1} \), \( k_{e2} \) represent the back-EMF constant of two motor modules respectively (\( k_{e1} = k_{e2} \) for identical motor modules); \( e_j(\theta_e) \) is the unit back-EMF voltage of phase \( j \), \( i_j \) is the phase current of phase \( j \) and \( \theta_e \) is the electrical rotor position.

From equation (2.17), it can be seen that the output torque in one phase is proportional to the product of the unit back-EMF voltage and the excitation current, and it can be maximized if the back-EMF voltage is in phase with the corresponding phase current. Therefore, the torque control of the motor drive can be transformed into current control as described in the previous section. A sample measured currents and the total electromagnetic torque waveforms in a fault tolerant three-phase PMAC motor drive are shown in Figure 2.14. As it can be seen in the figure, none of the waveforms is ideal. As a result of this, the resulting electromagnetic torque has ripples.

To quantify the rate of ripple in this study, a peak-to-peak torque ripple factor is defined as

\[ T_{\text{ripple}} = \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{ave}}} \times 100\% \]  

(2.18)

Here \( T_{\text{max}} \), \( T_{\text{min}} \) are the maximum and minimum instantaneous torque value respectively and \( T_{\text{ave}} \) is the average output torque value over an electrical period of the electromagnetic torque.

There are two major sources contributing to the torque ripple, one principally motor related while the other predominantly inverter related. The motor related source causes the back-EMF waveform distorted which can be minimized by various PM motor design improvement techniques. The inverter related source is that no ideal sinusoidal or rectangular excitation current may be supplied by a practical inverter due to the position sensor and current sensor resolution, digital motor controller computational error and switching frequency limitation. The distortion in DC link power supply also
produce the torque ripple.

The torque ripple may result in vibration and acoustic noise in the motor drive system. In fault tolerant motor drive system, the torque ripple in faulty operation may be more serious and can not be accepted in some applications. Therefore, in this research, torque ripple minimization techniques will be studied in the later chapters.

![Current and Torque Waveforms](image.png)

Figure 2.14 A sample measured phase currents (top) and the total electromagnetic torque (bottom) waveforms in a fault tolerant PMAC motor drive.

2.6 Conclusions

The conventional brushless PM motor drives have been widely used in industries due to their higher power density and lower noise. The theoretical fundamentals of the brushless PMAC motor configuration used in a fault tolerant motor drive were discussed in this chapter. The difference between the conventional brushless PM motor drive and the brushless fault tolerant PM motor drive is that the electrical, magnetic and thermal interactions between different phases are minimized which is achieved by the special design and adopting isolated H-bridge inverter circuit for each phase.
Although a single motor module fault-tolerant drive system may be sufficient in some critical applications; it does not offer any redundancy in the case of a complete motor drive failure. Therefore, a dual motor module fault tolerant drive configuration on a common shaft was proposed in this thesis to increase the reliability of the entire motor drive system.

The current control schemes used in the fault tolerant motor drive and electromagnetic torque mathematical models of single and dual motor module fault tolerant drive configurations were also provided in this chapter. The detailed fault analysis of various faults and their effect on the motor drive performance will be provided in the next chapter. In addition, the fault remedial strategies will also be discussed next.
Chapter 3
Fault Analysis and Fault Remedial Strategy Investigation

3.1 Introduction

As motor drives become more complex, the probability of failure increases. In safety critical applications, a failure is not acceptable and may cause loss of human life or lead to unacceptable downtime. As mentioned previously, the brushless fault tolerant PM motor drive is comprised of three main components as in the conventional motor drives: motor, inverter circuits and controller. Although the previous studies addressed a number of issues to increase the reliability of the fault tolerant motor systems, a number of potential faults may occur during the operation of the motor drive. Therefore, when a fault occurs, an effective fault remedial strategy is required to compensate the torque loss in the drive. Fault remedial strategies usually performed together with additional measures in order to decrease the vibration in the drive system and to avoid the higher local temperature. Therefore fault remedial strategies also integrate techniques to make the torque ripple and copper loss as small as possible. As described in literature review, the previous studies of fault analysis and fault remedial strategies were concentrated on standard three phase motor drives [23-26, 46-48]. Although the investigations on fault tolerant motor drives were undertaken in [12, 13, 22, 50], there is no systematic fault analysis and practical fault remedial strategies for this fault tolerant PM motor drive because the previous studies did not consider the output torque, torque ripple, and copper loss at the same time. In addition, very limited studies were found on dual fault tolerant PM motor drives.

This chapter will investigate the potential faults which may occur in the motor drive, then propose practical fault remedial strategies for the dual fault tolerant PM motor drives. The systematic fault classification and fault analysis will also be conducted in
this chapter. The simulation results of the effects of faults on phase current, output torque, torque ripple and copper loss will be provided and the comparison of various fault remedial strategies will be investigated.

3.2 Potential Faults and Fault Classification

3.2.1 Potential faults in motor drives

The principal component of the fault tolerant brushless PM motor drive is given in Figure 3.1 in which every component is prone to failure. Therefore, single or multiple potential faults may occur in any sections of the motor drive. In the motor section, the faults can be grouped as bearing faults, stator winding faults and rotor faults [69]. The research in this thesis will only consider electrical related fault: stator winding faults. The survey results reported in [70] indicates that the stator related faults are the major faults in three phase induction machines and 35-40 % faults are related to the stator winding insulation and core. Moreover, it is generally believed that a large portion of stator winding-related failures is initiated by insulation failures in several turns of a stator coil within one phase. This is because the organic materials used for insulation in electric machines are subjected to deterioration from a combination of thermal overloading and cycling, transient voltage stresses on the insulating material, mechanical stresses, and contaminations. Among the possible causes, thermal stresses are the main reason for the degradation of the stator winding insulation [71]. In addition, the terminal connector failure may also result in winding faults.

![Figure 3.1 Structure of the fault tolerant PM motor drive](image)

Due to the similar stator winding structure of the induction machine and the brushless PM machine, the same stator winding faults may occur in the brushless PM motor drive. Regardless of the causes, stator winding-related failures can be divided into winding
open-circuit fault, winding short-circuit fault (including winding terminal short-circuit and winding turn-to-turn short-circuit fault), and winding to ground short-circuit fault.

The main devices in the inverter circuits are power switches such as MOSFET and IGBT. Due to the voltage, current and switching characteristics, MOSFETs (IRF540) are utilized in the inverter circuits of this thesis. MOSFETs are well known to be prone to fail if any of their rating are exceeded, especially in soft-switching conditions [72]. The main failure modes of the power MOSFETs are avalanche failure, $dV/dt$ failure, excess power dissipation, excess current [73, 74]. If the maximum operating voltage of a MOSFET is exceeded, it goes into avalanche breakdown. The $dV/dt$ failure is also the biggest cause of MOSFET failure and is more common on motor control systems. The cause of this failure is a very high voltage and fast transient spike. If a fast transient appears onto the drain of a MOSFET, it is coupled through the MOSFETs internal capacitance to the gate. If sufficient energy is present and if the voltage on the gate rises above the maximum allowable level, the MOSFET will be damaged instantaneously. The initial transient destroys the gate-body insulation, so that the gate is connected to the body which results in the failure of the MOSFET. In addition, slow reverse recovery of the intrinsic body diode under low reverse voltage is also believed to be the root cause of the MOSFET failures in power electronics circuits. The possible concluding failures of the power MOSFET are in the form of switch open-circuit fault and switch short-circuit fault.

It can be concluded that the winding and the switch faults are an inevitable consequence of long-term or over-stressed operation in the motor drive. Moreover, it is likely that the faults occur in the rotor position sensor, phase current sensor, DC link power supply, and motor controller. From the above discussions, the potential electrical faults in fault tolerant motor drives can be classified into seven groups: winding open-circuit fault, winding short-circuit fault (including winding turn-to-turn short-circuit fault), switch open-circuit fault, switch short-circuit fault, power supply fault and controller fault, position sensor fault and combinations of the above faults.

It should be mentioned that the power supply failure and motor controller failure in a single fault tolerant motor drive will result in the total loss of the drive function if no redundancy is considered in these sections. Therefore, the dual fault tolerant motor drive...
is considered to overcome the disadvantage existed in the single fault tolerant motor drive. The redundancy should also be considered for the rotor position sensor, which is the most critical component of the drive system. The rotor position information can be estimated by the sensorless rotor position algorithm which is addressed by another researcher [75].

3.2.2 Fault classification

In a dual fault tolerant motor drive, the potential electrical faults may occur in different phases or in different switches in inverter circuits and the effect of fault on the output torque and the torque ripple may be different due to the type of fault mode and positions in which these faults occur. In order to investigate the effects of faults and develop effective fault remedial strategies, the systematic fault classification is performed in this thesis. The specific symbols (SC$_{ij}$ and OC$_{ij}$) are used in the thesis to present potential electrical faults in the drive. Here SC denotes “Short-Circuit” fault and OC denotes “Open-Circuit” fault; subscribe $i$ is phase or inverter number and $j$ is the location of the fault.

As mentioned previously, there are a total of six phase windings and six H-bridge inverters in the dual fault tolerant motor drive studied in this thesis. Phases 1, 2, 3 represent three phases of the motor module 1 and Phases 4, 5, 6 represent three phase of the motor module 2. The locations of possible short-circuit faults in a phase (Phase 1) is presented in Figure 3.2. In this inverter circuit, as the freewheeling diodes are integrated into the switches, no extra freewheeling diodes are connected in the inverter circuit. Using this fault classification approach, seven short-circuit faults and six open-circuit faults in Phase 1 can be identified as listed in Table 3.1. Similarly, the short-circuit faults and open-circuit faults in Phase 2 can be expressed as SC$_{21}$…SC$_{27}$ and OC$_{21}$…OC$_{26}$.

In the fault control section, when a switch open-circuit fault occurs in a H-bridge inverter, the other switches in the same inverter will be turned off. Therefore, the switch open-circuit fault can be classified as a winding open-circuit fault. If one switch in an inverter circuit has a short-circuit fault, the corresponding switch in the other phase-leg can be turned on, and the effect of this fault becomes analogous to the winding short-
circuit fault. Under the above approach, the switch open-circuit faults and the winding open-circuit fault in Phase 1 can be considered as a Phase 1 open-circuit fault and can be labeled as OC₁. Similarly, the switch short-circuit faults and the winding short-circuit fault in Phase 1 can be classified as Phase 1 short-circuit fault which can be labeled by SC₁. Therefore, all the switch and winding open-circuit and short-circuit faults in entire motor drive can be represented by OC₁, OC₂, …OC₆ and SC₁, SC₂, …SC₆.

![Graphical representations of the location of the possible short-circuit fault in Phase 1](image)

**Figure 3.2** Graphical representations of the location of the possible short-circuit fault in Phase 1

<table>
<thead>
<tr>
<th>Fault name</th>
<th>Fault description</th>
<th>Fault name</th>
<th>Fault description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC₁₁</td>
<td>Switch T₁ short-circuit</td>
<td>OC₁₁</td>
<td>Switch T₁ open-circuit</td>
</tr>
<tr>
<td>SC₁₂</td>
<td>Switch T₂ short-circuit</td>
<td>OC₁₂</td>
<td>Switch T₂ open-circuit</td>
</tr>
<tr>
<td>SC₁₃</td>
<td>Switch T₃ short-circuit</td>
<td>OC₁₃</td>
<td>Switch T₃ open-circuit</td>
</tr>
<tr>
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<td>Switch T₄ short-circuit</td>
<td>OC₁₄</td>
<td>Switch T₄ open-circuit</td>
</tr>
<tr>
<td>SC₁₅</td>
<td>Partial winding short-circuit</td>
<td>OC₁₅</td>
<td>Winding open-circuit</td>
</tr>
<tr>
<td>SC₁₆</td>
<td>Full winding short-circuit</td>
<td>OC₁₆</td>
<td>Power supply open-circuit</td>
</tr>
<tr>
<td>SC₁₇</td>
<td>Power supply short-circuit</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3.3 Mathematical Model of Reference Current Calculation

In general, whether the motor drive has a single motor module or two motor modules, the back-EMF voltages of an *n*-phase fault tolerant PM motor drive can be given as

\[
e_j = k_e \omega_n e_j(\theta_e)
\]

(3.1)

Here the subscript *j* is an integer representing the phase number of the motor (*j*=1, 2, ..., *n*).
If we consider a motor module with two isolated phases, the output torque $T_0$ can be given as a function of the phase currents and corresponding back-EMF voltages as

$$T_0 = k_e [e_1(\theta_e)i_1 + e_2(\theta_e)i_2] \quad (3.2)$$

Here $i_1$ and $i_2$ denote the instantaneous phase currents. From equation (3.2), the current $i_2$ can be derived as:

$$i_2 = \frac{T_0 - e_1(\theta_e)i_1}{e_2(\theta_e)} \quad (3.3)$$

Here the instantaneous copper loss of this motor module can be expressed by

$$P_{cu0} = (i_1^2 + i_2^2)R \quad (3.4)$$

Here $R$ is the resistance of the phase winding. As can be seen in this equation, in order to achieve minimum instantaneous copper loss, the value of $y = i_1^2 + i_2^2$ should be minimum, which can be substituted using (3.3) as

$$y = i_1^2 + \frac{1}{e_2^2(\theta_e)} \left[ \frac{T_0^2}{k_e^2} - \frac{2T_0}{k_e} e_1(\theta_e)i_1 + e_1^2(\theta_e)i_1^2 \right] \quad (3.5)$$

The above equation has a minimum value, and can be found by its derivative reference to the phase current $i_1$, $\left( \frac{dy}{di_1} = 0 \right)$. The solutions for two phase currents can be given as

$$i_1 = \frac{e_1(\theta_e)}{e_1^2(\theta_e) + e_2^2(\theta_e)} \cdot \frac{T_0}{k_e} \quad (3.6)$$

$$i_2 = \frac{e_2(\theta_e)}{e_1^2(\theta_e) + e_2^2(\theta_e)} \cdot \frac{T_0}{k_e} \quad (3.7)$$

From the above equations, it can be seen that at any point in time, the minimum copper loss to produce a given output torque is obtained by keeping the ratio of the instantaneous phase currents equal to the ratio of the instantaneous phase back-EMF voltages.
Equations (3.6) and (3.7) are valid for back-EMF waveforms of any shape and can be extended to single multiple-phase motor drives or dual multiple-phase motor drives as follows

\[ i_j = \frac{e_j(\theta_c)}{e_1^2(\theta_c) + e_2^2(\theta_c) + \ldots + e_n^2(\theta_c)} \frac{T_0}{k_c} \]  

(3.8)

Here \( n \) is the total number of the motor phase.

3.4 Fault Analysis in Fault Tolerant Motor Drives

3.4.1 Winding open-circuit fault analysis

The winding open-circuit fault is the most common fault, and can be detected by the phase current sensor. Such fault can be identified using the phase voltage and the power supply voltage when the phase current is zero.

In a single three-phase fault tolerant motor drive, if the back-EMF voltages are sinusoidal, the desirable phase currents for zero torque ripple operation can be given as

\[
\begin{align*}
    i_1 &= I_{m0} \sin \theta_c \\
    i_2 &= I_{m0} \sin(\theta_c - \frac{2\pi}{3}) \\
    i_3 &= I_{m0} \sin(\theta_c - \frac{4\pi}{3})
\end{align*}
\]  

(3.9)

Where \( I_{m0} \) is the peak value of the phase current in the single motor drive. Hence, in a healthy operation, the total output torque for a single motor module drive is

\[ T_0 = k_c I_{m0} \left[ \sin^2 \theta + \sin^2 \left( \theta - \frac{2\pi}{3} \right) + \sin^2 \left( \theta - \frac{4\pi}{3} \right) \right] = \frac{3}{2} k_c I_{m0} \]  

(3.10)

If Phase 1 is open-circuit and no fault remedial strategies are adopted, the total output torque of this single motor drive can be expressed by

\[ T_{F0} = k_c I_{m0} (1 + \frac{1}{2} \cos 2\theta_c) \]  

(3.11)

Here \( T_{F0} \) represents the torque in single motor drive under faulty conditions. The relative output torque waveforms in the healthy operation and in one phase open-circuit
fault operation are provided in Figure 3.3. From the figure, it can be seen that in winding open-circuit fault operation, the average output torque decreases 33% and the peak-to-peak torque ripple increases 100%.

\[ T = 2k_c I_m \left[ \sin^2 \theta_c + \sin^2 \left( \theta_c - \frac{2\pi}{3} \right) + \sin^2 \left( \theta_c - \frac{4\pi}{3} \right) \right] = 3k_c I_m \]  

(3.12)

Here \( I_m \) is the peak value of the phase current. \( T \) denotes the torque in dual motor drive under healthy operation. From equations (3.10) and (3.12), we can see that in order to obtain the same total output torque value in single and dual motor drives \( T_o = T \), \( I_m \) should be equal to the half of \( I_{m0} \). In dual fault tolerant motor drive, if Phase 4 suffers the open-circuit fault, the total output torque is

\[ T_F = k_c I_m \left( \frac{5}{2} + \frac{1}{2} \cos 2\theta_c \right) \]  

(3.13)

\( T_F \) represents the output torque in dual motor module drive under faulty conditions. Figure 3.4 illustrates the relative output torque waveform when the open-circuit fault occurs in Phase 4 at 0.2s. The figure shows that the average output torque decreases 17% after the fault and the torque peak-to-peak ripple is 40% higher than the healthy operation.
3.4.2 Switch open-circuit fault analysis

Inverter switch open-circuit fault is also a common fault in the motor drive. If one of the inverter switches becomes open-circuit and non remedial strategy is adopted, the inverter will operate in unipolar conduction mode, where the phase current can only be controlled for either positive or negative half-cycles. Figure 3.5 and Figure 3.6 illustrate the relative output torque waveforms when one switch open-circuit fault occurs in single and dual motor module fault tolerant drives. In a single motor drive, the average output torque reduces to $0.83 T_0$ and the peak-to-peak torque ripple factor becomes 80%. In a dual motor drive however, the torque waveform indicates that the average output torque decreases to $0.92 T$ and the peak-to-peak torque ripple factor is 36%. From above analysis it can be seen that under winding or switch open-circuit fault condition, the torque ripple in a dual motor drive is lower than the torque ripple in a single motor drive.
3.4.3 Winding short-circuit fault analysis

The winding short-circuit fault is one of the most critical faults in PM motor drives. For the H-bridge inverter configuration, if either all the upper switches or all the lower switches are turned on, or the DC link is short-circuited, the winding of the fault-tolerant motor would be subjected to a short-circuit fault. The equivalent circuit of winding short-circuit fault is shown in Figure 3.7 (a).

If the back-EMF voltage of the motor is sinusoidal, during short-circuit fault operation, a sinusoidal short-circuit current $i_{sc}$ will be generated in the winding and the peak steady-state current can be given by

$$I_{scm} = \frac{E_m}{\sqrt{R^2 + (N_p\omega_m L)^2}}$$  \hspace{1cm} (3.14)

Since $E_m$ is the product of back-EMF constant and rotor speed, the maximum value of
short-circuit current can be given as a function of the mechanical angular speed of the motor as

\[ I_{SCm} = \frac{k_m \omega_m}{\sqrt{R^2 + (N_p \omega_m L)^2}} \]  \hspace{1cm} (3.15)

The sinusoidal short-circuit fault current in the winding results in copper loss which can be expressed by

\[ P_{cuSC} = \left( \frac{I_{SCm}}{\sqrt{2}} \right)^2 R = \frac{E_m^2}{2} \frac{R}{R^2 + (N_p \omega_m L)^2} \]  \hspace{1cm} (3.16)

The short-circuit current also generates a drag torque in the motor drive and the average of the drag torque can be given by

\[ T_{avedrag} = \frac{1}{2 \omega_m} E_m I_{SCm} \cos \phi \]  \hspace{1cm} (3.17)

Where \( \phi \) is the phase difference between the back-EMF voltage and the short-circuit current and can be calculated using the winding impedance as

\[ \cos \phi = \frac{R}{\sqrt{R^2 + (N_p \omega_m L)^2}} \]  \hspace{1cm} (3.18)

By substituting the equation (3.15) and (3.18) into (3.17) the average drag torque becomes

\[ T_{avedrag} = \frac{E_m^2}{2 \omega_m} \frac{R}{R^2 + (N_p \omega_m L)^2} = \frac{k_m^2}{2} \frac{R \omega_m}{R^2 + (N_p \omega_m L)^2} \]  \hspace{1cm} (3.19)

If it is assumed that the base voltage is equal to the back-EMF voltage at the rated rotor speed and the base current is equal to the winding short-circuit current under the same speed, the per-unit short-circuit current \( I_{SCpu} \), average drag torque \( T_{AVEDRAGpu} \) and copper loss \( P_{cuSCpu} \) can be expressed as follows.

\[ I_{SCpu} = \frac{\omega_{pu}}{\sqrt{R_{pu}^2 + (\omega_{pu} L_{pu})^2}} \]  \hspace{1cm} (3.20)
\[ T_{\text{avdrag}, pu} = \frac{\omega_{pu} R_{pu}}{R_{pu}^2 + (\omega_{pu} L_{pu})^2} \]  

\[ P_{\text{cuSc}, pu} = \frac{\omega_{pu}^2 R_{pu}}{R_{pu}^2 + (\omega_{pu} L_{pu})^2} \]  

Where \( R_{pu} \) and \( L_{pu} \) represent the per-unit resistance and the inductance of the short-circuited windings, \( \omega_{pu} \) is the per-unit value of the angular speed of the motor.

