Fault Tolerant Motor Drive System with Redundancy for Critical Applications

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***Abstract*: Some of the recent research activities in the area of electric motor drives for critical applications (such as aerospace and nuclear power plants) are focused on looking at various motor and drive topologies. This paper presents a motor drive system, which provides an inverter topology for three-phase motors, and also proposes an increased redundancy. The paper develops a simulation model for the complete drive system including synthetic faults. In addition, the hardware details including the implementation of DSP based motor controller, inverter module, and brushless PM motor system are provided and some experimental results are presented.**

I. INTRODUCTION

Safety critical systems are taking on increasing importance in the industrial world. Some examples of such systems are aerospace, transportation, medical and military applications, and nuclear power plants. These all accommodate a number of electric motor drives installed to a point where the plants rely heavily upon them. Any failure in these drives may cause catastrophic failures in the plants, which may be very costly in term of human resources and capital cost, and clearly undesirable.

The safety of the above plants is very much depended on the failure-free operation of the electric motor drives. These drives include an electric motor and its controller. Ideally, to prevent catastrophic failures and inspire confidence each component of the motor drive (motor, controller hardware, sensors and software) should be individually fault-tolerant, robust, reliable, and should have a degree of redundancy, which will be specified as safety requirements.

A number of studies have reported to investigate various types of motors and their fault-tolerant features for some critical applications [1-9]. However, in these earlier studies there is a lack of control methodology of a practical drive, and not all possible faults, complete motor drive failure or redundancy issues are considered, which are crucial in safety-critical applications.

The first fault-tolerant motor drives were reported in [1,2,3]. Following these studies, a number of research reports were published, which provided some comparative studies [4], investigated the effect of the numbers of phases [4], explored the fault detection methods in switched reluctance motor drives [8], and studied the fault-tolerant power electronic circuit topology to improve the reliability of the motors [2,8].

Our investigation indicates that the techniques behind most of the electric drives on the market today are not adequate for safety-critical applications. Therefore, there is a need to improve the survivability of critical systems given the increasing dependence on them, and the serious consequences of their failure. Furthermore, there is a need to gain knowledge on which requirements must be put on electric motor drive systems with regard to the needs of the applications and what requirements can realistically be satisfied with regard to technology. In addition, there is a very limited knowledge about the performance of truly integrated motor and control hardware, estimation, and diagnostic algorithms for safety-critical applications.

A safety critical system is the system whose failure may cause injury or death [11], which should have the ability (fault-tolerance) to respond to an unexpected hardware or software failure. There are many levels of fault-tolerance in safe systems, the lowest level being the ability to continue operation in the event of a power failure.

One of the common tools used in the design of safety-critical systems is redundancy. Ideally, many fault-tolerant systems should mirror all operations; that is, every operation should be performed on two or more duplicate systems, so if one fails the other can take over. Therefore, redundancy within the system is an essential aspect. For modular systems with redundancy, the structure of the system is usually a mixture of series and parallel modules.

Reliability is a measure of the time between failures occurring in a system. Hardware and software components have different failure characteristics. Hence it is difficult to find formulas for predicting software and hardware reliability. However, reliability (which is a measure of the time between failures occurring in a system.) can be increased by having alternative backup systems and by dividing some sections of hardware into small electrically and physically isolated units.

Various components of a fault tolerant drive system has already been studied by the authors in [10], which utilized two conventional electric motors and allowed the user to observe the system's reaction to some synthetic faults. This paper reports the further developments and the real-time implementation related issues.

As stated previously, it was envisaged that a high-performance and safe motor drive can be designed if all the components of a drive are made individually fault-tolerant. As stated previously, a high-performance motor drive can be considered having a number of components: motor and controller hardware, sensors, and software. In the following section each component of a safe system will be considered separately and their desired features will be identified.

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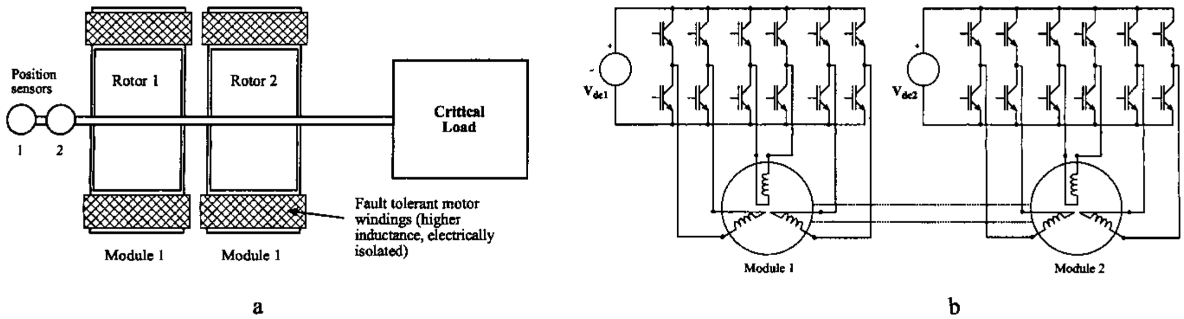


Fig. 1. Multiple segment/modular motor drive with redundancy (a), an alternative motor/inverter configuration against the device and winding failure (b).