Figure 3.8, Figure 3.9 and Figure 3.10 show the calculated per-unit short-circuit current, average drag torque and copper loss curves as a function of rotor angular speed under winding short-circuit fault condition in different inductance and resistance values. It can be seen in Figure 3.8 that the short-circuit current remains constant at higher rotor speeds. In addition, the results indicates that increasing the per-unit inductance of the windings, the short-circuit current can be reduced. If the inductance is equal to 1.0 pu, the short-circuit current can be limited at 1.0 per-unit (rated value). In contrast, the short-circuit current at higher rotor speed is not affected by the per-unit resistance of the windings.

![Figure 3.8 Calculated per-unit short-circuit current curves as a function of rotor angular speed under winding short-circuit fault condition for various inductance and resistance values.](image)

Figure 3.9 shows that the drag torque increases significantly with rotor speed at lower rotor speeds, and decreases exponentially with the increase of speeds. As shown in the same figure for different inductance values, for the same rotor speeds, the higher
inductance results in lower drag torques. For the same inductance, the maximum drag torque remains the same although per-unit resistances are different. However, the lower per-unit resistance can decrease the average drag torque.

It is can be seen in Figure 3.10 that higher per-unit inductance also results in lower copper loss. In addition, for the same per-unit inductance value, smaller resistance results smaller copper loss in the short-circuited windings as expected. From the above results, it can be concluded that increasing per-unit inductance can reduce the winding short-circuit current, average drag torque and copper loss, which may be accommodated in the design stage of a fault tolerant motor drive.

**Figure 3.9** Calculated per-unit drag torque curves as a function of rotor angular speed under winding short-circuit fault condition for various inductance and resistance values.

**Figure 3.10** Calculated per-unit copper loss curves as a function of rotor angular speed under winding short-circuit fault condition for various inductance and resistance values.
3.4.4 Switch short-circuit fault analysis

If a switch or a diode in the H-bridge inverter circuit is short-circuited, the winding is also subject to a short-circuit fault through the diode in the other phase leg. The resulting equivalent circuit under such a fault is shown in Figure 3.7 (b).

Figure 3.11 and Figure 3.12 show the simulated (using PSIM software) steady state short-circuit current and drag torque waveforms respectively under winding short-circuit fault and switch short-circuit fault conditions and reference to the back-EMF voltage waveforms. The motor parameters using in the simulations are \( R = 0.55 \Omega \), \( L = 2.1 \text{ mH} \), \( k_e = 0.8903 \text{ V/rad/s} \), \( N_p = 24 \), \( \omega_m = 62.8 \text{ rad/s} \). The diode voltage drop is neglected in the simulation.

**Figure 3.11 Simulated back-EMF voltage and current waveforms under winding and switch short-circuit fault conditions**

**Figure 3.12 Simulated back-EMF voltage and drag torque waveforms under winding and switch short-circuit fault conditions**
It can be seen in Figure 3.11 that the short-circuit current under winding short-circuit fault condition has a sinusoidal waveform. However, the short-circuit current waveform is forced to be unidirectional by the freewheeling diode under switch short-circuit fault condition. From Figure 3.12 it can be found that the difference of the maximum drag torque value and the minimum drag torque value under switch short-circuit fault condition is bigger than the value under winding short-circuit fault condition which will result in larger torque ripple in the motor drive.

Figure 3.13 is given to describe the relationship between the rms value of the short-circuit current and the average value of drag torque as a function of the rotor speed under both winding and switch short-circuit fault conditions with identical simulation parameters. The figure shows that when the rotor speed is higher than 250 rpm, both the short-circuit current and the average drag torque values under switch short-circuit fault condition are larger than the values under winding short-circuit fault condition. The operating speed of the motor drive is normally higher than 250 rpm. From these curves, it can be concluded that the negative effects on the motor drive under a switch short-circuit fault is worse than that under a winding short-circuit fault. Therefore, if a switch short-circuit fault occurs in the inverter, it is desirable to turn on the opposite switch to transform the switch short-circuit fault into a winding short-circuit fault. The similar conclusions were also reported for star-connected interior PM machines in [24].

![Figure 3.13 Relationships between RMS short-circuit current and average drag torque with rotor speed under winding and switch short-circuit fault conditions.](image-url)
3.5 Investigation of Fault Remedial Strategies

3.5.1 Introduction

From previous sections, it can be seen that the faults are inevitable and usually the consequences of long-term or over-stressed operation in motor drives. Whether or not such faults are caused by hardware, power supply, or software failures, systematic fault remedial strategies are required to reduce or eliminate the effect of the faults.

In principle, there are two functions for the fault remedial strategies in motor drives. The first function is to avoid the faults to prevent catastrophic failures and the second function is to compensate the torque loss and reduce the torque ripple due to the loss of phase current in faulty phases and the drag torque produced by the short-circuit fault.

A number of papers have been published to study the various fault remedial strategies on fault tolerant PM motor drives [12, 13, 22, 50]. For the winding and switch open-circuit fault, it is common to turn off all switches in the faulty H-bridge inverter circuit. On the other hand, for the winding or switch short-circuit fault, the post-fault action is normally to turn on the two of the upper switches or the two of the lower switches and to turn off the remaining switches in the inverter circuit.

Since the output torque is proportional to the phase current, in order to compensate the torque loss, the first fault remedial strategy is to increase the current in healthy phases which will be explained in later sections. The disadvantage of this strategy is that the higher torque ripple will be produced. As mentioned previously, torque ripple of the motor drives is a critical concern in many applications where low acoustic noise, high efficiency, or friendly human-machine interactions are highly demanded [52]. An optimal torque control technique in a fault tolerant PM motor drive with isolated phases was proposed in [61-63] and the computer simulation results were provided to verify the technique. However, the experimental results were not given in the previous studies. The previous studies reveal that the fault remedial strategies for single motor module fault tolerant drives are limited and non fault remedial strategy was reported for the dual motor module fault tolerant drive configuration. Therefore it is significant to investigate the fault remedial strategies for single and dual fault tolerant motor drives.
In addition to the common fault remedial strategy of increasing the current in healthy phases (remedial strategy 1 (RS 1)), two more fault remedial strategies for single and dual fault tolerant PM motor drives are proposed in this thesis. These two strategies are the fault remedial strategy 2 (RS 2) in which the current in the same phase of the second motor module is doubled, and the fault remedial strategy 3 (RS 3) in which the optimal phase currents are applied to the healthy phases to minimize the torque ripple. In addition, the performance of three fault remedial strategies are also examined to compare the torque ripple factor, the copper loss, and the highest phase copper loss and to consider the complexity and limitation of the application.

In this research, it is assumed that when a switch open-circuit fault occurs in the inverter, the other switches of the same inverter are turned off. In addition, if the switch short-circuit fault occurs in the inverter, the switch in the other phase-leg is turned on to provide a current path. Therefore, the winding open-circuit fault and switch open-circuit fault in Phase \( n \) are classified as Phase \( n \) open-circuit fault; and the winding short-circuit fault and switch short-circuit fault in Phase \( n \) are classified as Phase \( n \) short-circuit fault.

### 3.5.2 Increasing average current fault remedial strategy

As mentioned before, the output torque is proportional to the phase current in the fault tolerant PM machines. Therefore, in order to keep the output torque constant in faulty operations, the currents in healthy phases need to be increased. The fault remedial strategy 1 aims to increase the currents in healthy phases averagely. If the peak phase current in healthy operation is \( I_m \), in phase open-circuit fault operation, the phase current in healthy phases should be increased to \( I_{mRS} \) and can be expressed by

\[
I_{mRS} = \frac{n}{n-m} \cdot I_m
\]  

(3.23)

Here \( m \) is the number of phase with open-circuit fault.

For a single three phase fault tolerant motor drive, if an open-circuit fault occurs in Phase 1 (OC1), in order to maintain the same output torque as in healthy operation, the currents in phase 2 and 3 need to be increased to 1.5 times of the healthy operation current. Then the output torque can be expressed by
From (3.24), it can be seen that the peak-to-peak torque ripple factor under this fault remedial strategy is 100%. Similarly, the total copper loss in this mode of operation can be calculated as 50% higher than the healthy operating mode. The maximum phase copper loss in faulty operation is 2.25 times of the healthy operation.

For a dual three phase fault tolerant motor drive with two identical motor modules, if an open-circuit fault occurs in Phase 1 (OC1), the currents in the remaining healthy phases is 1.2 times higher than the phase current in the healthy operation and the torque can be given as

\[ T_{RS} = \frac{3}{2} k_e I_m (1 + \frac{1}{2} \cos 2\theta_c) \]  

(3.25)

From (3.25), the peak-to-peak torque ripple can be obtained as 40%. Similarly, the total copper loss and the maximum phase copper loss in the remedial strategy 1 are 1.2 and 1.44 times greater than the values of the healthy operation.

From above analysis, it can be concluded that under one-phase open-circuit fault operation and with the fault remedial strategy 1, the peak-to-peak torque ripple, the total copper loss and maximum phase copper loss are lower in the dual fault tolerant motor drive than in the single motor drive.

If two different phases in the dual fault tolerant motor drive (for example Phases 5 and 6) suffer an open-circuit fault, the current in healthy phases is 1.5 times of the healthy operation current and the output torque can be given by

\[ T_{RS} = 3 k_e I_m (1 - \frac{1}{4} \cos 2\theta_c) \]  

(3.26)

The peak-to-peak torque ripple is 50% in this situation. On the other hand, if phase open-circuit faults occur in the two same phases (for example Phases 1 and 4), the output torque can be given by

\[ T_{RS} = 3 k_e I_m (1 + \frac{1}{2} \cos 2\theta_c) \]  

(3.27)
In this fault state, the peak-to-peak torque ripple becomes 100%. Furthermore, if one of the motor modules has a complete open-circuit fault in the dual fault tolerant motor drive, the phase currents in the second motor module should be two times of the healthy operation current with a 0% torque ripple.

The torque ripple factor, total copper loss and the maximum phase copper loss values under different fault conditions with the fault remedial strategy 1 are summarized in Table 3.2. From the table it can be concluded that except in the one motor module complete open-circuit fault operation, the fault remedial strategy 1 results in significant torque ripple in the motor drive.

Table 3.2 The features of the fault remedial strategy 1 in different fault modes

<table>
<thead>
<tr>
<th>Open-circuit fault mode</th>
<th>Peak-to-peak torque ripple (%)</th>
<th>Relative total copper loss</th>
<th>Relative phase maximum copper loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy operation</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>One phase open</td>
<td>100</td>
<td>1.5</td>
<td>2.25</td>
</tr>
<tr>
<td>Dual three phase motor drive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Healthy operation</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>One phase open</td>
<td>40</td>
<td>1.2</td>
<td>1.44</td>
</tr>
<tr>
<td>Two different phase open</td>
<td>50</td>
<td>1.5</td>
<td>2.25</td>
</tr>
<tr>
<td>Two same phase open</td>
<td>100</td>
<td>1.5</td>
<td>2.25</td>
</tr>
<tr>
<td>One motor complete open</td>
<td>0</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

If one phase has a short-circuit fault, the currents in healthy phases have to be increased more than the value under one phase open-circuit fault operation to compensate the torque loss and the drag torque produced by the short-circuit current. The peak value of the phase current in the healthy phases can be calculated by

\[
I_{mRS} = \frac{n}{n-1} I_m + \frac{k_{c} \omega_m}{n-1} \cdot \frac{R}{R^2 + (N_p \omega_m L)^2}
\]

Where \(n\) is the total number of phases in the motor drive which is equal to 3 for a single three phase fault tolerant motor drive and 6 for a dual three phase motor drive.

### 3.5.3 Doubling current fault remedial strategy

In the dual module three phase fault tolerant motor drive with a one phase open-circuit fault, it is possible to double the current in the corresponding phase of the second motor.
module to compensate the torque loss (fault remedial strategy 2). This strategy assumes that the motor windings are designed to be able to handle twice the rated current. This fault remedial strategy aims to keep the sum of the two same phase currents of the two motor modules constant before and after the fault. For example, if Phase 3 suffers an open-circuit fault (OC3), the current in Phase 6 is doubled.

Figure 3.14 illustrates the simulation results of this fault remedial strategy where the total output torque is the same as in the healthy operation, and the output torque ripple factor is zero. In addition, the average total copper loss of the motor drive under the faulty operation with fault remedial strategy 2 is increased to 1.33 times the healthy operation. Furthermore, it can be shown that the maximum value of the phase copper loss in Phase 6 increases 4 times the normal value.

The advantage of the fault remedial strategy 2 is that it is easy to implement to obtain zero torque ripples. The method can also be applied to open-circuit faults in two different phases and complete open-circuit faults in one motor module. However, the technique is not suitable for open-circuit faults in the same phases of the motor modules and the operation under phase short-circuit fault.

![Figure 3.14 Simulated results of the dual fault tolerant motor drive under one phase open-circuit fault in Phase 3 at 0.2s and the fault remedial strategy 2 is adopted after the fault. (a) Phase current waveforms; (b) Relative output torque and total copper loss waveforms.](image-url)
3.5.4 Zero torque ripple with minimum copper loss fault remedial strategy

The fault remedial strategy 3 aims to achieve a zero torque ripple with minimum copper loss. In a single three-phase fault tolerant motor drive, if Phase 3 is open-circuit fault, this phase does not contribute to the output torque. In order to produce the same output torque as in the healthy operation, the currents in Phases 1 and 2 need to be changed. The output torque in this strategy can be expressed by the following equation.

\[ T_{rs0} = k_e [e_i(\theta_e) i_1 + e_2(\theta_e) i_2] = T_0 \]  

(3.29)

Where \( i_1 \) and \( i_2 \) represent the currents of Phases 1 and 2. From equation (3.29), the current \( i_2 \) can be derived as

\[ i_2 = \frac{T_0 - e_i(\theta_e) i_1}{e_2(\theta_e)} \]  

(3.30)

Hence, the instantaneous copper loss of the motor under Phase 3 open-circuit fault condition can be given as

\[ P_{cu0} = (i_1^2 + i_2^2) R \]  

(3.31)

In order to minimize the copper loss, the value of \( y = i_1^2 + i_2^2 \) should be minimum. If the equation (3.30) is substituted into (3.31) and rearranged, then

\[ y = \frac{1}{e_2^2(\theta_e)} \left[ \frac{T_0^2}{k_e} - 2 \frac{T_0}{k_e} e_i(\theta_e) i_1 + e_1^2(\theta_e) i_1^2 \right] + i_1^2 \]  

(3.32)

As it is known, the resultant value of the function \( y \) has a minimum value at \( \frac{dy}{di_1} = 0 \). Therefore, the phase currents that meet this condition can be obtained as

\[ i_1 = \frac{e_i(\theta_e)}{e_i^2(\theta_e) + e_2^2(\theta_e)} \frac{T_0}{k_e} \]  

(3.33)

\[ i_2 = \frac{e_2(\theta_e)}{e_i^2(\theta_e) + e_2^2(\theta_e)} \frac{T_0}{k_e} \]  

(3.34)

These two equations can be generalized as
The above equation can be extended to the single fault tolerant motor drive and the dual fault tolerant motor drive with \( n \) phases in which \( m \) phases are suffering an open-circuit fault. Then the general equation of the phase current can be rewritten as

\[
i_j = \frac{e_j(\theta_c)}{\sum_{i=1}^{n} e_i^2(\theta_c) - e_k^2(\theta_c)} \cdot \frac{T_0}{k_e} \quad j \neq k
\]  

(3.35)

Here \( k \) is integers representing the faulty phase number in the motor drive, which should be excluded in the above equation. For a single three phase fault tolerant motor drive \( n \) is equal to 3 and for a dual three phase motor drive \( n \) is equal to 6.

If Phase \( k \) has a short circuit fault, due to the drag torque produced by the short circuit current, the current in healthy phases will be significantly higher than the current in the open-circuit fault operation. In this case, the current in the healthy phases should satisfy the equation below.

\[
i_j = \frac{e_j(\theta_c)}{\sum_{i=1}^{n} e_i^2(\theta_c) - \sum_{k} e_k^2(\theta_c)} \cdot \frac{T_0}{k_e} [\frac{T_n}{k_e} + e_k(\theta_c) i_k] \quad j \neq k
\]  

(3.36)

(3.37)

Where \( i_k \) is the short-circuit current in Phase \( k \), and the extra term \( e_k(\theta_c) i_k \) represents the drag torque produced by the short-circuit current.

From equation (3.36) and (3.37), it can be seen that under the minimum copper loss and zero torque ripple constraint, the instantaneous phase currents should be in phase with the instantaneous back-EMF voltages. However, this results in non-sinusoidal reference currents even if the back-EMF voltages are sinusoidal.

From equation (3.8) and (3.36), we can derive the following equations to calculate the instantaneous copper loss of the motor drive under healthy operation and under an open-circuit fault condition with the fault remedial strategy 3 respectively.
Then the relative copper loss under the phase open-circuit fault condition with the fault remedial strategy 3 can be obtained as

\[ P_{\text{curelative}} = \frac{\sum_{i=1}^{n} e_i^2(\theta_c)}{\sum_{i=1}^{n} e_i^2(\theta_c) - \sum_{k} e_k^2(\theta_c)} \]  

(3.40)

For single and dual module brushless PM motor drives with sinusoidal back-EMF voltages, the copper loss in healthy condition can be given as

\[ P_{cu0} = \frac{3}{2} R I_{m0}^2 \]  

(3.41)

\[ P_{cu} = 3 R I_m^2 \]  

(3.42)

For the same motor module, when Phase 3 experiences open-circuit fault (OC3), the relative instantaneous copper loss in a single and dual module three phase fault tolerant motor drive can be calculated by equation (3.43) and (3.44) respectively.

\[ P_{\text{curelative0}} = \frac{3}{2 + \cos(2\theta_c - \frac{2\pi}{3})} \]  

(3.43)

\[ P_{\text{curelative}} = \frac{6}{5 + \cos(2\theta_c - \frac{2\pi}{3})} \]  

(3.44)

Figure 3.15 and Figure 3.16 provide the simulation results of the single and dual three-phase fault tolerant motor drives when Phase 3 has an open-circuit fault and under the fault remedial strategy 3. Under this mode of operation, Figure 3.15 shows that the phase current waveforms are significantly distorted in the regions where Phase 3 would normally be generating a significant output torque. From these results, it can also be observed that after this remedial strategy is adopted, the output torque is kept constant as in the healthy operation, while the total average copper loss increases 73%.

\[ P_{\text{curelative}} = R \left( \frac{T_0}{k_c} \right)^2 \cdot \frac{1}{\sum_{i=1}^{n} e_i^2(\theta_c)} \]  

(3.38)

\[ P_{\text{curelative3}} = R \left( \frac{T_0}{k_c} \right)^2 \cdot \frac{1}{\sum_{i=1}^{n} e_i^2(\theta_c) - \sum_{k} e_k^2(\theta_c)} \]  

(3.39)
addition, the average maximum phase copper loss becomes 2.6 times greater than the value in the healthy operation.

![Graph](image)

**Figure 3.15** Simulated results of the single module fault tolerant motor drive under Phase 3 open-circuit fault condition with the fault remedial strategy 3. (a) Phase current and back-EMF waveforms; (b) Relative output torque and total copper loss waveforms.

As shown in Figure 3.16, since the two motor modules are identical and are arranged in phase in simulation study, Phases 1 and 4, Phases 2 and 5 have the identical back-EMF voltages and same phase current waveforms. The results illustrates that Phase 6 has the maximum peak current that is 1.5 times greater than the current in the healthy operation. In addition, it can be seen that the zero torque ripple can be achieved in this fault remedial strategy. Furthermore, the average total copper loss and the average maximum phase copper loss increase 1.22 times and 1.84 times respectively both reference to the healthy operation. As these values are lower than the values achieved in the single motor drive with one phase open-circuit fault, the dual fault tolerant motor drive shows the better performance compared to the single motor drive. Furthermore, the fault remedial strategy 3 can also be utilized in two-phase open-circuit fault and three-phase open-circuit fault operations of the fault tolerant motor drive.
Chapter 3 Fault Analysis and Fault Remedial Strategy Investigation

Figure 3.16 Simulated results of the dual module fault tolerant motor drive under Phase 3 open-circuit fault condition with the fault remedial strategy 3. (a) Phase current and back-EMF waveforms; (b) Relative output torque and total copper loss waveforms.

The simulation results of two different phase open-circuit fault (Phases 2 and 3) operation with the fault remedial strategy 3 in the dual module motor drive are given in Figure 3.17. In this mode of operation, the average total copper loss was found 1.55 times greater than the value in the healthy operation. In addition, the average maximum phase copper loss occurred in the healthy Phases 5 and 6 increased 2.79 times.

If two same phase open-circuit faults (for example Phases 3 and 6) occur simultaneously, the fault remedial strategy 3 can be adopted as well, and the similar simulation results as in Figure 3.15 can be achieved.

3.5.5 Comparison of different fault remedial strategies

The comparison of the features of the different fault remedial strategies are summarized in Table 3.3 which shows the torque ripple, the relative average total copper loss and the highest phase copper loss. The latter value is important as it relates to the maximum winding temperature in the machine. From the table, the following conclusions can be obtained:
Chapter 3 Fault Analysis and Fault Remedial Strategy Investigation

Figure 3.17 Simulated results of the dual module fault tolerant motor drive under Phase 2 and Phase 3 open-circuit fault condition under the fault remedial strategy 3. (a) Phase current and back-EMF waveforms; (b) Relative output torque and total copper loss waveforms.

Table 3.3 Feature comparison of different fault remedial strategies

<table>
<thead>
<tr>
<th>Operation modes</th>
<th>Peak-to-peak torque ripple (%)</th>
<th>Relative total copper loss</th>
<th>Relative phase maximum copper loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single motor drive one-phase open fault</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Healthy operation</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Remedial strategy 1</td>
<td>100</td>
<td>1.5</td>
<td>2.25</td>
</tr>
<tr>
<td>Remedial strategy 3</td>
<td>0</td>
<td>1.73</td>
<td>2.6</td>
</tr>
<tr>
<td>Dual motor drive one phase open fault</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Healthy operation</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Remedial strategy 1</td>
<td>40</td>
<td>1.2</td>
<td>1.44</td>
</tr>
<tr>
<td>Remedial strategy 2</td>
<td>0</td>
<td>1.33</td>
<td>4</td>
</tr>
<tr>
<td>Remedial strategy 3</td>
<td>0</td>
<td>1.22</td>
<td>1.84</td>
</tr>
<tr>
<td>Dual motor drive two different phase open fault</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remedial strategy 1</td>
<td>50</td>
<td>1.5</td>
<td>2.25</td>
</tr>
<tr>
<td>Remedial strategy 2</td>
<td>0</td>
<td>1.67</td>
<td>4</td>
</tr>
<tr>
<td>Remedial strategy 3</td>
<td>0</td>
<td>1.55</td>
<td>2.79</td>
</tr>
<tr>
<td>Dual motor drive two same phase open fault</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remedial strategy 1</td>
<td>100</td>
<td>1.5</td>
<td>2.25</td>
</tr>
<tr>
<td>Remedial strategy 3</td>
<td>0</td>
<td>1.73</td>
<td>2.6</td>
</tr>
<tr>
<td>Dual motor three phase open fault</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remedial strategy 3</td>
<td>0</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>
• The fault remedial strategy 1 is the simplest mode and causes the minimum copper loss. However, this fault remedial strategy has a relatively higher torque ripple factor both in single and dual motor drives;

• The fault remedial strategy 3 is more complex to implement, but has zero torque ripple factor and slightly higher copper loss than the fault remedial strategy 1. In addition, this fault remedial strategy can be used in any faulty operation;

• For the dual motor module drive, the fault remedial strategy 2 is the easiest method to obtain zero torque ripple factor, although at the cost of the highest copper loss. However, this method is not suitable for two same phase open-circuit fault operation.

It should be noted here that in the case of a complete motor module open-circuit fault operation, all three types of fault remedial strategies can be adopted and the same result can be obtained: the same output torque as in the healthy operation and with zero torque ripple factor.

3.6 Conclusions

The output torque of a brushless fault tolerant PM motor drive is a function of the phase current. In this chapter, a general phase current mathematical model to produce the desirable output torque was developed, which aims to minimize copper loss in the motor drive and is suitable for single and dual motor module fault tolerant drives with sinusoidal or trapezoidal back-EMF waveforms.

The fault mode analysis presented in the chapter demonstrates that electrical faults are inevitable in motor drives. In order to investigate potential faults, the systematic fault classification was also performed in this chapter. It was concluded that the winding open-circuit and short-circuit faults, switch open-circuit and short-circuit faults are the most common electrical faults in the motor drive. In addition, the effect of various faults on output torque and torque ripple reveals that after a fault, the output torque decreases and a degree of torque ripple is produced. The degree of torque ripple is more serious specifically under switch short-circuit fault condition due to the resulting higher drag torque from the short-circuit current. The winding and switch short-circuit fault analysis indicates that higher winding inductance (1.0 pu) can limit the short-circuit current and...
drag torque values.

As it was demonstrated in the chapter, the inverter switches can be used to alter the states of fault. For example, a switch open-circuit fault can be made as a winding open-circuit fault, and a switch short-circuit fault can be transformed into a winding short-circuit fault by providing suitable trigger signals to the relevant switches of the inverter. Therefore, all the winding and switch faults in the motor drive are classified as: one phase open-circuit fault and short-circuit fault, two different or two same phase open-circuit faults and short-circuit faults, three-phase open-circuit faults and short-circuit faults (including one motor module complete open-circuit fault). In the following chapters of this thesis, some of these fault types will be studied in detail.

Furthermore, in the case of a given fault, to compensate the decrease in the output torque and to reduce the torque ripple, fault remedial strategies were studied. Such studies aimed to provide the rated (or nearly rated) output torque even under faulty operation. Except the fault remedial strategy that increases the current in healthy phases (Fault remedial strategy 1), two additional fault remedial strategies for single and dual module fault tolerant PM motor drives were proposed in this thesis. These strategies are named as the fault remedial strategy 2 in which the current in the same phase of the second motor module is doubled, and as the fault remedial strategy 3 in which the optimal phase currents are provided to the motor drive. In the chapter, the current and copper loss mathematical models of the fault remedial strategy 3 under open-circuit and short-circuit faults were also discussed which is suitable for both single and dual module fault tolerant PM motor drives.

Moreover, the performance of the above three fault remedial strategies were examined in detail, which includes the values of output torque ripple, the copper loss and the highest phase copper loss as well as complexity and application limitations. It was concluded that the fault remedial strategy 1 is the simplest mode achieving minimum copper loss. However, the method causes a relatively higher torque ripple factor both in single and dual module motor drives. Although the fault remedial strategy 2 can provide zero torque ripple factor, this fault remedial strategy can only be utilized in the dual fault tolerant motor drive and for certain fault types. In addition, this fault remedial strategy results in the maximum copper loss in the motor drive. It was found that the
fault remedial strategy 3 is the best algorithm in which the zero torque ripple factor can be achieved with only a modest increase in copper loss comparing to the minimum possible value in the fault remedial strategy 1. Furthermore, considering the entire features list in Table 3.3, the dual module fault tolerant motor drive has better performance than the single module fault tolerant motor drive which accommodates the same fault remedial strategy.

The following chapter will discuss the implementation details of the two motor drive setups, investigate their performances and demonstrate the proposed fault remedial strategies using simulation studies.
Chapter 4
Simulation Study of Fault Tolerant PMAC Motor Drives With Redundancy

4.1 Introduction

As stated in previous chapters, fault tolerant motor drives are required in various safety critical applications and using special motor design and inverter topologies, brushless permanent magnet AC motor drives can have a fault-tolerant capability. In addition, it has been proven that a dual module fault tolerant motor drive configuration can improve the reliability of the motor drive. However, due to the complexity of the system and potential fault scenarios that may occur even in a fault tolerant system, it is important to understand and investigate the operations and limitations of such system in detail. The fault mode analysis, fault effect investigation on output torque and torque ripple, and the fault remedial strategies for various faults both in single and dual module fault tolerant motor drives were studied in previous Chapter.

Since computer simulation is a powerful engineering tool, it can save time and money by avoiding extensive and destructive experimental testing. Therefore, the simulation studies on fault tolerant motor drives are performed in this chapter. A complete computer simulation model of the fault tolerant PMAC motor drives with different pole numbers and structures were developed. The key parameters of the motor used in the simulation studies were determined experimentally from the real machines.

Since the power loss and the motor efficiency are the important characteristics in the dual fault tolerant motor drive, and can significantly affect the operation and control strategies of the motor drive, a motor drive efficiency estimation method based on experimental test is presented in this chapter. Then the predicted results are verified by the computer simulation study. Furthermore, the fault effect on motor drive efficiency is investigated. In addition, the simulation studies in this chapter on the real motor drive
system (dual 48-pole motor module fault tolerant PMAC drive setup) under both healthy and various faulty conditions are performed to investigate the validity of the proposed fault remedial strategies.

4.2 Dual Module Fault Tolerant Motor Drive Setups

4.2.1 Four-pole fault tolerant motor drive setup

As emphasized in the previous chapters, in order to obtain a fault-tolerant brushless PM motor, it is important to minimize or eliminate the electrical, magnetic and thermal coupling between the motor windings. Thus, in the case of a failure in one winding, the other windings can keep functioning. This may be achieved by physically separating the motor windings and driving each winding using a separate single phase H-bridge inverter circuit.

Figure 4.1 shows the winding arrangement and the photo of a dual module four-pole three phase fault tolerant brushless PMAC motor drive setup. As shown in Figure 4.1 (a), the windings of different phases of the fault tolerant motor are arranged in different slots. The winding arrangement shown here is known as concentrated windings which provides a minimum electrical, magnetic and thermal interaction between phases.

![Cross section of winding arrangement](image1.png) ![Photo of motor drive setup](image2.png)

Figure 4.1 Dual 4-pole three phase fault tolerant motor module drive setup

It should be reported here that although the two motor modules in Figure 4.1 (b) setup has identical outer dimensions and similar torque ratings, they have different winding parameters. This is due to different number of winding turns and different gauge wires used in the design of each motor module. Table 4.1 summarizes the measured motor parameters of each motor module. As can be seen in the table, the motor module 2 has a
winding inductance that is about 4.5 times and a back-EMF constant about 2 times greater than the values of motor module 1. This dual fault tolerant motor drive setup shown in Figure 4.1 (b) is used to investigate the fault tolerant operation concept in Chapter 6, which also includes a DC machine for loading purposes.

Figure 4.2 is given to illustrate the back-EMF waveforms of one of the phases of Motor module 1 and Motor module 2, which were measured at a constant rotor speed of 880 rpm. As can be seen in the figure, two motor modules have similar back-EMF profiles that can be approximated to ideal sinusoidal waveforms. Therefore, for simplicity in the simulation and implementation study, it is assumed that the back-EMFs and reference current waveforms are sinusoidal waveforms for both motor modules.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Motor 1</th>
<th>Motor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winding resistance (Ω)</td>
<td>0.275</td>
<td>0.87</td>
</tr>
<tr>
<td>Winding inductance (mH)</td>
<td>0.46</td>
<td>2.1</td>
</tr>
<tr>
<td>Back-EMF constant (V/rad/s)</td>
<td>0.041</td>
<td>0.093</td>
</tr>
</tbody>
</table>

Figure 4.2 Measured 4-pole motor back-EMF voltages at 880 rpm rotor speed.

### 4.2.2 48-pole fault tolerant motor drive setup

A second fault tolerant motor drive setup was also considered in this study, which has identical motor modules. The motor modules are outer rotor concentrated winding brushless PMAC motors (Fisher & Paykel washing machine motors) which has 48 poles. Figure 4.3 is the photo of the motor drive setup and the structure of the motor module. The original Fisher & Paykel washing machine are star-connected windings, so the windings are reconfigured to provide electrical isolation. After the winding reconfiguration, each phase has 12 teeth in which six sections (each section has two windings connected in series) are connected in parallel. Table 4.2 describes the
measured parameters of the identical motor modules. In the tests, the resistance and inductance of the motor are measured by Power Analyzer in which the measured phase is powered by the 50 Hz AC voltage to obtain the reactance and resistance. In Figure 4.3 (a), two identical Fisher & Paykel three-phase machines are utilized for loading purpose, which also connected to the common shaft of the motor drive.

The peak back-EMF voltage is equal to the back-EMF constant times the rotor mechanical speed. Figure 4.4 is given to illustrate the measured phase back-EMF voltage waveforms in 44 rpm rotor speed. From the back-EMF waveforms it can be seen that the back-EMF waveforms of the motor module are sinusoidal with 120° phase difference with each other. It should be noted that the back-EMF voltages of the two motor modules are aligned in this study.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance</td>
<td>0.55 Ω</td>
<td>Back-EMF constant</td>
<td>0.89 V/rad/s</td>
</tr>
<tr>
<td>Inductance</td>
<td>2.1 mH</td>
<td>Rated current</td>
<td>12 A</td>
</tr>
</tbody>
</table>

Figure 4.3 Pictures of an identical motor modules and generator arrangement (left) and the structure of the fault tolerant motor module (right)

Table 4.2 48-pole motor parameters

Figure 4.4 Measured back-EMF waveforms of the 48-pole fault tolerant PM motor at 44 rpm rotor speed
4.3 Efficiency Prediction of 48-pole Motor Drive Setup

4.3.1 Open-circuit power loss test

The setup which is used to perform the power loss test is shown in Figure 4.5. In this setup, one of the 48-pole motor modules is connected to a brush DC motor that is driven by an external DC power supply. In the test, the torque and mechanical loss characteristics of the DC motor is obtained first. This is done under no load condition (without connecting the PMAC motor) and as a function of the rotor speed. Secondly, the DC motor is used to drive the brushless PMAC motor to obtain the total torque loss of the test setup. Finally, the open-circuit torque loss of the fault tolerant PMAC motor module is calculated, which is equal to the difference between the total torque loss of the test setup system and the DC motor torque loss. The measured torque loss as a function of the rotor speed is illustrated in Figure 4.6. The open-circuit torque loss equation of the PMAC motor is obtained from the same figure by fitting a curve that is given below.

\[
T_{open\loss0} = 0.00245\omega_m + 0.3451
\]  

(4.1)

Here \(\omega_m\) is the rotor mechanical speed (rad/s). The open-circuit torque loss consists of the iron and mechanical torque loss. Since two identical motor modules are used in this study, it is assumed that the total open-circuit torque loss \(T_{open\loss}\) of a dual fault tolerant motor drive is equal to \(2T_{open\loss0}\).

![Figure 4.5 The setup photo and block diagram for motor open-circuit power loss tests](image)
4.3.2 Copper loss calculation

As analyzed in Chapter 3, the total electromagnetic torque $T$ and the copper loss $P_{cu}$ in a dual three phase fault tolerant motor drive with sinusoidal back-EMF voltages are the functions of the phase current. Using the equations (3.12) and (3.42), the copper loss $P_{cu}$ can be obtained as a function of torque $T$ as

$$P_{cu} = R \frac{T^2}{3k_e^2}$$  \hspace{1cm} (4.2)

Here total electromagnetic torque of the dual motor drive $T$ is equal to the sum of the total open-circuit torque loss and the load torque $T_L$ as given below.

$$T = T_L + 2T_{\text{open loss}}$$  \hspace{1cm} (4.3)

4.3.3 Efficiency prediction of the dual fault tolerant motor drive

The total open-circuit power loss and copper loss obtained above can be used to predict the efficiency characteristics of the dual module fault tolerant PMAC motor drive. The efficiency of the motor drive can be calculated by

$$\eta = \frac{P_{out}}{P_{out} + P_{cu} + P_{\text{open loss}}} \times 100\%$$  \hspace{1cm} (4.4)
where $P_{\text{out}}$ and $P_{\text{openloss}}$ represent the output power and open-circuit power loss of the dual fault tolerant motor drive respectively, which are given by

$$P_{\text{out}} = T_L \cdot \omega_m$$

(4.5)

$$P_{\text{openloss}} = 2T_{\text{openloss0}} \cdot \omega_m = T_{\text{openloss}} \cdot \omega_m$$

(4.6)

Figure 4.7 illustrates the change of output power, copper loss and open-circuit power loss and the predicted efficiency as a function of the rotor speed under 9.0 Nm electromagnetic output torque condition. As expected, since the output torque is kept constant, the copper loss almost remains constant while the open-circuit power loss increases with the rotor speed, and the efficiency at higher rotor speed almost remains constant. Therefore, in order to increase the efficiency of the motor drive, it is important to decrease the open-circuit power loss, which can be achieved by using lower friction bearings and by utilizing lower iron loss magnetic material in the motor construction.

Figure 4.7 The estimated power and the efficiency curves as a function of rotor speed under 9.0 Nm output electromagnetic torque condition

Figure 4.8 displays the estimated contour plot of the efficiency calculations. It can be observed from this figure that the efficiency of the dual motor drive increases with the load torque. In addition, the efficiency at lower rotor speeds is smaller than the efficiency at higher speeds. Using the rated current and the back-EMF constant, the rated output torque of the dual fault tolerant motor drive is calculated as 45 Nm.
It should be noted here that the efficiency value of the motor setup given in Figure 4.3 is lower than the results predicted in this section which is due to the presence of friction produced by the bearings in the real system.

![Figure 4.8 The estimated contours of the dual fault tolerant motor drive at different rotor speeds and output torque values.](image)

### 4.4 Simulation Studies of Motor Drive Efficiency

#### 4.4.1 Simulation study of predicted efficiency

In this section the simulation study is performed by modeling the entire motor drive system using Matlab/Simulink. The principal block diagram of the simulation model is given in Figure 4.9 in which the control parameters are the rotor speed and the load torque. In this simulation model, the rotor speed is compared with the reference speed and the error is used to determine the value of the reference phase current peak value, and the hysteresis current control scheme is utilized to control the phase currents.

Since the motor drive efficiency is equal to the ratio of the output power and the input power, the simulation utilizes equation (4.5) to calculate the output power, and the input power is obtained by the following equation

\[
P_{in} = \sum_{j=1}^{6} \frac{1}{\Delta T} \int_0^{\Delta T} V_{DC} i_j(t) dt
\]  

(4.7)
Figure 4.9 MATLAB/Simulink block diagram of the dual fault tolerant motor drive with closed loop speed control
Here $V_{DC}$ is the DC link voltage of the inverter, $j$ represents the phase number of the motor drive; $i_j(t)$ is the phase current and $\Delta T$ is the integration time. The open-circuit torque loss function is based on the test result described in section 4.3.1 and as mentioned before the total open-circuit torque loss of the dual fault tolerant motor drive is equal to $2T_{\text{openloss0}}$.

The mathematical models used in the computer simulation include phase voltage equation, torque equation, dynamic motion equation. These equations can be summarized as follows:

$$v_j(t) = R_i(t) + L\frac{di_j(t)}{dt} + e_j(t) \quad j = 1, 2, 3, 4, 5, 6$$  \hspace{1cm} (4.8)

$$T(t) = \frac{1}{\omega_m(t)} \sum_{j=1}^{6} e_j(t)i_j(t)$$  \hspace{1cm} (4.9)

$$T(t) = J\frac{d\omega_m(t)}{dt} + T_{\text{openloss}}(t) + T_L(t)$$  \hspace{1cm} (4.10)

$$\omega_e(t) = N_p\omega_m(t) = \frac{d\theta_e(t)}{dt}$$  \hspace{1cm} (4.11)

Where $e_j(t)$ and $v_j(t)$ are the back-EMF voltage and the phase voltage of phase $j$ respectively; $T(t)$, $T_{\text{openloss}}(t)$ and $T_L(t)$ are the total output electromagnetic torque, the open-circuit torque loss and the load torque; $\omega_m(t)$ and $\omega_e(t)$ are the mechanical and the electrical angular speed; $\theta_e(t)$ is the electrical rotor position; the inertia of the entire system $J$ is assumed as 0.008 kg.m$^2$.

The simulation study is used to examine the efficiency in different speeds and load torques. In addition, it is assumed that the load torque is not a function of the rotor speeds, and under healthy operating conditions the output torque of each motor module is assumed the same due to the identical motor parameters.

Figure 4.10 is given to illustrate the simulation results of the efficiency under three different constant loads. In the figure the estimated values that were based on the motor characteristics obtained in the previous section are also shown. From the figure it can be
observed that the efficiency values from two different prediction methods are almost equal.

![Graph showing efficiency characteristics](image)

**Figure 4.10** The estimated and simulated efficiency characteristics as a function of rotor speed under three load torques

### 4.4.2 Fault effect on motor drive efficiency

Although a dual module fault tolerant motor drive can continue to operate under faulty conditions, it is necessary to investigate the efficiency of the entire motor drive under these conditions. As mentioned in Chapter 3, one phase open-circuit and short-circuit faults are the most common faults in a dual module fault tolerant motor drive. Therefore, this section will investigate the efficiency at the motor drive under these faulty conditions.

It can be assumed that since the motor has identical and electrically and magnetically independent phases, if the rotor speed remains the same, the iron and mechanical losses of the motor drive will also remain the same both in healthy and phase open-circuit fault conditions.

If the motor drive experiences the phase open-circuit fault, in order to obtain the rated torque as in the healthy condition, the currents in healthy phases have to be increased. As it was discussed in the section 3.5.2, the current increase accommodates equation (3.23), the total copper loss in the motor drive under phase open-circuit fault conditions can be expressed as
Here $P_{cu}$ is the total copper loss of the dual motor drive under healthy operation which can be calculated using equation (4.2). The changes of coefficient of the total motor drive copper loss versus the number of phase under open-circuit fault can be calculated by $P_{cuRS}$ divided by $P_{cu}$. Figure 4.11 displays the calculation results which illustrates that the total copper loss increases with the number of faulty phases. Therefore, under the same rotor speed and the output torque while keeping the open-circuit torque loss same; the efficiency of the motor drive under open-circuit fault condition will be lower than the efficiency under the healthy operation.

![Figure 4.11 Changes in the coefficient of copper loss as a function of the number of open-circuit phase faults.](image)

As mentioned previously, under phase short-circuit fault condition, the short-circuit current generates some drag torque in the faulty phase. In order to keep the output torque and rotor speed same as in the healthy operation, it is necessary to increase the current in healthy phases (much more than the value under open-circuit fault). This further reduces the efficiency of the motor under phase short-circuit fault condition, which is even lower at slower rotor speeds.

The main simulation block diagram for the 48-pole dual fault tolerant motor drive setup described in Figure 4.3 is given in Figure 4.12. It should be noted here that there are subsystems in the motor model to simulate a given fault such as short-circuit or open-circuit faults. The control parameter in the simulation is the peak value of the reference phase current which is related to the output electromagnetic torque.
Figure 4.12 The main MATLAB simulation block diagram for the torque control of the dual module fault tolerant motor drive
It is considered that due to the presence of a larger number of bearings in the motor drive setup, the open-circuit torque loss (including iron and mechanical torque loss) may be higher than the measured result described in section 4.3.1. Therefore, the total open-circuit torque loss of the dual motor drive is assumed 3 times of $T_{\text{openloss0}}$

$$T_{\text{openloss}} = 0.00735\omega_m + 1.035$$  \hspace{1cm} (4.13)

In the experimental study, the output of generator 2 in Figure 4.3 is connected to a three-phase rectifier and a 12.4 $\Omega$ resistor. Therefore, the load torque is the function of the rotor speed. It was also determined by the initial tests that for different rotor speed, the load torque can be approximated as

$$T_L = 0.391 \omega_m + 4.505 \quad 0 \leq n < 90 \text{ rpm}$$  \hspace{1cm} (4.14)

$$T_L = 0.1359 \omega_m + 7.07 \quad n \geq 90 \text{ rpm}$$  \hspace{1cm} (4.15)

Since the rotor speed can be varied by the reference current, Figure 4.13 shows the simulation results of the 48-pole dual fault tolerant motor drive under healthy; one phase open-circuit fault and one phase short-circuit fault conditions.