II. Fault-Tolerant Motor Drive System and Potential Faults

Although a fault-tolerant system with a single motor drive may overcome most of the problems in critical applications, the non-existent redundancy in the case of a complete motor failure is the primary concern. In addition, the redundancies of the controllers and the feedback systems have to be considered for reliable operation.

It is suggested that the use of direct drive multiple motors on the same shaft improves redundancy (Fig.1a). If a higher power rating is needed, another segment(s) can be added to the same shaft. Although the complexity of the drive circuit and the cost increases due to the multiple and independent controllers, even 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 power.

An alternative fault-tolerant motor configuration for PM ac motors can be obtained by separating the three-phase windings and driving each motor phase from a separate single-phase inverter (Fig.1b). It is evident that this new configuration doubles the number of power devices. However, the device voltage ratings are reduced since the devices withstand the phase voltage rather than the line voltage, hence the switching losses of the inverter will be reduced which in turn reduces the heat sink requirements, which also means less room and less weight.

Furthermore, in the event of the failure of one motor phase, the reduction of the developed average torque can be compensated by overrating each phase of the motor by a fault-tolerant factor [6], which is a function of the number of phases. Although there is a marginal advantage in increasing the number of phases of the motor under open-circuit faults, there is no overall benefit since the complexity of the drive circuit increases, which reduces the reliability. Therefore a three-phase modular motor configuration is selected.

Although switched reluctance (SR) motors are inherently fault tolerant, they have significantly less torque density and efficiency than their PM ac counterparts, hence not preferred in certain applications such as aerospace.

It was found that the motor system (modular structure), which is suitable as a direct drive in the critical applications should have the specifications summarized in Table I

Table I

Specifications of a fault tolerant motor.

- Higher redundancy, by using identical motor segments on the same shaft,
- Higher efficiency design over the operating speed range to better utilize the power supply,
- Electrically isolated phases to prevent phase to phase short-circuit and reduce inverter faults,
- Magnetically uncoupled windings to avoid reduction of performance in the case of a failure of the other phases,
- Physically isolated phases to prevent propagation of the fault into the neighboring phases and to increase the thermal isolation,
- Higher winding inductance to limit the winding short-circuit current,
- Minimum weight and power loss design utilizing Cobalt-Iron based laminations,
- Effective cooling.

A central requirement for a safety-critical application is that it has to be able to cope with faults. Safety critical applications must detect and handle all situations. Some of these situations might be classified as normal, some as unusual and still others as impossible. However, a good system should address all of these types of situations to facilitate the constructions of safety critical applications. The fault scenarios, which may occur in a high-performance drive are identified and listed in Table II.

Table II

Fault scenarios in the drive.

- Winding open-circuit
- Winding short-circuit (partial turn to turn or complete)
- Inverter switch open-circuit (analogous to winding terminal open-circuit)
- Inverter switch short-circuit (analogous to winding terminal short-circuit)
- Power supply failure
- Position sensor (which can also be use for speed sensing) failure
- Controller failure
- Combination of the above faults

The motor drive is prone to open-circuit faults due to the failure of power switches or winding failures. Such faults can be observed by current transducers located in each phase, and the remaining switches in that phase(s) is turned off.

One of the most critical faults in the motor drive is a partial (turn to turn winding short-circuit) or a complete winding short circuit due to the failure of two switches or a terminal short-circuit. The fault current in this case can be controlled by the increased self-inductance of the windings in the design stage [15]. It is desired that the short-circuit fault current be limited to the rated steady-state current. This fault can be detected and controlled by the controller if the fault is a complete short-circuit and if it occurs before the current sensor of the phase. However, it is impossible to eliminate in the case of a turn-to-turn short-circuit, in which the solution is to shut down the motor segment completely and run the remaining segment at maximum (for a short period) or at rated (continuously) condition.

Inverter switch open-circuit faults are analogous to winding terminal becoming open-circuit. Hence similar measures explained above can be undertaken to eliminate such faults.

Similarly, inverter switch/diode short-circuits are analogous to winding terminal short-circuits, but can easily be eliminated by turning off the other switch.

Power supply failure is probably the most critical fault in the safety critical systems. The solution is to use multiple and electrically isolated power sources for every critical section of the drive instead of a single supply.

Failure of position sensors (can also be use for speed sensing) can be avoided by using two direct position sensors and an indirect (sensorless) position detection method [13, 14] operating simultaneously.