![Figure 4.13 The efficiency characteristics obtained in the simulation as a function of the rotor speed.](image-url)
The figure indicates that the motor drive efficiency under the phase open-circuit fault is lower than the efficiency under healthy operation. The short-circuit fault operation results in the lowest motor drive efficiency. The simulation results are consistent with the analysis results discussed earlier.

4.5 Simulation Studies of 48-pole Motor Drive Setup

The computer simulation tool not only provides quick answer to various parameter changes in the drive models, but also allows performing destructive studies to any sections of the system without physical damage of the motor drive system. These include theoretically unlimited phase current and voltage ratings for the DC power supply model that is required at higher rotor speeds. A detailed simulation study of the dual 48-pole fault tolerant PMAC motor drive and various corresponding fault remedial strategies will be provided in this section.

The block diagram of the MATLAB simulation model used in this study is similar to Figure 4.12 and the open-circuit torque loss and the load torque are calculated using equations (4.13), (4.14) and (4.15). In simulation study, the hysteresis current control scheme is utilized in which the hysteresis bandwidth $\pm \Delta h/2$ is setup as $\pm 0.05$ A. The simulation time step is 0.02 ms for all the simulation studies performed in this chapter.

The average output torque $T_{ave}$ and the total average copper loss $P_{ave}$ in the dual module fault tolerant motor drive can be calculated by

$$T_{ave} = \frac{1}{\Delta T} \int_{0}^{\Delta T} T(t) \, dt \tag{4.16}$$

$$P_{ave} = \frac{1}{\Delta T} \int_{0}^{\Delta T} \sum_{j=1}^{6} R \, i_j^2(t) \, dt \tag{4.17}$$

4.5.1 Simulation of healthy operating condition

The aim of healthy operating simulation is to obtain the general features of the drive at slower and higher rotor speeds. In Figure 4.14, the phase current waveforms of motor module 1 and the total output torque waveforms under healthy operation are provided. Since the motor module 2 has identical parameters as the motor module 1, its current waveforms are the same as motor module 1, hence they are not shown. The simulation
results indicate that in the healthy operating state the mean output torque is 9.12 Nm, the peak-to-peak torque ripple is 12.5% and the rotor mechanical speed is 86 rpm.

The phase current waveforms of the motor module 1 under different DC link voltages (32 V and 70 V) and the same reference current value (6.2 A) are presented in Figure 4.15. From the simulation results it can be seen that at higher rotor speeds, the phase current waveforms are distorted waveforms that is due to the relatively large back-EMF voltage comparing to the applied DC link voltage.

![Figure 4.14 Simulated motor module 1 phase current and total torque waveforms under healthy operation (Im=3.45 A, Vdc=20 V).](image1)

![Figure 4.15 Simulated phase current waveforms of motor module 1 under different DC link voltages and same peak reference current value of 6.2 A](image2)

Figure 4.16 illustrates the total output torque waveforms of the motor drive which indicates that the output torque is reduced from 15.46 Nm to 13.25 Nm. The steady rotor speed is also reduced from 492 rpm to 345 rpm under the above operating condition that is due to the distorted phase current waveforms. The corresponding
torque ripple values in Figure 4.16 are 22% and 27% respectively, which is caused by
the hysteresis current control inherent feature and the limited simulation time step. In
addition, the higher DC link voltage results in larger torque ripples. For the DC link
voltage of 70 V and the reference peak current of 6.2 A, the average total copper loss is
estimated as 56.6 W and the average phase copper loss is estimated as 9.4 W.

![Figure 4.16 Simulated total output torque waveforms under different DC link
voltages and same peak reference current value of 6.2 A](image)

**4.5.2 One phase open-circuit fault simulation**

In the simulation of this fault, it is assumed that one phase open-circuit fault occurs in
Phase 4 of motor module 2 at 2000 ms. Figure 4.17 is given to provide the
electromagnetic waveforms in different operating conditions under slower rotor speeds.
In Figure 4.17 (a), torque waveform without fault remedial strategy before and after the
fault is shown. In this mode of operation, the total average torque output drops to 7.61
Nm which is about the 5/6 of the torque value of 9.12 Nm in the healthy operation, and
the torque ripple increases from 12.5% to 52.8%.

In Figure 4.17 (b), (c) and (d), the torque waveforms are given when the fault remedial
strategies 1, 2 and 3 were adopted. The simulation results indicate that the average
output torque remains the same (9.12 Nm) as in the healthy operation under three
different fault remedial strategies. However, the torque ripple values change in each
fault remedial strategy, which are 50.2%, 12.2% and 13% for the fault remedial
strategies 1, 2 and 3 respectively. Figure 4.18 illustrates the simulated phase current
waveforms with the fault remedial strategy 3 before and after the fault.
Figure 4.17 Simulation results of the output torque waveforms under one phase open-circuit fault in Phase 4 of motor module 2 at 2000ms ($I_m=3.45$ A, $V_{dc}=20$ V in healthy operation)
Figure 4.18 Simulated phase current waveforms when Phase 4 open-circuit fault occurred at 2000 ms and remedial strategy 3 was adopted ($I_m=3.45\,A$, $V_{dc}=20\,V$ in healthy operation). Motor 1 phase currents (top) and motor 2 phase currents (bottom)

Figure 4.18 indicates that all the remaining healthy phase currents are adjusted by the fault remedial strategy 3 in order to achieve the desirable torque in the motor drive.

Table 4.3 summarizes the simulation results under a higher rotor speed of 492 rpm in which Phase 4 of the motor module 2 experiences open-circuit fault while the DC link voltage was 70 V. The ideal results obtained from the analytical investigation are also given in the table. It can be concluded from the simulation results that three fault remedial strategies can compensate the torque loss under the one phase open-circuit fault. However, the fault remedial strategy 1 does not offer any improvement for the torque ripple but can deliver the minimum copper loss. On the contrary, fault remedial strategy 2 and 3 can reduce the torque ripple to the level of the healthy condition. It should be noted that the relatively lower torque ripple results are achieved by increasing the copper loss in the motor drive. These simulation results demonstrate that the proposed fault remedial strategies are effective both in slower and faster rotor speed operations.
Table 4.3 Feature comparisons of different fault remedial strategies for one phase open-circuit fault operation at higher speed ($I_m=6.2\ A$, $V_{dc}=70\ V$, 492 rpm)

<table>
<thead>
<tr>
<th>Open-circuit fault operating modes</th>
<th>Simulated average output torque (Nm)</th>
<th>Simulated (ideal) peak-to-peak torque ripple (%)</th>
<th>Simulated (ideal) relative total copper loss</th>
<th>Simulated (ideal) relative maximum phase copper loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy operation</td>
<td>15.46</td>
<td>23.5 (0)</td>
<td>1.0 (1.0)</td>
<td>1.0 (1.0)</td>
</tr>
<tr>
<td>No fault remedial strategy adopted</td>
<td>13.2</td>
<td>61.7 (40)</td>
<td>0.85 (0.83)</td>
<td>1.03 (1.0)</td>
</tr>
<tr>
<td>Fault remedial strategy 1</td>
<td>15.48</td>
<td>59.4 (40)</td>
<td>1.2 (1.2)</td>
<td>1.45 (1.44)</td>
</tr>
<tr>
<td>Fault remedial strategy 2</td>
<td>15.61</td>
<td>24.8 (0)</td>
<td>1.35 (1.33)</td>
<td>4.18 (4.0)</td>
</tr>
<tr>
<td>Fault remedial strategy 3</td>
<td>15.61</td>
<td>23.6 (0)</td>
<td>1.25 (1.22)</td>
<td>1.89 (1.84)</td>
</tr>
</tbody>
</table>

4.5.3 Two different phase open-circuit fault simulation

In the simulation study of this section, it is assumed that two different phase open-circuit faults occur in Phases 4 and 5 of the motor module 2 at 2000 ms. Figure 4.19 is given to illustrate the simulated torque results at slower rotor speeds. Figure 4.20 presents the phase current waveforms of the motors with the fault remedial strategy 3. It can be seen in Figure 4.19 that the total output torque drops to 6.1 Nm and the torque ripple increase to 62.2%. After the fault remedial strategy 1 is adopted, although the average output torque was increased to the healthy operation value of 9.13 Nm, the torque ripple remained the same as in the faulty operation. In the fault remedial strategies 2 and 3, however, the healthy values of the output torque and the torque ripple were achieved.

Similar to the results given in Table 4.3, Table 4.4 is provided to summarize the simulation results at higher rotor speed of 492 rpm under the above mentioned fault and the fault remedial strategies.

The ideal values obtained from the analytical investigation are also given in Table 4.4. The simulation results have verified the analytical results described in Chapter 3.
Figure 4.19 Simulation results of the output torque waveforms under two different phase open-circuit faults in Phases 4 and 5 of the motor module 2 at 2000 ms ($I_m=3.45$ A, $V_{dc}=20$ V in the healthy operation)
Figure 4.20 Simulation results of the phase current waveforms before and after Phases 4 and 5 open-circuit faults at 2000 ms and the remedial strategy 3 was adopted (I_m=3.45 A, V_dc=20 V in healthy operation)

Table 4.4 Feature comparisons of different fault remedial strategies for two different phase open-circuit fault operations in higher speed (I_m=6.2 A, V_dc=70 V, 492 rpm)

<table>
<thead>
<tr>
<th>Open-circuit fault operating modes</th>
<th>Simulated average output torque (Nm)</th>
<th>Simulated (ideal) peak-to-peak torque ripple (%)</th>
<th>Simulated (ideal) relative total copper loss</th>
<th>Simulated (ideal) relative maximum phase copper loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy operation</td>
<td>15.46</td>
<td>23.5</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>No fault remedial strategy adopted</td>
<td>10.8</td>
<td>73.3</td>
<td>0.72</td>
<td>1.1</td>
</tr>
<tr>
<td>Fault remedial strategy 1</td>
<td>15.55</td>
<td>66.7</td>
<td>1.51</td>
<td>2.26</td>
</tr>
<tr>
<td>Fault remedial strategy 2</td>
<td>15.75</td>
<td>19.45</td>
<td>1.75</td>
<td>4.21</td>
</tr>
<tr>
<td>Fault remedial strategy 3</td>
<td>15.75</td>
<td>19.24</td>
<td>1.61</td>
<td>2.85</td>
</tr>
</tbody>
</table>

4.5.4 Two same phase open-circuit fault simulation

In the simulation, it is assumed that two same phases (Phase 1 and 4) of the motor module 1 and 2 have the open-circuit faults. The fault remedial strategy 2 is not considered in this faulty operation since it is not suitable. Figure 4.21 shows the simulation results at slower rotor speed (healthy operating speed of 86 rpm). The results
indicate that the average output torque and torque ripple were 6.1 Nm and 113% respectively before the fault remedial strategies were applied. After the fault remedial strategy 1 was applied, however, the average output torque and the torque ripple were 9.14 Nm and 110%. After the fault remedial strategy 3 was adopted, 9.13 Nm of the output torque and 12.2% of the torque ripple were achieved that is almost equal to the values obtained under healthy operation.

Table 4.5 summarizes the simulation results obtained in this section. It can be concluded from these results that the fault remedial strategy 3 can compensate the torque loss under this fault and also limit the torque ripple to the value achieved in the healthy operation.

![Figure 4.21 Simulation results of the output torque waveforms under two same phase open-circuit faults occurred in Phases 1 and 4 of two motor modules at 2000 ms ($I_m=3.45$ A, $V_{dc}=20$ V in healthy operation). Without fault remedial strategy (top), with the fault remedial strategy 1 (middle), and with fault remedial strategy 3 (bottom).]
### Table 4.5 Feature comparisons of different fault remedial strategies for two same phase open-circuit fault operations in higher speed ($I_m=6.2$ A, $V_{dc}=70$ V, 492 rpm)

<table>
<thead>
<tr>
<th>Open-circuit fault operating modes</th>
<th>Simulated average output torque (Nm)</th>
<th>Simulated (ideal) peak-to-peak torque ripple (%)</th>
<th>Simulated (ideal) relative total copper loss</th>
<th>Simulated (ideal) relative maximum phase copper loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy operation</td>
<td>15.46</td>
<td>23.5</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>No fault remedial strategy adopted</td>
<td>10.8</td>
<td>128.5</td>
<td>0.72</td>
<td>1.1</td>
</tr>
<tr>
<td>Fault remedial strategy 1</td>
<td>15.75</td>
<td>116</td>
<td>1.56</td>
<td>2.33</td>
</tr>
<tr>
<td>Fault remedial strategy 3</td>
<td>15.75</td>
<td>24.7</td>
<td>1.8</td>
<td>2.72</td>
</tr>
</tbody>
</table>

#### 4.5.5 Simulation of one motor module complete open-circuit fault

As stated previously, in a dual three phase fault tolerant motor drive, the DC link power supply failure and the controller failure will result in a complete motor module failure. In the simulation study, it is assumed that the complete motor fault occurs in motor module 2. As expected, if no fault remedial strategy is adopted after such a fault, the total output torque will be the half of the torque under healthy operation, and due to the absence of one of the motor modules, it can be proven that three fault remedial strategies can obtain the same current, the torque and the torque ripple values. Figure 4.22 is given to illustrate the simulation results of the fault under slower rotor speed of 86 rpm. As it can be seen in the figure that after the fault occurred, the phase currents of motor module 1 were increased twice the value of the healthy operation to compensate the torque loss of the motor module 2. This simulation results prove that the proposed fault remedial strategy is effective for the complete motor module failure. The simulation results obtained in higher rotor speed also verify the same conclusion.

#### 4.5.6 One phase short-circuit fault simulation

In the simulation, it is assumed that one phase short-circuit fault occurs in the Phase 4 of the motor module 2 at 2000 ms. The simulation studies are conducted both under slower rotor speed light load and higher rotor speed heavy load conditions. In each rotor speed, the simulation results without fault remedial strategy and with the fault remedial strategies 1 and 3 are given.
Figure 4.22 Simulation results of the output torque waveforms with the fault remedial strategy 1 after complete failure of the motor module 2 at 2000 ms ($I_m=3.45$ A, $V_{dc}=20$ V in healthy operation). Motor 1 phase current waveforms (top), motor 1 torque waveforms (middle), and motor 2 and total torque waveforms.

(a) Effect of the drag torque

As studied previously, under phase short-circuit fault condition (in addition to the loss of 1/6 of the total torque), the drag torque generated by the short-circuit current reduces the total output torque further. In order to compensate this drop and achieve the rated torque, the phase currents in healthy phases need to be increased which should be greater than the value obtained under open-circuit fault operation. Figure 4.23 illustrates the variation of the drag torque in the dual 48-pole fault tolerant motor drive and the current increment which is used to compensate the drag torque under different rotor speeds. As it can be seen in the figure, the largest drag torque occurs at a rotor speed of 100 rpm where the current increment is also the highest to compensate the drag torque.
(b) Slow speed and light load condition

Figure 4.24 illustrates the simulation results of the torque waveforms at a rotor speed of 86 rpm and under a light load condition. No fault remedial strategy was adopted in this mode of fault. As it can be seen in the figure this fault generates a large drag torque in the motor module 2, which reduces the total output torque to 5.5 Nm and increases the torque ripple to 179%. The simulation results after the fault remedial strategy 1 is adopted are given in Figure 4.25. As it is can be seen in these results the amplitude of the short-circuit current after the fault remedial strategy is higher than the amplitude of the healthy phase currents. Therefore, the healthy phase currents need to be increased to compensate the torque loss due to the fault. It can be concluded from the torque curves that although the average output torque is increased to the healthy operation value after the fault remedial strategy 1, the torque ripple increased further to 199%.
Chapter 4 Simulation Study of Fault Tolerant PMAC Motor Drives with Redundancy

Figure 4.25 Simulation results when the Phase 4 short-circuit fault occurred at 2000 ms and the fault remedial strategy 1 was adopted ($I_m=3.45$, $n=86$ rpm, $V_{dc}=20$ V). The motor 1 phase currents (top), the motor 2 phase currents (middle), and the torque waveforms (bottom).

Figure 4.26 presents the simulation results with the fault remedial strategy 3 in which non sinusoidal waveform currents were applied to the healthy phases. The results indicate that both the output torque value (9.11 Nm) and the torque ripple (13.1%) are improved to the values as in the healthy operating mode.

(c) High speed and heavy load operation

The simulation results under higher rotor speed (435 rpm) and heavier load (37.7 Nm) are given in Figure 4.27 and Figure 4.28. Figure 4.27 shows the torque waveforms when a phase short-circuit fault occurs and no fault remedial strategy is adopted. The results indicate that after the fault the output torque reduces to 29.1 Nm and the torque ripple becomes 91%. In addition, the rotor speed reduces to 260 rpm.
Figure 4.26 Simulation results when the Phase 4 short-circuit fault occurred at 2000 ms and the fault remedial strategy 3 was adopted ($I_m=3.45$, $n=86$ rpm, $V_{dc}=20$ V). The motor 1 phase currents (top), the motor 2 phase currents (middle), and the torque waveforms (bottom).

Figure 4.27 Simulated torque waveforms when phase 4 short-circuit fault occurred at 2000 ms and no fault remedial strategy was adopted ($I_m=14.5$, $n=435$ rpm, $V_{dc}=90$ V)
Figure 4.28 illustrates the simulation results in which the fault remedial strategy 3 is applied after the phase short-circuit fault occurs. The results demonstrate that the fault remedial strategy 3 is effective against the phase short-circuit fault under higher speed and heavy loading conditions as the torque and the torque ripple produced after the fault remedial strategy 3 is almost equal to the values obtained under the healthy operation.

In addition, from the current waveforms it can be seen that the short-circuit current under this fault is nearly equal to the healthy phase current. Therefore, the relative effect of the short-circuit fault on the torque output is less than the previous fault case of lower speed and light load condition.

Figure 4.28 Simulation results when Phase 4 short-circuit fault occurred at 2000 ms and the fault remedial strategy 3 was adopted ($I_{im}=14.5$ A, $n=435$ rpm, $V_{dc}=90$ V). The motor 1 phase currents (top), the motor 2 phase currents (middle), and the torque waveforms (bottom)
4.6 Conclusions

In order to investigate the various features of the fault tolerant motor drive with redundancy, a complete MATLAB based simulation model of the fault tolerant PMAC motor drive were developed in this chapter. In addition, the efficiency of the motor drive was predicted based on the torque loss measurements, which were also verified by the simulation study. Furthermore, the fault effect on the motor drive efficiency was studied in the simulation. The analytical and simulation results has shown that the total copper loss of the motor drive is increased under different faulty conditions if the rated torque and the rotor speed is aimed after the faults.

Further studies performed on the simulation model revealed that the efficiency under the winding short-circuit fault condition is lower than that under winding open-circuit fault, which is due to the presence of the drag torque produced by the short-circuit current.

In the chapter, the simulation studies on various faulty conditions under slower and higher rotor speeds were also performed. The results demonstrated that under the selected faults (one phase open-circuit fault, one phase short-circuit fault, two different phase open-circuit fault, two same phase open-circuit fault, and one motor module complete open-circuit fault), the output torque reduces and the torque ripple increases. It was observed that all three fault remedial strategies studied in the simulation increases the average torque to the value under the healthy operation, while different torque ripple and total copper loss values are obtained under different fault remedial strategies. It was also observed that the fault remedial strategy 1 does not improve the torque ripple feature, but delivers minimum copper loss. In addition, the fault remedial strategy 3 decreases the torque ripple to the value obtained under the healthy operation. The disadvantage of this method is slight increase in the copper loss. Moreover, it was found that the fault remedial strategy 2 improves the torque ripple value but develops the maximum copper loss.

The simulation results have also demonstrated the validity of the analytical conclusions obtained in Chapter 3. The following chapters will describe the details of the implemented real motor drive and will provide various experimental results to verify the simulation and other estimated studies.
Chapter 5
Implementation of Fault Tolerant PMAC Motor Drives with Redundancy

5.1 Introduction

Although the entire motor drive simulation studies have been performed in previous chapter, the proposed algorithm and the simulation results are needed to be verified by the experimental results. Therefore, this chapter aims to develop a flexible hardware system, and relevant software solutions to be able to introduce a fault and perform suitable remedial strategies. The hardware and software of the motor control system will be investigated. The hardware includes current measurement circuit boards; inverter and switch driver circuit boards; motor controller based on dsPIC30F4011 DSC (Digital Signal Controller). The software of the motor drive is developed in C language.

As mentioned before, the fault detection and identification is the significant step before various fault remedial strategies are applied. In addition, after winding short-circuit fault or switch short-circuit fault occurs, the post-fault action must be applied on time to protect the motor winding and inverter circuit especially if these faults incur a large short-circuit current. The previous studies usually utilized phase current sensors to detect winding open-circuit and short-circuit faults and multiple on-state voltage sensors for each switch to detect switch faults which may increase the cost of the whole motor drive significantly. Therefore, this chapter introduces the principle of the practical fault detection and identification method which can detect the switch open-circuit fault, switch short-circuit fault, and the winding short-circuit fault.

The detail experimental results including healthy and faulty operations will be provided in the next chapter.
5.2 Structure and Function of Motor Drive System

Figure 5.1 illustrates the principal block diagram of the dual fault tolerant PMAC motor drive that includes two three phase fault tolerant brushless PMAC motor modules, six H-bridge inverters with fault detection function, six Hall-effect current sensors and measurement circuits, one encoder and two dsPIC30F4011 DSC based motor controllers. Each of the electrically isolated phase windings of the motor modules is driven by a separate H-bridge circuit, and each inverter group is powered from a separate power supply. Therefore, this structure allows the two motor drive control systems to be able to operate independently, and even if one motor module fails completely, the second motor module can continue to operate. It should be noted here that every major section of the drive system has redundancy except the rotor position sensor.

![Figure 5.1 Block diagram of the dual motor module fault tolerant drive.](image)

5.3 Details of Hardware Implementation

The actual hardware of the fault tolerant motor drive control system implementation in this study includes phase current measurement circuits, inverters and switch drive circuits, fault detection and switch protection circuits, controllers and its I/O interface circuits. Due to the practical limitations and complexity of the entire control and
interface circuits, various implementation hints of these circuits are provided in this chapter. In this section, the phase current measurement circuits, the controller circuits, and the inverter circuits are explained in details. The fault detection and switch protection circuits and the fault detection principle will be provided in Section 5.4.

### 5.3.1 Current measurement circuit

Since the torque control of the fault tolerant PM motor drive is achieved by the current control, the real time current measurement is required for each motor phase. Figure 5.2 shows the circuit diagram of a phase current measurement which includes the signal conditioning circuit and Figure 5.3 illustrates the photo of the PCB board where three phase current measurement circuits were accommodated. The Hall Effect based current transducer, LTS 15-NP was used in the current measurement circuits. The accuracy of the current transducer used in the circuit is better than ±0.2 % at 25 °C and has a bandwidth of 100 kHz [76]. This transducer requires a unipolar power supply of +5V, and can measure DC and AC currents.

The reference point of the transducer with zero primary current is 2.5V, which is equal to the half of the supply rail voltage. With the current configuration used in Figure 5.2, the maximum gain of 0.125V/A can be achieved and the output voltage of the current transducer $V_{in}$ can be given by

$$ V_{in} = 0.125 I_{in} + 2.5 \quad (V) \tag{5.1} $$

In order to increase the gain of the current measurement further and to provide a buffer circuit, a high speed, precision operational amplifier of AD711 is utilized. For the values of resistances selected ($R_1 = R_2 = R_3$), the output voltage of the amplifier can be given by

$$ V_{out} = 0.25 I_{in} + 2.5 \quad (V) \tag{5.2} $$

As can be seen in the above equation, the gain of the current measurement circuit is increased to 0.25 V/A, which indicates that for a current of ±10A, the output voltage of this signal conditioning circuit varies between 0 V and 5 V. this voltage range matches the input voltage of the A/D converter used.
Figure 5.2 The current transducer and signal conditioning circuit used in the real motor drive.

Figure 5.3 Photo of the PCB layout that accommodates three phase current measurement circuits.

5.3.2 Motor controller and interface circuit

A simplified diagram of the motor controller is shown in Figure 5.4 and the photo of the PCB board is given in Figure 5.5. The high performance Microchip dsPIC30F4011 DSC is utilized in the motor controller system, which is specially designed for real time motor control and power conversion applications. This microcontroller combines the high performance required in DSP applications with standard microcontroller features required for embedded applications.

This microcontroller has a 16-bit modified Harvard architecture with an enhanced instruction set, including significant support for Digital Signal Processing (DSP). The maximum operation speed of the controller is 30 MIPS and most of the instructions are executed in a single cycle. It has 16K flash program memory and 2K data memory, and
has various real time control peripheral interfaces such as 10-bit analog-to-digital converter (A/D), Pulse Width Modulation (PWM) module, encoder input module, digital input and output ports and UART communication modules. These features can meet the requirement of the real time fault tolerant motor drive control [77-79].

In the microcontroller interface circuit, the input AN2 is used to provide the amplitude of the reference current under healthy operating condition, which is related to the desired torque output. A/D input ports AN6, AN7 and AN8 are used to measure three-phase currents that is connected to the phase current measurement board (Figure 5.3). The input AVDD in Figure 5.4 is the reference voltage of the A/D converter.
As the operation of a brushless PM motor requires accurate knowledge of the rotor position, a three-channel optical encoder of HEDS-5640 is used. The phase A and phase B channels are two primary signals generated by this encoder, which are square waves 90° out of phase (i.e. in quadrature). These channel information are also used to determine the direction of the rotation. For example, if phase A leads phase B, the motor runs in forward direction, and if phase A lags phase B, the motor operates in reverse direction. In addition, the encoder has an I channel output (an index pulse once per revolution). The outputs of the encoder are connected to the Quadrature Encoder Interface (QEI) module ports (INDX, QEA and QEB) of the dsPIC30F4011 DSC [80].

The QEI module of the motor controller provides an interface to the incremental encoder, which consists of the quadrature decoder logic to interpret the phase A and phase B signals and an up/down counter to accumulate the count. The Quadrature Decoder module in the controller captures the phase signals and index pulse and converts the information into a numeric count of the position pulses. The count will increment when the shaft is rotating one direction and decrement when the shaft is rotating in the other direction. Since the encoder used has 500 cycles per revolution for both phase A and B channels; the QEI module counter can counts up and down on every count pulse, so the maximum value of the position counter is 2000.

The ports PWM0-PWM5, RF0-RF6 and RC13 of the microcontroller are utilized to separately control the status of the inverter switches. RD0-RD3 ports are used to monitor four switch fault signals in one phase of the motor module. To simplify the hardware design, in this research only the fault in phase A of the motor drive is monitored, which can easily be extended using additional digital I/O pins. PGC and PGD pins of the microcontroller are used to debug the program and download the program code from the desktop computer to the motor controller. In control operation mode, these pins work as the UART communication interface.

5.3.3 Inverter and drive circuit

Since the operation of a fault tolerant brushless PM motor drive requires regulated current waveforms for all the motor phases, a total of 6 H-bridge inverters were constructed. The simplified diagram of the inverter circuits and a photo of the
implemented PCB board are given in Figure 5.6 and 5.7 respectively. In the H-bridge inverter circuits, four N-channel power MOSFETs with integrated freewheel diodes are used, which has an ultra low on-resistance 0.04Ω.

![Four optocoupler circuits](image1)

**Figure 5.6 The simplified diagram of an Inverter and drive circuits.**

![The photo of the PCB board that accommodates a single phase H-bridge inverter circuit.](image2)

**Figure 5.7 The photo of the PCB board that accommodates a single phase H-bridge inverter circuit.**

The IR2121 and IR2125 are the low side and high side high speed power MOSFET drivers with built in over-current limiting protection circuits. The purpose of a drive circuit is to convert an input switching signal to a level which can turn on and off the corresponding power switch. The drive circuit also accommodates the fault detection and protection function which will be introduced in detail in the next subsection. A four-channel optocoupler (TIL919) is used to electrically isolate the controller circuit and the inverter circuit.

It should be noted that the selection of the input and output resistors of the optocoupler is critical to make sure that the minimum and similar phase delay between input and output signals. Figure 5.8 illustrates the measured optocoupler signals for three different output resistance values.
In addition, Figure 5.9 is given to demonstrate the practical delays in the driver circuit including the controller output signal, optocoupler output signal, low side switch drive output signal and the inverter voltage signal. In order to avoid the shoot-through fault in the inverter switches, $3 \mu s$ “dead time” is inserted, which is realized by the controller program of the motor drive.

![Figure 5.9 Measured waveforms of controller output signal, optocoupler output signal, low side switch drive output signal, and inverter output signal.](image)

**Figure 5.8 Test results of the input signal (1) and the output signals for three different resistance values 1.2 kΩ (2), 820 Ω (3) and 680 Ω (4).**

**Figure 5.9 Measured waveforms of controller output signal, optocoupler output signal, low side switch drive output signal, and inverter output signal.**

### 5.4 Fault Detection and Identification

#### 5.4.1 Introduction

The most common electrical faults are winding open-circuit fault, winding short-circuit fault, switch open-circuit fault and switch short-circuit fault. To detect the motor winding and inverter faults, it is necessary to monitor the phase currents and the switch
on-state voltages. The winding open-circuit fault can be easily detected by the phase current sensors. This fault can be identified when the phase voltage equals to the voltage of the power supply while the phase current is kept as zero. Several real time motor fault detection and identification methods were proposed and developed in [12, 29-35]. Some of these methods are only suitable for certain type of motor or certain type of faults. In addition, the previous techniques which rely on significant number of on-state voltage sensors to detect the switch fault significantly increase the total cost and add significant burden to the processing power of the motor controller (12 voltage sensors and signal conditioning circuits for the motor topology considered in this research are required). Therefore, the previous techniques can not be utilized to detect the faults in this thesis.

Due to the above mentioned issues, this thesis developed a practical fault detection and identification method to detect winding short-circuit fault, switch open-circuit fault and switch short-circuit fault. No extra on-state voltage sensors are needed in this research. The hardware of this fault detection method includes phase current sensors which are already used for the motor control and the driver circuit, which is easy to implement and has lower cost. The following subsection will introduce the principle of this fault detection method in detail.

5.4.2 The principle of electrical fault detection

As mentioned in section 5.3.3, separate low side and high side MOSFET drivers with over-current limiting protection circuitry are utilized in the inverter circuit. The logic inputs of the drivers are compatible with standard CMOS or TTL outputs, down to 2.5V logic and the output of the driver features a high pulse current buffer stage designed for minimum driver cross-conduction. The protection circuitry can detect over-current in the driven switch and limit the gate drive voltage. The high side driver (IR2125) can operate in the floating voltage up to +500V.

Figure 5.10 illustrates a complete driver circuit with a switch including the fault detection circuit [81-83]. D₀ and C₄ in the circuit are the bootstrap diode and capacitor. The ERR pin is multifunctional, providing status reporting, linear mode timing, and cycle-by-cycle control. When the IN signal is low ERR pin is pulled low, and after the IN signal is switched high the ERR pin is switched to a high impedance state. When the
output stage switches to linear mode due to an over-current signal at CS, the ERR pin is set to drive a 100 μA charging current into the capacitor C₅. The capacitance of C₅ determines the voltage rising rate of ERR pin when over-current occurs in the circuit. The values of C₄ and C₅ in the circuit must be chosen carefully for the correct operation.

![High Side Switch and Driver Circuit](image)

**Figure 5.10** A high side switch and its driver circuit with the fault detection circuit.

If there is no gate signal in the circuit, the \( V_{CS} \) pin is zero. If there is a gate signal however, the switch T₁ turns on and the diode D₂ is forward biased. Hence \( V_{CS} \) can be given as

\[
V_{CS} = \frac{R_4}{R_3 + R_4} (V_D + V_{DS})
\]

where \( V_D \) is the diode voltage drop, \( V_{DS} \) is the on-state voltage of the MOSFET switch which is proportional to the switch current \( I_D \). If an over-current flows through the switch, \( V_{CS} \) will exceed the threshold value of driver that is about 230 mV. Then the protection circuit is triggered and the gate voltage \( V_g \) becomes zero to turn the switch off, and the pin ERR goes high to indicate the fault.

When the switch T₁ has an open-circuit fault however the value of \( V_{CS} \) will be bigger than the threshold voltage and the gate driver of the switch will be turned off as before. The voltage \( V_{CS} \) in this mode is given by
The measured input signal, output signal and fault flag signal of switches T₁, and T₂ drivers in the H-bridge inverter circuit are provided in Figure 5.11, 5.12 and 5.13, which illustrate the healthy operation, over-current operation and switch T₂ open-circuit fault operation respectively. In Figure 5.11, all the switches operate in the normal condition and the fault flag signals in both drives are low voltage.

In Figure 5.12, the over-current goes through the switches, which results in the voltage \( V_{CS} \) exceeding the threshold value of the driver. After the switch T₁ and T₂ are turned on, their driver circuit detects the over-current status, then the drivers generate the fault flag signals in ERR pins and turn off the switches automatically. In Figure 5.13, switch T₁ operates under normal operating condition and switch T₂ operates in open-circuit fault condition. Therefore, the output signal of T₂ driver is almost zero and the fault flag signal is high level when it has an input pulse signal. These results show that the switch driver circuit can generate the fault flag signal in ERR pin to the motor controller in the case of an over-current fault or switch open-circuit fault occurs. When these faults are detected, the control signals for switches are also blocked to turn off the corresponding switches.
It should be noted here that this fault detection and identification method can be used for different levels of over-current faults by adjusting the resistance of the voltage divider, R3 and R4 in Figure 5.10. It should be emphasized here that the over-current fault may result from the switch short-circuit fault or the winding short-circuit fault due to the power supply short-circuit fault or the winding terminal short-circuit fault.

Figure 5.12 Switch T1, T2 driver input, output and ERR waveforms in over-current operation.

Figure 5.13 Switch T1, T2 driver input, output and ERR waveforms in T2 open-circuit fault operation.
5.4.3 Fault identification

As stated earlier, a fault flag signal of a switch driver may be the result of a switch short-circuit fault, or a winding short-circuit fault. In addition, in a practical system, the switch open-circuit fault and some electrical disturbances may also generate a fault flag signal in ERR pin of the driver circuit. Therefore, to identify the type of faults accurately, a fault identification algorithm is required in the controller for each switch.

The chart flow of the fault identification algorithm (that is related to the inverter circuit in Figure 5.6) is given in Figure 5.14. In the following paragraphs, the function of this algorithm is explained.

When the ERR flag of T1 is detected, all of the switches in the associated inverter are turned off first, and then T1 is turned on again. If the fault flag is not set again, however, the switches T1 and T2 are turned on to identify the winding short-circuit fault or the malfunction of the fault detection circuit. If the fault flag is reported either by switches T1 or T2, this will rectify the winding short-circuit fault. No fault flag signal in the drivers of switches T1 and T2 indicates the malfunction of the fault detection circuit. If the fault flag is set again after turning on T1, then T1 is turned off and T3 is turned on. If the phase current increases, a short-circuit fault in T4 will be identified. Otherwise T1 suffers an open-circuit fault.

From the above explanations, it can be seen that T1 open-circuit fault, T4 short circuit fault and the winding short-circuit fault can be identified by the algorithm. Similarly, T1 short-circuit fault can be identified by T4 fault identification program. In the second leg of the inverter circuit, T2 and T3 short-circuit faults can be identified by T3 and T2 fault identification programs.

It can be reported here that the winding short-circuit fault can be further identified by comparing the measured phase current and the predicted phase current values. If there is a significant difference between the measured and predicted currents, the winding short-circuit fault can be indicated. The proposed fault detection method has been verified using the real time waveforms obtained by an oscilloscope and the fault identification algorithm has been demonstrated using the simulation results of MPLAB IDE (Microchip Integrated Development Environment). However, it has not been included in the motor control program of this thesis.
Figure 5.14 The fault identification subroutine flow chart in the H-bridge inverter circuit.
5.5 **Software Development**

5.5.1 **Software development tools**

The motor controller software is written in C. The software development tools include MPLAB C30 compiler, MPLAB IDE (Integrated Development Environment) and MPLAB ICD2 (In-Circuit Debugger).

The MPLAB C30 C Compiler is a fully ANSI compliant product with standard libraries for the dsPIC Digital Signal Controller (DSC) architecture. It is a highly optimized tool and takes advantage of many dsPIC DSC architecture specific features to provide a platform for developing dsPIC DSC program. MPLAB IDE is a comprehensive editor, project manager and design desktop for application development of embedded designs using Microchip dsPIC DSCs [84-86].

MPLAB C30 compiles C source files, producing assembly language files. These compiler-generated files are assembled and linked with other object files and libraries to produce the final application program in executable COFF (Common Object File Format) or ELF (Executable and Linking Format) file formats. The COFF or ELF file can be loaded into the MPLAB IDE, where it can be tested and debugged. The MPLAB IDE also can convert the COFF or ELF file to Intel hex format which is suitable for loading into the command-line simulator or a device programmer.

The MPLAB ICD 2 module is a low-cost development tool that connects between the PC and the designer’s target board, allowing direct in-circuit debugging of a target dsPIC DSC. Programs can be executed in real time or single step, and watch variables established, break points set, memory read/writes accomplished and more. It can also be used as a development programmer for the microcontroller.

5.5.2 **Software structure**

The motor controller software is designed as a modular structure which includes main program, initiation and motor start subroutines, calculating desired phase output state subroutine, update phase output state subroutine, fault identification subroutine (as explained in section 5.4.3), fault remedial strategies subroutine and A/D interrupt service subroutine. The main program flow chart is shown in Figure 5.15 [87, 88].
Figure 5.15 Flow chart of the main program.
In the main program, the initiation of peripherals is to setup the operation mode and original values for A/D converter module, QEI (Quadrature Encoder Interface) module, input capture module, output module (including motor control PWM module), and the timer module.

It should be noted here that there is no INDEX pulse available during the starting of the motor drive. Therefore, after the program is started, the low frequency sinusoidal phase currents are provided to start the motor at low speed. Then as soon as the INDEX signal is detected, the program controls the phase current in each phase using the reference torque command.

### 5.5.3 Synchronization of the rotor position

In the real motor drive system, the encoder index signal does not align with the phase 1 back-EMF waveform. Therefore, in the software design, it is necessary to synchronize the rotor position counter value. The synchronization of the rotor position in a 4-pole motor drive is shown in Figure 5.16. There is a phase shift between the measured rotor position and the real rotor position values.

![Figure 5.16 Synchronization of the rotor positions in a 4-pole PM motor drive. (a) Phase 1 back-EMF waveform; (b) Encoder INDEX pulse; (c) Rotor position counter signals.](image)

### 5.5.4 Hysteresis current control implementation

As it was described previously, the output torque is proportional to the phase currents. In this research, hysteresis current control scheme is utilized in which the reference
current is compared with the measured phase current. This current control scheme works based on the following principles.

\[
\text{If } \Delta i = i_{\text{reference}} - i_{\text{measured}} > \frac{\Delta h}{2}, \quad V_{\text{phase}} = +V_{\text{DC}} \quad \text{(Positive supply)}
\]

\[
\text{If } \Delta i = i_{\text{reference}} - i_{\text{measured}} < \frac{\Delta h}{2}, \quad V_{\text{phase}} = -V_{\text{DC}} \quad \text{(Negative supply)} \quad (5.5)
\]

\[
\text{If } -\frac{\Delta h}{2} \leq \Delta i \leq \frac{\Delta h}{2}, \quad V_{\text{phase}} \text{ is not changed}
\]

Here \(i_{\text{reference}}\) and \(i_{\text{measured}}\) are the reference and the measured phase currents respectively; \(\Delta i\) is the current error; \(V_{\text{phase}}\) is the phase voltage, \(V_{\text{DC}}\) is the DC link supply voltage; and \(\Delta h\) is the hysteresis bandwidth.

Referring to the inverter circuit given in Figure 5.6, two inverter states can be defined: positive and negative states. In the inverter positive state, switches \(T_1\) and \(T_2\) are turned on and switches \(T_3\) and \(T_4\) are turned off. Similarly, in the inverter negative state, switches \(T_1\) and \(T_2\) are turned off and switches \(T_3\) and \(T_4\) are turned on. However, due to the turn-on and turn-off time delays as explained in Section 5.3.3, the inverter state can not be changed from a positive (or negative) state to a negative (or positive) state immediately to prevent shoot through fault. Therefore during the transition of the inverter states, all of the switches in the inverter should be turned off first. The duration of the inverter off-state is the dead time and is set as 3\(\mu s\) in this work.

The flow chart of a phase update state subroutine for an H-bridge inverter is shown in Figure 5.17. One of the measured waveforms of phase voltage and current is given in Figure 5.18.

As it is known the current commutation is linked to the rotor position and in the healthy operating mode, the reference current has a sinusoidal profile in this study. After the fault is detected, a suitable fault remedial strategy is applied. In the faulty operating modes, however the reference current waveforms diverts from the ideal sine wave reference current. Therefore, the reference current functions in faulty operating modes need to be integrated into the control algorithm, which are obtained using a look-up table approach which will be discussed in next section.
Figure 5.17 Flow chart of the phase 1 update state subroutine in a H-bridge inverter circuit.
5.6 Look-up Tables for Reference Current Calculation

As mentioned previously, in this study the unit back-EMF voltages of two three phase motor modules are sine waves and the phase differences between three phases within one motor module are $120^\circ$. In addition, it is assumed that the two motor modules are identical and are aligned. As it is known, the aim of the hysteresis current control is to keep the phase current to track the reference current, and the phase reference current is the product of the desired current peak value with the sinusoidal function. In the implementation, in order to increase the processing speed, the sinusoidal function is stored as a look-up table. Furthermore, if a fault occurs, the fault remedial strategy 3 may be applied to obtain the desired output torque with minimum torque ripple as in the healthy operation. The coefficients for the reference current calculation include sine wave functions, and multiplication and division calculations. Therefore, to increase the processing speed, the coefficient calculations are also implemented using look-up tables. The methods to obtain suitable look-up tables are explained below.

5.6.1 Look-up tables for one-phase open-circuit fault

As mentioned previously, in the healthy operation, the output torque of a dual module three phase motor drive can be given by equation (3.12). If one phase open-circuit fault occurs, the reference currents for fault remedial strategy 3 operations can be given by
equation (3.36). Using equations (3.12) and (3.36), the proportional coefficient of the reference current calculation can be achieved as

\[
i_j(\theta_e) = \frac{3 e_j(\theta_e)}{\sum_{j=1}^{6} e_j(\theta_e) - e_i^2(\theta_e)} \cdot I_m = K_{k,j}(\theta_e) \cdot I_m \quad j \neq k \tag{5.6}
\]

\[
K_{k,j}(\theta_e) = \frac{3 e_j(\theta_e)}{\sum_{j=1}^{6} e_j^2(\theta_e) - e_i^2(\theta_e)} \quad j = 1 \sim 6, \ j \neq k \tag{5.7}
\]

Here \(K_{k,j}(\theta_e)\) is the proportional coefficient of the reference current of phase \(j\) when phase \(k\) open-circuit occurs and \(K_{k,k}(\theta_e) = 0\).

If Phase 4 has an open-circuit fault, the reference current coefficients in the healthy phases can be given as

\[
K_{41}(\theta_e) = \frac{\sin \theta_e}{1 - \sin^2 \theta_e} = K_1(\theta_e) \tag{5.8}
\]

\[
K_{42}(\theta_e) = K_{45}(\theta_e) = \frac{\sin(\theta_e - 2\pi/3)}{1 - \sin^2 \theta_e} = K_2(\theta_e) \tag{5.9}
\]

\[
K_{43}(\theta_e) = K_{46}(\theta_e) = \frac{\sin(\theta_e - 4\pi/3)}{1 - \sin^2 \theta_e} = K_3(\theta_e) \tag{5.10}
\]

If Phase 5 has an open-circuit fault, the reference current coefficients in the healthy phases will be

\[
K_{51}(\theta_e) = K_{54}(\theta_e) = \frac{\sin \theta_e}{1 - \sin^2(\theta_e - 2\pi/3)} = K_3(\theta_e - 2\pi/3) \tag{5.11}
\]

\[
K_{52}(\theta_e) = \frac{\sin(\theta_e - 2\pi/3)}{1 - \sin^2(\theta_e - 2\pi/3)} = K_1(\theta_e - 2\pi/3) \tag{5.12}
\]

\[
K_{53}(\theta_e) = K_{56}(\theta_e) = \frac{\sin(\theta_e - 4\pi/3)}{1 - \sin^2(\theta_e - 2\pi/3)} = K_2(\theta_e - 2\pi/3) \tag{5.13}
\]
Similarly, the reference current coefficients for Phase 6 open-circuit fault can be expressed by

\[ K_{o1}(\theta_e) = K_{o4}(\theta_e) = K_2(\theta_e - 4\pi / 3) \]  
\[ K_{o2}(\theta_e) = K_{o5}(\theta_e) = K_3(\theta_e - 4\pi / 3) \]  
\[ K_{o3}(\theta_e) = K_1(\theta_e - 4\pi / 3) \]  

Here, \( K_1(\theta_e), K_2(\theta_e), \) and \( K_3(\theta_e) \) are the reference current coefficients for the fault remedial strategy 3 operation when one phase open-circuit fault occurs which is functions of electrical rotor position as shown in Figure 5.19. From the above equations, it can be seen that if the values of \( K_1(\theta_e), K_2(\theta_e) \) and \( K_3(\theta_e) \) are known, all of the remaining coefficients can easily be obtained by using the rotor position data.

![Figure 5.19 The reference current coefficient waveforms in the healthy phases for the fault remedial strategy 3 operation when the one phase open-circuit fault occurs in the motor drive.](image)

### 5.6.2 Look-up tables for two phase open-circuit fault

If two different phases of the motor drive have open-circuit faults, for the fault remedial strategy 3 operations, the reference currents and the proportional coefficient can be given by

\[ i_j(\theta_e) = \frac{3e_j(\theta_e)}{\sum_{j=1}^{6} e_j^2(\theta_e) - e_k^2(\theta_e) - e^2(\theta_e)} \cdot I_m = K_{kl}(\theta_e) \cdot I_m \quad j \neq k \]
Chapter 5 Implementation of Fault Tolerant PMAC Motor Drives with Redundancy

\[ K_{k+l}(\theta_e) = \frac{3e_j(\theta_e)}{\sum_{j=1}^{6} e_j^2(\theta_e) - e_k^2(\theta_e) - e_l^2(\theta_e)} \quad j = 1 \sim 6, j \neq k, l \]  \hspace{1cm} (5.18)

Here \( K_{k+l}(\theta_e) \) is the proportional coefficient of Phase \( j \) for the fault remedial strategy 3 operation when phase \( k \) and \( l \) have open-circuit faults.

If Phases 4 and 5 have open-circuit faults, the reference current coefficients in the healthy phases are

\[ K_{451}(\theta_e) = \frac{\sin \theta_e}{1 - \frac{\sin^2 \theta_e - \sin^2(\theta_e - 2\pi/3)}{3} \sin^2(\theta_e - 2\pi/3)} = K_4(\theta_e) \]  \hspace{1cm} (5.19)

\[ K_{452}(\theta_e) = \frac{\sin(\theta_e - 2\pi/3)}{1 - \frac{\sin^2 \theta_e - \sin^2(\theta_e - 2\pi/3)}{3} \sin^2(\theta_e - 2\pi/3)} = K_5(\theta_e) \]  \hspace{1cm} (5.20)

\[ K_{453}(\theta_e) = K_{456}(\theta_e) = \frac{\sin(\theta_e - 4\pi/3)}{1 - \frac{\sin^2 \theta_e - \sin^2(\theta_e - 2\pi/3)}{3} \sin^2(\theta_e - 2\pi/3)} = K_6(\theta_e) \]  \hspace{1cm} (5.21)

Similarly, if Phases 4 and 6 have open-circuit faults, the reference current coefficients in the healthy phases will be

\[ K_{461}(\theta_e) = K_5(\theta_e - 4\pi/3) \]  \hspace{1cm} (5.22)

\[ K_{462}(\theta_e) = K_{465}(\theta_e) = K_6(\theta_e - 4\pi/3) \]  \hspace{1cm} (5.23)

\[ K_{453}(\theta_e) = K_4(\theta_e - 4\pi/3) \]  \hspace{1cm} (5.24)

and, if Phases 5 and 6 have open-circuit faults, the reference current coefficients in the healthy phases are

\[ K_{561}(\theta_e) = K_{564}(\theta_e) = K_6(\theta_e - 2\pi/3) \]  \hspace{1cm} (5.25)

\[ K_{562}(\theta_e) = K_4(\theta_e - 2\pi/3) \]  \hspace{1cm} (5.26)

\[ K_{563}(\theta_e) = K_5(\theta_e - 2\pi/3) \]  \hspace{1cm} (5.27)

Here \( K_4(\theta_e) \), \( K_5(\theta_e) \), and \( K_6(\theta_e) \) are the reference current coefficients for the fault remedial strategy 3 operation when two different phase open-circuit fault occurs. As
these coefficients are functions of the rotor electrical position, they vary as in Figure 5.20 and are stored in the program memory as look-up tables.

![Figure 5.20 The reference current coefficient waveforms in the healthy phases for the fault remedial strategy 3 operation when two phase open-circuit fault occurs in the dual three phase fault tolerant motor drive.](image)

### 5.6.3 Reference current calculation for one phase short-circuit fault

If Phase $k$ has a short circuit fault, the reference currents in the healthy phases for fault remedial strategy 3 operations can be given by equation (3.37).

For example, if Phase 4 has a short-circuit fault, the reference currents in the healthy phases for fault remedial strategy 3 operation can be given by

\[
\begin{align*}
i_1(\theta_e) &= K_1(\theta_e) \cdot [I_m + \frac{1}{3} \sin \theta_e i_4(\theta_e)] \\
i_2(\theta_e) &= i_5(\theta_e) = K_2(\theta_e) \cdot [I_m + \frac{1}{3} \sin \theta_e i_4(\theta_e)] \\
i_3(\theta_e) &= i_6(\theta_e) = K_3(\theta_e) \cdot [I_m + \frac{1}{3} \sin \theta_e i_4(\theta_e)]
\end{align*}
\]

(5.28) (5.29) (5.30)

Where the coefficients $K_1(\theta_e), K_2(\theta_e)$ and $K_3(\theta_e)$ are calculated using equations (5.8), (5.9) and (5.10), and $i_4(\theta_e)$ can be given by

\[
i_4(\theta_e) = \frac{k_e \omega_m}{\sqrt{R^2 + (N_p \omega_m L)^2}} \sin[\theta_e - \tan^{-1}(N_p \omega_m L / R)]
\]

(5.31)
From equation (5.31), it can be seen that the peak short-circuit current value and the phase angle are the function of rotor speed, which can be measured in advance. The measured and the calculated phase 4 short-circuit current and the phase difference between this current and the back-EMF voltage of the dual three phase 48-pole motor drive are shown in Figure 5.21. It can be seen in this figure that when the rotor speed is higher than 200 rpm, the peak value of the short-circuit current nearly remains constant of about 16 A. This is due to the fact that in higher rotor speeds the winding reactance is much greater than its resistance, and hence the impedance of the winding becomes proportional to the rotor speed, similar to the relationship between the back-EMF voltage and the rotor speed. In the controller design, these curves can be expressed in lookup tables and stored in the program memory of the motor controller.

![Figure 5.21 Measured and calculated short-circuit fault features of phase 4 in the 48-pole fault tolerant motor drive as a function of the rotor speed. Short-circuit peak current (top) and phase difference between short-circuit current and back-EMF voltage (bottom).](image-url)
5.7 Conclusions

This chapter developed the hardware and the software of the dual three phase fault tolerant PMAC motor drive control system. Each motor module accommodated a separate motor control system. The hardware of the control system includes one controller board, one parameter measurement board and three inverter boards. In order to decrease the complexity and the cost, the Microchip dsPIC DSC (Digital Signal Controller) was selected to control the motor module. A functional diagram of the main motor control system is provided in Figure 5.22, which includes six separate functions. The four functions outside the dash line area have been implemented in the real time motor control.

![Figure 5.22 A functional diagram of the motor control system.](image)

The fault detection and identification is the significant prerequisite before various fault remedial strategies can be applied. The winding open-circuit fault is easy to be identified by comparing the measured phase current with the predicted phase current. However, it is difficult to detect the switch open-circuit fault, short-circuit fault and winding short-circuit fault. The previous studies usually utilize multiple on-state voltage sensors for each switch to detect switch faults which may increase the cost of the entire motor drive significantly.

The complete inverter circuit including driver circuits, which possesses switch on-state voltage detection function, has been developed. By combing the fault identification algorithm, the practical fault detection and identification method for switch open-circuit...
fault, switch short-circuit fault and winding short-circuit fault was developed. The two main advantages of the fault detection and identification method are fast response to the faults to protect the switches and cost effectiveness of the motor drive control system due to the absence of on-state sensors. In addition, by adjusting the resistance of the voltage divider in Figure 5.10, the fault detection and identification method can easily be used in different level of over-current fault detection. The proposed fault detection method has been verified by the real tests, and the fault identification algorithm has only been tested by the simulation study.

In the fault tolerant PMAC motor drive control system, the hysteresis current control scheme is implemented to regular the phase current. Since various faults may occur in different phase and different switch and multiple faults may occur simultaneously, the calculation of reference currents for the fault remedial strategy 3 operations is very complicated and requires significant processing power. Therefore, in order to increase the real time control performance, the coefficients of the reference current calculations are implemented using look-up tables. By analysing the relationships of the coefficients under different faults, the simplified lookup tables were established. The reference current calculation method for fault remedial strategy 3 operation is implemented, which accommodates the lookup tables to reduce memory requirement and increase speed.

The next chapter will provide the experimental verification of the proposed motor control algorithm.
Chapter 6

Experimental Verification of Fault Tolerant PMAC Motor Drives with Redundancy

6.1 Introduction of the Experimental Tests

In order to verify the analytical and simulation results and demonstrate the flexibility of the proposed remedial strategies, two setups of the dual fault tolerant brushless PMAC motor drive were established. Since the hardware and software of the motor control system were described in previous chapter, this chapter will provide the procedures and results of the experiments.

The principal block diagrams of the experimental setups are shown in Figure 6.1 and 6.2, and corresponding photos are shown in Figure 6.3 and 6.4. As it can be seen in these figures, both motor setups had identical motor control hardware, but the mechanical loading sections were different. In addition, the 48-pole exterior rotor motor setup had two identical motor modules, while the 4-pole interior rotor motor setup did not. The software of two motor setups was also slightly different due to the difference of the pole number of the motor modules. It should be mentioned here that, the phase currents of two motor modules and the load current and voltage were monitored by LABVIEW based data acquisition system where eight analog signals were measured simultaneously. The measured data were then saved in the computer for off-line data processing.

Since a high-bandwidth in-line torque transducer was not available, the output electromagnetic torque of the motor drives in this thesis was calculated using measured phase currents and back-EMF voltage waveforms. As described in Chapter 4, the motor back-EMF voltages in both motor drive setups have sinusoidal waveforms and are a function of the rotor position. In addition, when a motor drive is running under healthy or faulty conditions, the phase currents are always controlled to be in phase with the
corresponding back-EMF waveforms. Therefore, to calculate the electromagnetic torque output, the unit back-EMF waveforms are obtained using the measured current waveforms. Then the electromagnetic torque and corresponding torque ripple values can be calculated using equations (2.17) and (2.18) respectively.

As mentioned previously, in both experimental setups, Phases 1, 2 and 3 denote the three phases of the motor module 1, and Phases 4, 5 and 6 are the three phases of the motor module 2. As also mentioned earlier, since the motor modules were also physically aligned in each setup, Phases 1 and 4, Phases 2 and 5, and Phases 3 and 6 are in phase, which are named in the text as “two same phase”. Similarly, Phases 1 and 2, Phases 1 and 3, or Phases 1 and 5 are named as “two different phase” since their back-EMF voltages are out of phase.

**Figure 6.1** Block diagram of the 48-pole dual motor module fault tolerant PMAC drive experimental setup

**Figure 6.2** Block diagram of the 4-pole dual motor module fault tolerant PMAC drive experimental setup
Chapter 6 Experimental Verification of Fault Tolerant PMAC Motor Drives with Redundancy

Figure 6.3 The photo of the 48-pole dual motor module drive experimental setup

Figure 6.4 The photo of the 4-pole dual motor module drive experimental setup.
The experimental tests performed in this chapter include healthy operation, one phase open-circuit and short-circuit faults, two different phase open-circuit faults, two same phase open-circuit faults, and one motor completely open-circuit fault experiments. The experimental results without and with the fault remedial strategies will also be provided and compared in this chapter. In addition, the efficiency test results of the motor drive under different operating conditions will be given.

### 6.2 Healthy Operation Experiment

The aim of this first experiment is to find out whether the hardware and software of the motor control system operate correctly without any fault. In order to avoid overloading of the motor modules, the DC link power supplies of the six inverters were kept at 20 V and the peak value of the reference currents were 3.45 A for the 48-pole motor drive and 3.2 A for the 4-pole motor drive. The load resistance was 12.3 Ω in both motor drive setups. The instantaneous values of the motor drive setup were measured at 5 kHz sampling speed. Figure 6.5 and Figure 6.6 provides a set of measured phase currents and corresponding electromagnetic torque waveforms of the 48-pole and the 4-pole dual three-phase fault tolerant PMAC motor drives.

It can be seen in Figure 6.5 that the average output electromagnetic torque of the dual 48-pole motor drive is 9.0 Nm, and the estimated torque ripple is 19%. As given previously in Figure 4.14, the similar results were obtained in the corresponding simulation study (9.12 Nm of average torque and 12.5% of the torque ripple).

Figure 6.6 illustrates the similar test results as in Figure 6.5 for the 4-pole motor setup. The total electromagnetic torque was calculated as 0.61 Nm with a torque ripple of 21%. As mentioned previously, since two motor modules in this setup are not identical, their electromagnetic torque values are also different as shown in the figure.

The presence of such high torque ripples in the healthy operating state is primarily due to the limitation of controller word length, the resolutions of the encoder and the current sensors, and also measurement setup. In addition, there is an expected source of ripple in the current waveforms as the hysteresis current control scheme can not eliminate the error of the reference current. In conclusion, it can be noted here that the torque ripples
can be reduced significantly by addressing the above limitations both in the hardware and the software level.

Figure 6.5 Test results of the dual 48-pole motor module drive under healthy operation. Measured motor 2 phase current waveforms (top) and estimated torque waveforms (bottom).

Figure 6.6 Test results of the dual 4-pole motor module drive under healthy operation. Measured motor 2 phase current waveforms (top) and estimated torque waveforms (bottom).
6.3 One Phase Open-Circuit Fault Operation Experiment

The aim of this experiment is to demonstrate the effects of the one phase open-circuit fault on phase currents, output electromagnetic torque and torque ripple, with and without the fault remedial strategies. In order to prove the flexibility of the proposed fault remedial strategies, the experiments are performed in both motor drive setups. The set values of the experimental tests are similar to the values in Section 6.2.

6.3.1 Four-pole motor drive experimental results

The dual 4-pole motor drive results with one phase open-circuit fault (Phase 4) operation are given in the following three figures (Figures 6.7, 6.8 and 6.9). As mentioned previously since the back-EMF constants of the two motor modules are different, it is difficult to adopt any fault remedial strategy to the entire motor drive. Therefore, the fault remedial strategies are only applied to motor module 2 and the motor module 1 is kept under healthy condition.

In Figure 6.7, no fault remedial strategy was adopted after the fault occurred in Phase 4 at 1000 ms. As a result of the fault, the output torque of motor module 2 was reduced from 0.45 Nm to 0.3 Nm which resulted in the decrease in the total output torque of the motor drive from 0.61 Nm to 0.46 Nm. The torque ripple in motor module 2 was increased from 17% to 116% which resulted in a large vibration in the motor drive.

Figure 6.8 illustrates the experimental results under the fault remedial strategy 1 in motor module 2 after one phase open-circuit fault occurred in Phase 4 at 1000 ms. From the calculated electromagnetic torque waveforms of motor module 2, it can be seen that although the average output torque of motor module 2 was increased to the healthy value of 0.45 Nm, the peak-to-peak torque ripple (123%) was similar to the value without the fault remedial strategy as described in Figure 6.7.

Figure 6.9 is given to describe the performance of the motor drive under the fault remedial strategy 3. The results indicate that the torque ripple of the motor module 2 is 17% which is the same value as in the healthy operation. In this test, the total electromagnetic output torque and the torque ripple of the motor drive are 0.61 Nm and 22% respectively, which are also the similar results as in the healthy operation.
Figure 6.7 Test results of the dual 4-pole motor module drive under Phase 4 open-circuit fault condition without fault remedial strategy: measured motor 2 phase current waveforms (top) and the calculated electromagnetic torque waveforms (bottom).

Figure 6.8 Dual 4-pole motor drive test results in one phase open-circuit fault operation. Remedial strategy 1 was adopted in the motor module 2 after the fault. Measured motor module 2 phase current waveforms (top) and the calculated electromagnetic torque waveforms (bottom).
Figure 6.9 Dual 4-pole motor drive experiment results in one phase open-circuit fault operation. Fault remedial strategy 3 was adopted in the motor module 2 after the fault. Measured motor module 2 phase current waveforms (top) and the estimated torque waveforms (bottom).

6.3.2 Dual 48-pole motor drive experimental results

Dual 48-pole motor drive experiment results under one phase open-circuit fault operation (Phase 4) are described in the Figures 6.10-6.13. In Figure 6.10, the results are given without the fault remedial strategy after the fault occurred in Phase 4 of the motor module 2. It can be seen in the torque curves that under this mode of operation, the output torque is reduced to 7.68 Nm, which is about the 5/6 of the torque of 9.0 Nm in the healthy operation. In addition, the torque ripple increased significantly after the fault (from 19% in healthy operation to 58% under the fault). Therefore, it is necessary to adopt suitable fault remedial strategy to compensate the torque loss and to decrease the torque ripple. The cleaner phase current waveforms after the fault occurred is due to the disappearance of the small mutual inductance existed in the practical motor module.

In Figure 6.11, the fault remedial strategy 1 was applied in two motor modules after the open-circuit fault occurred at 1000 ms. The peak value of the reference currents in the remaining five healthy phases was 1.2 times of the value in the healthy operation. The
waveforms of the motor drive output torques indicates that the average value of the electromagnetic output torque is kept almost the same value as in the healthy operation after the remedial strategy 1 is adopted. However, the torque ripple value after fault increases to 56%, which is nearly equal to the torque ripple value under no fault remedial strategy operation. This conclusion is consistent with the analytical results presented in Sections 3.4.1 and 3.5.2.

Figure 6.12 is given to illustrate the operation of the motor drive when the fault remedial strategy 3 was adopted in both motor modules after the open-circuit fault occurred at 1000 ms. From the figure, it can be seen that the output torque and the torque ripple values of the motor drive under the healthy operation, and under the faulty operation while the fault remedial strategy 3 adopted remained the same. However, the peak value of the current in Phase 1 of motor module 1 increased 1.5 times the value in the healthy operation, which results in large copper loss in this phase.

![Figure 6.10 Test results of the dual 48-pole motor module drive when one phase open-circuit fault occurred in Phase 4 at 1000ms and no fault remedial strategy was adopted. Measured motor 2 phase current waveforms (top) and the estimated electromagnetic torque waveforms (bottom).](image-url)
Figure 6.11 Test results of the dual 48-pole motor module drive when one phase open-circuit fault occurred in Phase 4 at 1000ms and the fault remedial strategy 1 was adopted. Measured motor module 1 phase current waveforms (top), measured motor module 2 phase current waveforms (middle), and the calculated torque waveforms (bottom).

Figure 6.13 illustrates experimental results that are similar to the operation conditions in Figure 6.12. However, the fault remedial strategy 2 was applied to the drive under this test. It can be seen from the current waveforms in the motor module 1 that Phase 1 current was doubled after the open-circuit fault. Due to the fault remedial strategy adopted, the output torque and the torque ripple remained almost same as in the healthy operation. From the measured phase current waveforms it can be concluded that the maximum copper loss appears in Phase 1 and it increases 3.8 times compared to the healthy case.
Figure 6.12 Dual 48-pole motor drive test results under one phase open-circuit fault operation, the fault remedial strategy 3 was adopted after the fault in Phase 4: measured motor module 1 phase current waveforms (top), measured motor module 2 phase current waveforms (middle), and the calculated torque waveforms (bottom).

6.3.3 Comparison of the experimental results

Table 6.1 and Table 6.2 summarize the experimental results under different operating modes in single and dual motor module fault tolerant drives respectively in which the calculated average output electromagnetic torque, the torque ripple, the relative total copper loss and the relative phase maximum copper loss values are provided. The simulated values (in square brackets) obtained in Chapter 4 and the ideal (analytical) values (within brackets) obtained in Chapter 3 are also presented in the tables for comparison. From these tables the following conclusions can be obtained.
Figure 6.13 Dual 48-pole motor drive test results in one phase open-circuit fault operation, the fault remedial strategy 2 was adopted after the fault in Phase 4 at 1000ms: measured motor 1 phase current waveforms (top) and the calculated electromagnetic torque waveforms (bottom).

Table 6.1 Feature comparison of different fault remedial strategies for one phase open-circuit fault operation in 4-pole single motor module fault tolerant drive

<table>
<thead>
<tr>
<th>Open-circuit fault operating modes</th>
<th>Tested average output torque (Nm)</th>
<th>Tested (ideal) peak-to-peak torque ripple (%)</th>
<th>Tested (ideal) relative total copper loss</th>
<th>Tested (ideal) relative phase maximum copper loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy operation</td>
<td>0.45</td>
<td>17 (0)</td>
<td>1.0 (1.0)</td>
<td>1.0 (1.0)</td>
</tr>
<tr>
<td>No fault remedial strategy adopted</td>
<td>0.3</td>
<td>116 (100)</td>
<td>0.67 (0.67)</td>
<td>0.99 (1.0)</td>
</tr>
<tr>
<td>Fault remedial strategy 1</td>
<td>0.45</td>
<td>123 (100)</td>
<td>1.56 (1.5)</td>
<td>2.33 (2.25)</td>
</tr>
<tr>
<td>Fault remedial strategy 3</td>
<td>0.45</td>
<td>17.1 (0)</td>
<td>1.8 (1.73)</td>
<td>2.7 (2.6)</td>
</tr>
</tbody>
</table>

- One phase open-circuit fault both in single and dual fault tolerant motor drives result in significant reduction in the electromagnetic output torque and increase in the torque ripple. In addition, the torque ripple in the single motor module drive is larger than in the dual motor module drive. Thus it is necessary to adopt suitable fault remedial strategy to compensate the torque loss and to decrease the torque ripple.
Table 6.2 Feature comparison of different fault remedial strategies under one phase open-circuit fault operation in 48-pole dual motor module fault tolerant drive

<table>
<thead>
<tr>
<th>Open-circuit fault operating modes</th>
<th>Tested and [simulated] average output torque (Nm)</th>
<th>Tested, [simulated] and (ideal) torque ripple (%)</th>
<th>Tested, [simulated] and (ideal) relative total copper loss</th>
<th>Tested, [simulated] and (ideal) relative phase maximum copper loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy operation</td>
<td>9.01 [9.12]</td>
<td>19 [12.5] (0)</td>
<td>1.0 [1.0]</td>
<td>1.0 [1.0]</td>
</tr>
<tr>
<td>No fault remedial strategy adopted</td>
<td>7.68 [7.61]</td>
<td>58 [52.8] (40)</td>
<td>0.89 [0.84] (0.83)</td>
<td>1.0 [1.0] (1.0)</td>
</tr>
<tr>
<td>Fault remedial strategy 1</td>
<td>9.00 [9.12]</td>
<td>56 [50.2] (40)</td>
<td>1.2 [1.2] (1.2)</td>
<td>1.37 [1.48] (1.44)</td>
</tr>
<tr>
<td>Fault remedial strategy 3</td>
<td>9.09 [9.12]</td>
<td>18 [13] (0)</td>
<td>1.23 [1.23] (1.22)</td>
<td>1.77 [1.84] (1.84)</td>
</tr>
</tbody>
</table>

- The fault remedial strategy 1 can be implemented easily, which can provide the rated output torque under the one phase open-circuit fault condition. However, the strategy can produce large torque ripple that can cause large vibration in the motor drive. Therefore, fault remedial strategy 1 is not suitable for the applications where the torque ripple is concerned.

- For dual fault tolerant motor drive with identical motor modules, the fault remedial strategy 2 can be adopted to obtain the rated torque and almost similar value of the torque ripple as in the healthy operation. However, this fault remedial strategy results in the highest phase maximum copper loss (four times the healthy operation).

- In the case of one phase open-circuit fault, the fault remedial strategy 3 can provide the same output torque as in the healthy operation both in single and dual motor module fault tolerant drives. In this operating mode, only a modest increase in copper loss was observed. This fault remedial strategy can be adopted by the dual motor drives with identical or different parameter motor modules.

- The results presented in the tables have verified the simulation and analytical studies described in Chapters 4 and 3.
6.4 Two Different Phase Open-Circuit Fault Experiment

6.4.1 Explanation of the experiment

The two different phase open-circuit fault means that the winding open-circuit fault occurs in two different phases of the motor drive. It is assumed in this test that the open-circuit fault occurred in Phases 4 and 5 of the motor module 2 of the dual 48-pole motor drive at 1000 ms. The fault was simulated by disconnecting the terminals of Phases 4 and 5 windings while the motor drive was running, and then the results were obtained with and without the fault remedial strategies. The load, the DC link voltage of the inverter and the peak value of the reference current under the healthy operation were same as in the previous tests.

6.4.2 Analysis and comparison of the experimental results

Figure 6.14 is given to illustrate the electromagnetic torque waveforms without a fault remedial strategy. From the torque curves, it can be concluded that the torque was reduced to 6.11 Nm (9.01 Nm in the healthy operation), and the torque ripple increased to 71% in the faulty operation. In addition, the steady rotor speed was decreased from 86 rpm to 45 rpm after the fault. Therefore, these results indicate the need to compensate the torque loss and to reduce the torque ripple.

![Figure 6.14 Test electromagnetic torque waveforms in the dual 48-pole motor drive under two different phase open-circuit fault operation. No fault remedial strategy was adopted after the fault occurred in Phases 4 and 5 at 1000 ms.](image)

Figure 6.15 shows the test results of the fault remedial strategy 1 applied to two motor modules after the open-circuit fault. In this test, the peak value of the reference currents in the healthy phases was 1.5 times of the current value in the healthy operation. The
output torque waveforms of the motor drive indicate that the average torque in this mode is same as in the healthy operation after fault remedial strategy 1 was adopted. The torque ripple in this mode was found to be 70%, which is nearly equal to the value in Figure 6.14. Therefore, fault remedial strategy 1 is not suitable for the applications where lower torque ripple is required.

Figure 6.15 Dual 48-pole motor drive experiment results in two different phase open-circuit fault operation with the fault remedial strategy 1. Measured motor module 1 phase current waveforms (top), measured motor module 2 phase current waveforms (middle), and the estimated torque waveforms (bottom)

Figure 6.16 shows the operation in which the fault remedial strategy 2 was adopted in the motor module 1 after the open-circuit fault occurred in Phases 4 and 5 at 1000 ms. From the current waveforms it can be seen that the currents of Phases 1 and 2 in motor module 1 are doubled (which increases the copper losses 4 times) after the open-circuit
fault while the currents of Phases 3 and 6 remains the same. The torque output (9.17 Nm) and the torque ripple (22%) are similar to the healthy operation levels.

Figure 6.17 illustrates the measured results after open-circuit fault in Phases 4 and 5 at 1000 ms and the fault remedial strategy 3 was adopted. As can be observed in this test, the phase currents are not sinusoidal signals after this fault remedial strategy is applied, and since the motor modules were aligned in the setup, the currents of Phases 3 and 6 are almost the same. Similar to the fault remedial strategy 2 in the previous test, the torque (9.12 Nm) and torque ripple (23%) values are similar as in the healthy operation.

Figure 6.16 Dual 48-pole motor drive experiment results in two different phase open-circuit fault operation. The remedial strategy 2 was adopted after fault occurred in phase 4 and 5 at 1000 ms: The measured motor 1 phase current waveforms (top), measured motor 2 phase current waveforms (middle), and the estimated torque waveforms (bottom)
Table 6.3 is given to provide a summary and a comparison for the tests performed in this section. Similar to the previous tables, the simulation and analytical results were also included in the table. The results demonstrate a close correlation between the measured results and the simulation and analytical results. In addition, it was found that fault remedial strategy 3 and fault remedial strategy 2 are effective remedial strategies as they can obtain the similar output torque and lower torque ripple after two different phase open-circuit faults. The total copper loss and maximum phase copper loss under fault remedial strategy 3 increases slightly compared to the minimum copper loss value obtained in the fault remedial strategy 1.
From the table it can be seen that the experimental torque ripple values under faults and with fault remedial strategies are slightly higher than the values under the healthy operation. It is believed that this is due to the error in the alignment of two motor modules which results in a degree of phase difference between the back-EMF voltages of the same phases of two motor modules.

<table>
<thead>
<tr>
<th>Open-circuit fault operating modes</th>
<th>Estimated by measurement [simulated] average output torque (Nm)</th>
<th>Estimated by measurement, [simulated] and (ideal) torque ripple (%)</th>
<th>Estimated by measurement, [simulated] and (ideal) relative total copper loss</th>
<th>Estimated by measurement, [simulated] and (ideal) relative maximum phase copper loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy operation</td>
<td>9.01 [9.12]</td>
<td>19 [12.5]</td>
<td>1.0 [1.0]</td>
<td>1.0 [1.0]</td>
</tr>
<tr>
<td>No fault remedial strategy adopted</td>
<td>6.11 [6.1]</td>
<td>71 [62.4]</td>
<td>0.72 [0.69]</td>
<td>1.01 [1.0]</td>
</tr>
</tbody>
</table>

### 6.5 Two Same Phase Open-Circuit Fault Experiment

As defined in Section 6.1, Phases 1 and 4, Phases 2 and 5, Phases 3 and 6 are considered as two same phase at the motor drive. In this section, it is assumed that the two same phase open-circuit faults occur in Phase 1 of the motor module 1 and Phase 4 of the motor module 2.

As discussed previously, the fault remedial strategy 2 can not be applied to this fault as the current of the same phase of the second motor module needs to be doubled. In addition, the fault remedial strategy 1 which will result in significant torque ripple is also not suitable for this fault. Therefore, only the fault remedial strategy 3 is considered
in this fault. Since this fault remedial strategy can be adopted independently in two motor modules, it is not necessary to have two identical motor modules in the drive. Thus the experiments presented here were performed using both the dual 48-pole and the 4-pole three-phase fault tolerant PMAC motor drives. In the tests, while the motor drive operating in the healthy mode, the terminals of Phases 1 and 4 windings were disconnected to simulate two same phase open-circuit fault. The operating conditions such as the load, the DC link voltage of the inverter, and the reference current peak value in healthy operation are same as in the previous sections, and the experimental results are provided in Figure 6.18-6.21.

Figure 6.18 provides the calculated output torque curves of the dual three phase 48-pole motor drive where the two same phase open-circuit fault occurs at 1000 ms, and no fault remedial strategy was adopted. These results demonstrate that the torque is reduced to 6.1 Nm after the fault. In addition, it can be concluded that since the motor modules are in phase, the same phase fault generates large torque loss in the same time which develops large torque ripples of 116%. This result is consistent with the analytical conclusion presented in Table 3.3.

In Figure 6.19, the results are given after the fault remedial strategy 3 was applied to the two motor modules of the dual 48-pole motor drive. Since the two motor modules are identical in this setup, the phase currents and the torque waveforms of two motors are similar. The results illustrate that after the fault remedial strategy 3, the motor drive develops similar output torque and torque ripple values as in the healthy case, which is summarized in Table 6.4.
Figure 6.19 Experimental results of the dual 48-pole motor drive when the two same phase open-circuit fault occurs in Phases 1 and 4, and the fault remedial strategy 3 is adopted: measured motor 1 phase current waveforms (top), measured motor 2 phase current waveforms (middle), and the estimated electromagnetic torque waveforms (bottom).

Figure 6.20 and 6.21 are provided from the test results of the 4-pole motor drive. The results in Figure 6.20 show the operation without the fault remedial strategy. The estimated electromagnetic torque curves indicate that the total output torque is reduced significantly after the fault, which also develops a large torque ripple of 119%.

In Figure 6.21, the results illustrate the performance of the drive after the fault remedial strategy 3 is applied to each motor module. As the motor modules are not identical in the motor drive, the motor module 1 has a relatively higher current ripple which is a result of the lower phase inductance of this motor module (the inductance values of
Figure 6.20 Estimated torque waveforms of the dual 4-pole motor drive when the two same phase open-circuit fault occurs in Phases 1 and 4 without the fault remedial strategy after fault.

Figure 6.21 Experimental results of the dual 4-pole motor drive when the two same phase open-circuit fault occurs in Phases 1 and 4 and the fault remedial strategy 3 is adopted: measured motor 1 phase current waveforms (top), measured motor 2 phase current waveforms (middle), and the estimated electromagnetic torque waveforms (bottom).
motor module 1 and module 2 are 0.46 mH and 2.1 mH respectively). After the fault remedial strategy 3 is applied to motor 1 and motor 2, the output torque curves provide similar results as in the healthy operation, which results a similar total output torque in the motor drive.

Table 6.4 provides the summary of the test results in this section. It can be concluded from the results that two same phase open-circuit fault is a serious type of fault in the dual fault tolerant motor drive which produces significant torque ripple, and the fault remedial strategy 3 is the most suitable remedial strategy. This fault remedial strategy not only compensates the torque loss but also reduces the torque ripple.

<table>
<thead>
<tr>
<th>Motor drive</th>
<th>Operating modes</th>
<th>Tested and [simulated] average output torque (Nm)</th>
<th>Tested, [simulated] and (ideal) torque ripple (%)</th>
<th>Tested, [simulated] and (ideal) relative total copper loss</th>
<th>Tested, [simulated] and (ideal) relative phase maximum copper loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual 48-pole motor drive</td>
<td>Healthy operation</td>
<td>9.01 [9.12]</td>
<td>19 [12.5] (0)</td>
<td>1.0 [1.0]</td>
<td>1.0 [1.0]</td>
</tr>
<tr>
<td></td>
<td>No fault remedial strategy adopted</td>
<td>6.11 [6.1]</td>
<td>116 [113] (100)</td>
<td>0.74 [0.71] (0.67)</td>
<td>1.0 [1.0] (1.0)</td>
</tr>
<tr>
<td></td>
<td>Fault remedial strategy 3</td>
<td>8.99 [9.13]</td>
<td>20 [12.2] (0)</td>
<td>1.7 [1.74] (1.73)</td>
<td>2.66 [2.63] (2.6)</td>
</tr>
<tr>
<td>Dual 4-pole motor drive</td>
<td>Healthy operation</td>
<td>0.61 (0)</td>
<td>21 (0)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>No fault remedial strategy adopted</td>
<td>0.41 (100)</td>
<td>119 (0.67)</td>
<td>0.68 (0.67)</td>
<td>0.96 (1.0)</td>
</tr>
<tr>
<td></td>
<td>Fault remedial strategy 3</td>
<td>0.62 (100)</td>
<td>18 (1.73)</td>
<td>1.85 (1.73)</td>
<td>2.75 (2.6)</td>
</tr>
</tbody>
</table>

**6.6 One Motor Complete Open-Circuit Fault Experiment**

If all the phases in one of the motor module have open-circuit fault, this motor suffers one motor complete open-circuit fault. The power supply failure or the motor controller failure also develops this type of fault. In a single three phase fault tolerant motor drive, such fault results in the complete loss of the motor drive. However, in multiple module type of drives the system provides redundancy and if suitable fault remedial strategy is
adopted, the motor drive system can continue to provide even rated or nearly rated output torque as in the healthy operation.

The experiment to demonstrate the behavior of this fault is performed in the dual three phase fault tolerant motor drive accommodated the 48-pole PMAC motor modules. Since two motor modules are identical, if motor module 2 has a complete open-circuit fault, the total output torque will be a half value of the healthy operation. If the phase currents in motor module 1 are increased proportionally (two times of the healthy phase currents), the motor drive can generate rated output torque. It can be demonstrated that the phase current waveforms of three fault remedial strategies are the same. Figure 6.22 presents the experimental results of one motor complete open-circuit fault operation of the 48-pole PMAC motor drive.

As shown in the figure, two motor modules run normally until the instant of the fault at 1000 ms. After the motor module 2 has an open-circuit fault at 1000 ms, however the phase currents of the motor module 1 are doubled. The post-fault values of the torque and torque ripple were 8.93 Nm and 21% respectively which is similar to the healthy results. Using the phase current values, the relative total copper loss was estimated as 1.99 after the fault remedial strategy is adopted which is almost the same as the ideal value of 2.0, obtained from the analytical investigation. In addition, the relative maximum phase copper loss was calculated as 4.2 that is also very close to the ideal value of 4.0.

6.7 One Phase Short-Circuit Fault Experiment

The winding short-circuit fault may be in the form of a winding terminal short-circuit or a winding turn-to-turn short-circuit. For simplicity in this study one phase short-circuit fault was obtained by short circuiting the winding terminals.

As stated previously, the tests were performed in the dual 48-pole motor drive setup with a DC link voltage of 20 V and a peak reference current of 3.45 A. In the experiment, the two terminals of phase 4 winding were shorted to simulate the one phase short-circuit fault, and the results without fault remedial strategy is given in Figure 6.23.
Chapter 6 Experimental Verification of Fault Tolerant PMAC Motor Drives with Redundancy

Figure 6.22 The experimental results under one complete motor module open-circuit fault in the dual 48-pole motor drive with fault remedial strategy 1 after fault: (a) Measured motor 1 phase currents, (b) Measured motor 2 phase currents, (c) Estimated motor 1 torque, (d) Estimated motor 2 and total torques.
Figure 6.23 Experimental result of the dual 48-pole motor drive when one phase short-circuit fault occurs in phase 4 and no fault remedial strategy is adopted: (a) Measured motor 1 phase currents, (b) Measured motor 2 phase currents, (c) Estimated motor 2 phase torques, (d) Estimated motor drive torques.
The experimental results indicate that the peak short-circuit current in phase 4 is about 5.3 A which is higher than the peak phase current value of 3.45 A in the healthy phases, and the rotor speed is reduced from 83 rpm to 32 rpm. In addition, the estimated phase 4 torque waveform illustrates that the short-circuit current generates significant amount of negative torque which reduces the total torque from 9.0 Nm to 5.38 Nm and increases the peak-to-peak torque ripple from 19% to 172 %. These experimental results have verified the simulation studies in Chapter 4.

As can be observed from these results, the one phase short-circuit fault is a serious type of fault in the motor drive and post-fault actions are required to compensate the torque loss and to reduce the torque ripple. If the windings of the motor and the inverters can handle higher currents, the fault remedial strategy 3 can be applied.

Figure 6.24 provides the experiment results of one phase short-circuit fault operation after a fault remedial strategy 3 is adopted. From the figure it can be calculated that the total output torque of the motor drive has risen to 8.72 Nm which is very close to the healthy operation torque of 9.0 Nm, and the torque ripple has reduced to 38%. These results have demonstrated the simulation results provided in Figure 4.26 of Chapter 4. The experiment and simulation results have proven the validity of the fault remedial strategy 3 under the one phase short-circuit fault. From Figure 6.24 it also can be seen that the short-circuit fault current peak value in phase 4 reaches to 10.5 A, which generate significant drag torque in the motor drive, which can be compensated by increasing the currents in the healthy phases. However, it should be noted that this increases the copper losses to 2.84 times the healthy operation value.

Figure 6.25 illustrates the relationship between the measured short-circuit current and the estimated phase drag torque (its direction is opposite to the normal torque) in four different rotor speeds, which are also compared to the calculated values from the equivalent circuit. The results show very good correlation between the measured and the calculated values. The calculated curves also demonstrated that at higher rotor speeds the short-circuit current remains constant and the drag torque is reduced. Hence, it can be concluded that the effect of the short-circuit fault on the output torque at higher rotor speeds is not significant, which has been demonstrated by the simulation results provided in Chapter 4.
Figure 6.24 Experimental result waveforms of dual 48-pole motor drive when short-circuit fault occurs in phase 4 and fault remedial strategy 3 is adopted. Measured motor module 1 phase current waveforms (top), measured motor module 2 phase current waveforms (middle), and the estimated torque waveforms (bottom).

Figure 6.25 Relationship between the short-circuit current (peak values) and the drag torque as a function of the rotor speed.
6.8 Motor Drive Efficiency Test

As described in Chapter 4, when one phase open-circuit fault occurred in the motor drive, if the rotor speed and the output torque are kept the same as in the healthy operation, the phase currents in healthy phases have to be increased. This increases the copper loss, which reduces the efficiency of the motor drive. Under the winding short-circuit fault, the efficiency of the motor drive becomes worst. This is due to the fact that the winding short-circuit fault generates a negative torque in the subjected phase. Therefore, to achieve the same output torque and the rotor speed as in the healthy operation, it is necessary to increase the current in the healthy phases significantly (much greater than the value under the open-circuit fault).

The motor drive efficiency test experiment is performed using the dual 48-pole fault tolerant motor drive setup. Figure 6.26 is given to illustrate the power flow chart of the motor drive. As seen in the figure, the input power is the sum of the two motor modules which is measured by a universal power analyzer (Voltech PM 3000A). The output power includes the iron loss of two generators, the copper loss of generator 2, the rectifier loss and the power dissipated in the rheostat. Among of them, the generator iron loss is the function of the rotor speed, and the other three parts of the output power are the function of the current flowing in the rheostat. The total output power of the test setup can be expressed as

\[
P_{\text{out}} = V_R \cdot I_R + 2 V_F I_R + 11.44 I_R^2 + 0.00008 n^2 + 0.065 n
\]  

(6.1)

where \(V_R\) and \(I_R\) are the voltage and current of the rheostat, \(V_F\) is the voltage drop in the rectifier, \(n\) is the rotor speed in rpm, which can be obtained from the measured phase current waveforms.

Figure 6.27 shows the efficiency test results of the dual 48-pole fault tolerant motor drive under the healthy condition and two different faulty conditions: one phase open-circuit fault and one phase short-circuit fault. The rotor speed in the test setup was varied by adjusting the reference current. From the experiment results it can be concluded that the maximum efficiency under the healthy operation of the motor drive is slightly more than 80% as it was verified in the simulation study. In addition, the
results indicate that the efficiency under one phase short-circuit fault is lower than the efficiency under the one phase open-circuit fault. It can be noted here that due to the large drag torque produced by the induced short-circuit current, the rotor speed of the motor drive under one phase short-circuit fault cannot reach the operating speed under the healthy and one phase open-circuit conditions.

![Power Flow Chart](image)

**Figure 6.26** The power flow chart of the dual 48-pole fault tolerant motor drive setup.

![Efficiency Test Results](image)

**Figure 6.27** The dual 48-pole motor drive efficiency test results.

### 6.9 Conclusions

When various faults occur in the fault tolerant motor drives, the suitable remedial strategies should be adopted to make the motor drive continue to provide rated or near rated output torque with relatively lower torque ripple values. This chapter provided a
hardware implementation and the experimental results to verify the simulation and analytical studies which including the fault remedial strategies.

The results proved that the developed motor drive control system can perform the expected functions in both the 48-pole and 4-pole dual fault tolerant PMAC motor drives. In addition, it was shown that after a fault, a suitable fault remedial strategy can be adopted in real time to compensate the torque loss.

The experiments performed in this chapter included the operations under one phase open-circuit fault (1 OC), two different phase open-circuit fault (2 different OC), two same phase open-circuit fault (2 same OC), one motor complete fault (3 OC), and one phase short-circuit fault (1 SC). The relationship between relative total copper loss and the torque ripple under various operating modes is summarized in Figure 6.28. The experimental results demonstrated that the proposed fault remedial strategies are effective to compensate the torque loss due to the faults considered.

![Graph](image)

Figure 6.28 Relative total copper loss versus torque ripple under different operating modes. (a) One phase open-circuit fault with different fault remedial strategies; (b) Different fault modes with fault remedial strategy 3.

It was also demonstrated that although the fault remedial strategy 1 (RS 1) results in minimum copper loss, it develops significant torque ripple which may not be suitable in some applications where the lower torque ripple motor drive is required. The fault remedial strategy 3 (RS 3) is an effective post-fault control algorithm for a number of faults and it can achieve lowest torque ripple with only a modest increase in the copper loss comparing with the minimum possible value under the fault remedial strategy 1. In addition, the fault remedial strategy 2 (RS 2) is easy to implement in the dual fault
tolerant motor drive with identical motor modules in which the lower torque ripple can also be obtained. Furthermore, the efficiency characteristics of the motor drives were also studied to verify the simulation results.

In this chapter, it was demonstrated that the one phase short-circuit fault produces large drag torques. Therefore, in order to provide rated output torque, the phase currents in the healthy phases need to be much higher than the value under healthy operation. The efficiency of the practical motor drive is found significantly low under one phase short-circuit fault condition (less than 50% in the 48-pole dual motor drive). Therefore, it is important to reduce the value of the winding short-circuit current which can be done in the design stage of the motor drive. If the motor possesses the higher winding short-circuit current, in certain cases a series back-to-back thyristor configuration can be utilized to change a short-circuit fault into a phase open-circuit fault. Then the remedial strategies for the open-circuit fault operation can be adopted.

It can be concluded that the dual fault tolerant motor drive system possesses higher reliability than single motor drive system because it can continue to provide rated output torque even under one motor complete failure.

Finally, it should be noted here that due to the limitations of the resolution of the encoder, phase current sensors, the execution rate of the motor controller, and the inherent control error of the hysteresis current scheme, the phase currents in the motor drive are not smooth ideal sinusoidal waveforms which develops significant torque ripples even in the healthy operation. Therefore, it is recommended that to improve the performance of the motor drive, higher resolution current and position sensors and a higher speed motor controller with high performance A/D converters such as TMS320 DSP should be accommodated in the motor control system.
Chapter 7
General Conclusions and Future Work

7.1 General Conclusions

Safety critical motor drive systems are becoming more important in many areas such as aerospace, transportation, medical and military applications, and nuclear power plants. In these application systems, any failure of motor drives may result in loss of property and human life. Therefore, the motor drives utilized in safety critical applications must be fault tolerant, and they should continue to operate even in the presence of one or more faults. Although a single module fault-tolerant motor drive system may be sufficient in some safety critical applications, this motor drive system does not offer any redundancy.

This thesis investigated the dual module fault tolerant motor drive system in which two identical motor modules were connected on a common shaft to increase the reliability of the entire motor drive system. The research in this thesis includes four parts: analytical investigation on single and dual module fault tolerant PM motor drives; the investigation of fault remedial strategies for these motor drives; performance investigation and simulation studies on the designed motor drives; and implementation investigation of the dual module fault tolerant PMAC motor drives. The main conclusions in each part are summarized in the following subsections.

7.1.1 Analytical investigation of fault tolerant motor drive

Since the output torque in the motor drive is proportional to the phase current, the reference currents have to be calculated for the torque control. A general phase current mathematical model to produce the desirable output torque value for single and dual fault tolerant PM motor drives with both sinusoidal and trapezoidal back-EMF waveforms was established which can result in minimum copper loss in the motor drive.
The fault mode analysis showed that the potential electrical faults are an inevitable consequence of long-term or over-stressed operation. In order to investigate various faults, the systematic fault classification was performed. It was concluded that the winding open-circuit and short-circuit fault, switch open-circuit and short-circuit fault are the most common electrical faults in a brushless PM motor drive.

The fault effect investigation of various faults on output torque and torque ripple indicated that after faults occur, the total electromagnetic torque will be reduced and the torque ripple will be increased as well, especially in the switch short-circuit fault condition where the effect is more serious due to the large drag torque resulted from the short-circuit current.

Furthermore, the analytical results in single and dual fault tolerant motor drives proved that the fault effect on output torque and torque ripple in a dual motor module fault tolerant drive is less than in a single motor module fault tolerant drive. It has further demonstrated that the dual motor module fault tolerant drive configuration has better performance than the single fault tolerant motor drive.

In addition, the fault analytical study also demonstrated that if the per-unit inductance of a winding is unity, the short-circuit current under the winding short-circuit fault is limited to rated current. However, at rated rotor speed, the average drag torque under switch short-circuit fault condition is found to be greater than the value under winding short-circuit fault condition. Therefore, after a switch short-circuit fault was detected and identified, it is helpful for the reduction of drag torque and motor drive control to transfer the switch short-circuit fault into winding short-circuit fault by providing suitable control signals to the related switches. This conclusion also provided a theoretical guidance for the fault tolerant motor design.

After converting a switch open-circuit fault to a winding open-circuit fault and a switch short-circuit fault to a winding short-circuit fault, the faults in the motor drive can be classified as one phase open-circuit fault and short-circuit fault, two different phase or two same phase open-circuit fault and short-circuit fault, three phase open-circuit and short-circuit fault (including one motor complete open-circuit fault).
7.1.2 Investigation of fault remedial strategies

As mentioned above, after various faults occurred in a motor drive, the output torque would be decreased and the torque ripple might be significant. Therefore, it is necessary to adopt suitable fault remedial strategies to the motor drive to provide rated (or near rated) output torque as in healthy operation and keep the motor drive operating. Former fault remedial strategies were concentrated on single fault tolerant motor drives and did not consider the output torque ripple (just increased the current averagely in healthy phases to generate rated output torque).

The commonly used fault remedial strategy is to increase the average current in the healthy phases (the fault remedial strategy 1). Two additional fault remedial strategies for both single and dual motor module fault tolerant drives were proposed to compensate the torque loss in this thesis. They are fault remedial strategy 2 in which the current in the same phase of the second motor module is doubled and fault remedial strategy 3 in which the optimal phase currents for zero torque ripple and minimum copper loss are applied to the motor drive. The reference current mathematical models for fault remedial strategy 3 operation under open-circuit and short-circuit faults were established, which are suitable for both single and dual motor module drives.

According to the values of output torque ripple, the copper loss and the highest phase copper loss as well as complexity of the control implementation, the performance of the three fault remedial strategies were examined. The fault remedial strategy 1 is the simplest method and offers the minimum copper loss, but it causes a relatively higher torque ripple factor both in single and dual motor module drives. The fault remedial strategy 2 can provide zero torque ripples; however, it can only be utilized in the dual motor module fault tolerant drive and for certain fault types. In addition, this fault remedial strategy has the highest copper loss in all the fault remedial strategies. The fault remedial strategy 3 is the best algorithm and can achieve the zero torque ripple factor with only a modest increase in copper loss comparing with the minimum possible value for the same torque in the fault remedial strategy 1. Furthermore, referring to all the features such as the torque ripple factor, total copper loss, the dual-module fault tolerant motor drive has better performance than single-module fault tolerant motor drive when using the same fault remedial strategy.
7.1.3 Performance investigation and simulation study of fault tolerant PM motor drives

In order to investigate the features of the fault tolerant motor drive with redundancy, two practical fault tolerant brushless PMAC motor drive setups were designed: a 4-pole interior rotor PMAC motor drive and a 48-pole exterior rotor PMAC motor drive. In this thesis, the motor efficiency prediction of the 48-pole motor drive, based on parameter and open-circuit torque loss measurement, was presented, and the results were verified by MATLAB based simulation studies.

The effect of faults on the motor drive efficiency was investigated by the analysis and simulation studies. The analytical and simulation results have shown that the total copper loss of the motor drive is increased under different faulty conditions if the total output torque of the motor drive is kept at the same value as in healthy operation. It was also concluded that the efficiency of the motor drive under the phase short-circuit fault condition is much lower than that for the phase open-circuit fault condition due to the presence of the drag torque produced by the winding short-circuit current.

In addition, the simulation studies on the dual module 48-pole fault tolerant PMAC motor drive under healthy and faulty conditions both at low and high rotor speeds, and light and heavy loads were performed in this thesis. The simulation results have demonstrated that the total average output torque can be reduced and the torque ripple can be increased in various fault conditions. However, the simulation results have shown that the proposed fault remedial strategies can be applied to the motor drive to effectively compensate the torque loss and minimize the torque ripple.

7.1.4 Implementation and experimental verification of fault tolerant motor drives

In order to verify the proposed fault remedial strategies and verify the conclusions obtained in the analytical and simulation studies, the motor drive control system was developed in this thesis to control the designed motor drive setups. In order to decrease the complexity and the cost of the control system, the Microchip dsPIC30F DSC (Digital Signal Controller) was selected. The software was developed in C. The main functions of the motor control system which were implemented include: start-up algorithm, current and rotor position measurement, hysteresis current control, and the
implementation of fault remedial strategies. Each motor module has separate motor control system and can operate independently.

The fault detection and identification is an important prerequisite before an appropriate fault remedial strategy can be applied. The winding open-circuit fault can be easily identified by comparing the measured real time phase current with the predicted phase current. However, it is more difficult to detect the switch open-circuit fault, switch short-circuit fault and winding short-circuit fault. The previous studies usually utilized multiple on-state voltage sensors for each switch to detect switch faults which may increase the cost of the whole motor drive system significantly.

By carefully designing the interface circuits of the commercial switch drive integrated circuit which possesses a switch on-state voltage sensing function, and combining the fault identification algorithm, the practical fault detection and identification method for switch open-circuit fault, switch short-circuit fault and winding short-circuit fault was developed. As the fault detection circuit and the inverter drive circuit is combined, the need for additional switch on-state voltage sensors were eliminated. Therefore, the advantages of this fault detection and identification method are the simplicity of the implementation and reduction of the cost of the motor drive system. In addition, by appropriately selecting the resistance values, this fault detection and identification method can be easily used in different level over-current fault detection. The proposed fault detection method has been verified by experimental tests and the fault identification algorithm has been demonstrated by the simulation results of MPLAB IDE software tools.

In this fault tolerant PMAC motor drive control system, the hysteresis current control scheme is selected to keep the phase currents tracking the reference current. The various faults may occur in different phases and different switch and these faults may happen simultaneously, thus the calculation of reference currents for the fault remedial strategy 3 operations is quite complicated. In order to increase the real time control operating speed, the coefficients of the reference current calculations were implemented using look-up tables. By analysing the relationships of the coefficients in different fault situations, simplified lookup tables were established. This reference current calculation method offers a simple solution in real time motor control.
The experiments performed in this thesis include the one phase open-circuit fault test, the two different phase open-circuit fault test, the two same phase open-circuit fault test, the one motor complete fault test (may be caused by power supply failure or controller failure), and the one phase short-circuit fault test. The experimental results demonstrated that the proposed fault remedial strategies can be realized in a real time motor control system and are effective to compensate the torque loss due to the faults. The experimental results proved that the fault remedial strategy 1 which involves increasing the average current in the healthy phases will result in significant torque ripple which is not suitable for the applications where low torque ripple is required. The fault remedial strategy 3 can achieve the lowest torque ripple with only a slightly increase of copper loss comparing to the minimum value achieved in fault remedial strategy 1. Furthermore, the fault remedial strategy 2 is an easily implemented fault control algorithm for dual fault tolerant motor drive with identical motor modules and offers low torque ripple but the highest copper loss. In addition, tests involving a complete failure of a motor demonstrated that the dual fault tolerant motor drive system offers a higher reliability than single module motor drive system because it can continue to provide rated output torque under this serious fault. At last, the efficiency test results of the motor drive under both healthy and faulted operations were obtained to verify the simulation studies.

The single phase short-circuit fault experimental results demonstrated that in order to provide the same rated output torque as in healthy operation, the phase currents in the remaining healthy phases have to be increased significantly due to the large drag torque produced by the short-circuit current. It was found that under the above operating state and a heavy load condition, it was not possible for the motor drive to achieve the rotor speed as in the healthy operation. The efficiency of the motor drive was also found very low. For example, the efficiency of the 48-pole dual motor drive under the one phase short-circuit fault condition at 92 rpm was 38% while the efficiency in healthy operation at same speed was 68%. Therefore, it is necessary to design the motor module with higher inductance to reduce the short-circuit current. An alternative is to add back-to-back thyristors in series with the motor windings which can be used to block the short-circuit current associated with inverter faults, and then the remedial strategies for phase open-circuit fault operation can be adopted.
7.2 Future Work

The experimental machines have relatively high short-circuit currents which results in a large drag torque when a short-circuit fault occurred. Fault tolerant motor modules with higher inductance such that the short-circuit current equals rated current could be designed and developed to limit the short-circuit drag torque. In addition, the efficiency of the machines tested is less than 82%, higher efficiency motor modules could be designed to meet the various application requirements.

Due to the limitations of the resolution of the encoder, phase current sensors, the execution rate of the motor controller, and the inherent control error of the hysteresis current scheme, the phase currents contain significant current ripple even in healthy operation which results in torque ripple. For example, the peak-to-peak torque ripple of 48-pole motor drive is 19% at 86 rpm rotor speed and 20V DC link Supply. It is suggested that to improve the performance of the motor drive, a higher speed motor controller with high performance A/D converter such as TMS320 DSP should be used for controller. In addition, improved current control schemes may be investigated.

The proposed fault detection method has been verified by preliminary experimental tests and the proposed fault identification algorithm has been demonstrated using simulation results. Due to time limitations, the fault detection and identification method was not verified by real-time motor drive control experimental results. The communication subroutine between two motor drive controllers was also not implemented. These works could be done in the future.

In order to obtain a high level of operational performance from the PM motor drive, shaft position information is normally measured by encoder. However, the encoder is prone to failure. In order to provide redundancy for rotor position information for this dual motor module fault tolerant drive, a sensorless rotor position algorithm developed in [68] can be integrated into this study to obtain a complete fault tolerant motor drive.
Appendix A

List and Abstracts of Publications

This appendix contains the list of publications and the abstracts of the seven conference papers.
A.1 List of Publications


A.2 Abstracts of Publications

Minimum Torque Ripple Current Control Strategy in a Dual Fault Tolerant PM AC Motor Drive

Abstract-In this paper a dual fault tolerant motor drive utilizing brushless permanent magnet AC motors is investigated for safety critical applications. The motor modules are designed to provide both magnetic and electrical isolation between the phases, and the use of two modules also offers redundancy. This paper addresses an important issue, torque ripple and torque compensation due to the loss of a phase or phases in a practical dual motor drive. The mathematical models for reference current calculation in both healthy and various faulty operation modes are established under the zero torque ripple factor and minimum copper loss constraint conditions. These models are suitable for both sinusoidal and trapezoidal fault tolerant motor drives. The experimental results under various fault conditions are provided to verify the proposed fault remedial strategy.

An Indirect Rotor Position Estimation Technique for a Fault-Tolerant Brushless PM Motor Drive

Abstract-This paper proposes an indirect rotor position estimation method for a fault-tolerant brushless PM motor drive that has a dual motor module on a common shaft. The technique is based on flux linkage increments of phase windings and performing multiple rotor position estimations using pairs of phases in the motor drive. The paper provides the theory of the method and presents extensive test results to demonstrate its effectiveness using off-line real data obtained under various practical operating conditions including faulty states and parameter variations.

Detection and Remediation of Switch Faults on a Fault Tolerant Permanent Magnet Motor Drive with Redundancy

Abstract-Fault-tolerant motor drives are becoming more important in safety critical applications. Using a special motor design and an appropriate inverter topology,
brushless permanent magnet AC motor drives can have a fault-tolerant capability. This paper considers a dual motor drive system on a common shaft to introduce redundancy. The paper provides a systematic classification for the potential electrical faults which may occur in a real motor drive. In the paper, the switch and winding short circuit fault detection and identification methods are studied and experimental results are presented. In addition, the effects of switch faults on the phase currents and output torque are discussed, and remedial strategies for these faults are proposed. Furthermore, it was also demonstrated using simulation results that the proposed remedial strategies can compensate for the loss of torque due to the switch faults and can keep the peak-to-peak torque ripple factor comparable to healthy operation of the drive.

Fault Analysis and Remedial Strategies on a Fault-Tolerant Motor Drive with Redundancy

Abstract-Fault-tolerant motor drives are required in a range of safety-critical applications. Using a special motor design and an appropriate inverter topology, brushless permanent magnet AC motor drives can have an effective fault-tolerant capability. Although a single motor fault-tolerant drive system may be sufficient in many critical applications, a higher degree of fault tolerance requires redundancy in the motor system as considered in this paper. This is achieved by using a dual motor module on a common shaft. The simulation model of the entire drive system and the analysis of the various faults are presented in this paper. The effects of fault(s) on the phase current and output torque are provided. Three remedial operating modes are proposed and their features are compared. In addition, an experimental setup was introduced, which is based on dual electrically and magnetically isolated brushless AC motor modules, H-bridge inverters for individual phases and dsPICDEM MCU motor controller.

Performance Prediction of a Fault-Tolerant Motor Drive with a Winding Short-Circuit Fault

Abstract-Fault-tolerant motor drives are required in a range of safety-critical applications. Using a special motor design and an appropriate inverter topology,
brushless permanent magnet AC motor drives can have a fault-tolerant capability. This paper studies the performance of a fault-tolerant dual permanent magnet AC motor drive under a winding terminal short-circuit fault. Among the potential faults that may occur in such drives, this is one of the more critical faults and can significantly affect the drive performance. The paper presents computer simulation studies modeling the motor drive under such a fault condition and provides simulation results of winding currents, output torque and efficiency. Moreover, the paper provides the characteristics of the measured short-circuit winding currents and proposes a hardware solution to reduce the effect of such a fault.

Performance Investigation of a Fault-Tolerant Brushless Permanent Magnet AC Motor Drive

Abstract-Fault-tolerant motor drives are required in various safety critical applications. Using special motor design and inverter topology, brushless permanent magnet AC motor drives can have a fault-tolerant capability. In this paper, a dual motor drive configuration has been proposed which offer high robustness and reliability. This paper studies various critical performance characteristics of the dual motor drive including drive loss and system efficiency. The paper aims to address some of important performance issues in the motor drive, which has not been addressed previously. The paper presents the details of the experimental setup and explains the measurement methods for the motor parameters and for the open-circuit torque loss. The efficiency prediction method and corresponding results are also presented and verified by the computer simulation study both under healthy and various faulty conditions.

Modeling and Simulation of Electromagnetic Torque in Fault Tolerant Brushless PMAC Motor Drives

Abstract-This paper examines the torque production in two different fault-tolerant motor configurations, which include single and dual motor modules on a common shaft, each with three isolated windings. In the paper, the proposed fault tolerant motor drive configurations are modeled and simulated to study possible faults and their impacts on electromagnetic torque production. The operating characteristics of single and dual
motor configurations have also been compared. In addition, the remedial strategies to reduce the torque ripple and to increase the average output torque under selected faulty operating conditions have been investigated.
References