III. Simulation Model of the Two-Segment Brushless PM ac Motor

The design of a complete modular motor drive system is a significantly complex task as there is a wide array of design factors, which need to be considered. To understand the implementation of electromagnetic torque control and torque sharing, and to investigate of fault models and additional analysis capabilities, a computer simulation model of the complete drive has been developed.

A diagram of the main components of the fault-tolerant drive system that also represent the simulation is shown in Fig. 2. As seen in the figure, the system has redundant motor modules, redundant controllers, and redundant sensors. In the following paragraphs, the motor model used in the simulation is explained.

If the brushless PM ac motor segments can be assumed to be balanced and having identical resistance, R and equivalent winding inductance, L, the terminal voltage, v for each phase is given by

$$v_n(t) = R\, i_n(t) + L\frac{d\, i_n(t)}{dt} + e_n(t)\ ,\ n = 1,2,3,4,5,6 \qquad (1)$$

Where, e is the back emf of the phase windings. The solution of the above differential equation is obtained in LabVIEW using a numerical integration technique. It should be noted here that the complete simulation is achieved using LabVIEW software.

The electromagnetic torque, T_e produced by one phase of one motor is calculated by

$$T_e = \frac{e_n\, i_n}{\omega}\ ,\ n = 1,2,3,4,5,6 \qquad (2)$$

The total electromagnetic torque produced by the two motor segments operating on a single shaft can be calculated by adding together the output torque of each motor segment (a and b) as

$$T_{e(total)} = \frac{(e_{a1}i_{a1} + e_{a2}i_{a2} + e_{a3}i_{a3}) + (e_{b4}i_{b4} + e_{b5}i_{b5} + e_{b6}i_{b6})}{\omega} \qquad (3)$$

Note that in each motor segment, the back emf waveforms must be in phase between the corresponding phases of the two motor segments, but must be out of phase with the adjacent phase by 120° in the same motor segment, which is calculated for sine waveforms using the following relationship.

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} E_m \sin(\theta_e) \\ E_m \sin(\theta_e - \frac{2\pi}{3}) \\ E_m \sin(\theta_e - \frac{4\pi}{3}) \end{bmatrix} \qquad (4)$$

The torque ripple-free operation of the two-segment motor drive can be achieved by providing two segments having not only identical electrical parameters, but also having back emfs in phase.

Furthermore, the phase currents are regulated reference to the corresponding back emfs, which is also implemented in the real-motor drive providing a look-up table containing the actual back emf waveforms.

To calculate the rotor's angular velocity, ω the mechanical equation of the motion, which is given by

$$T_{e(total)} = J\frac{d\omega}{dt} + B\omega + T_L \qquad (5)$$

Here, J is the polar moment of inertia of the whole system, B is the damping coefficient and T_L is the load torque.

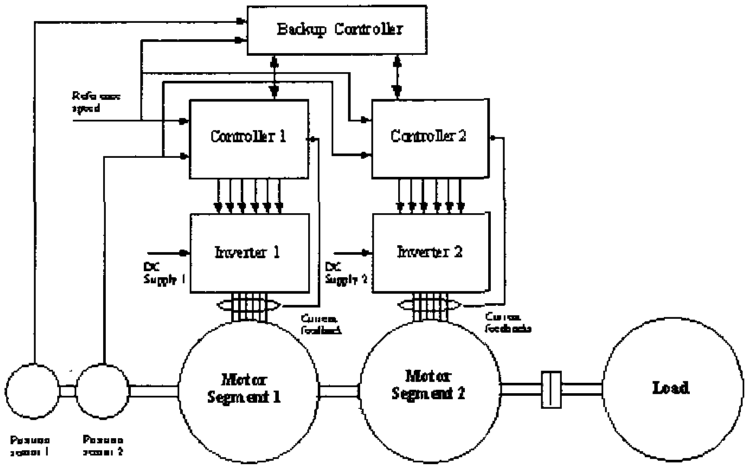


Fig. 2. The complete block diagram of the fault tolerant motor drive system with redundancy

A sample simulation result is given in Fig.3, which provides the user with a choice between Hysteresis or PWM current control. The simulation allows any of the six motor phases to be short-circuited or open circuited, and allows the user to vary the motor parameters.

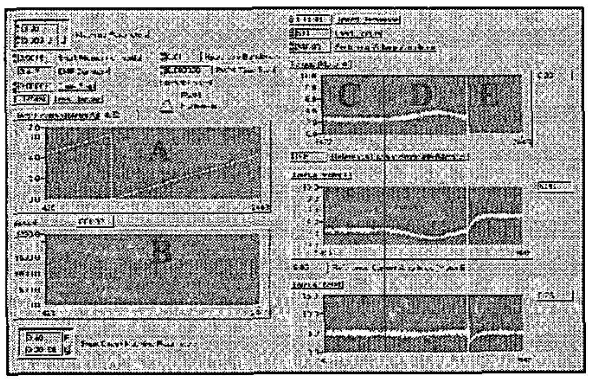


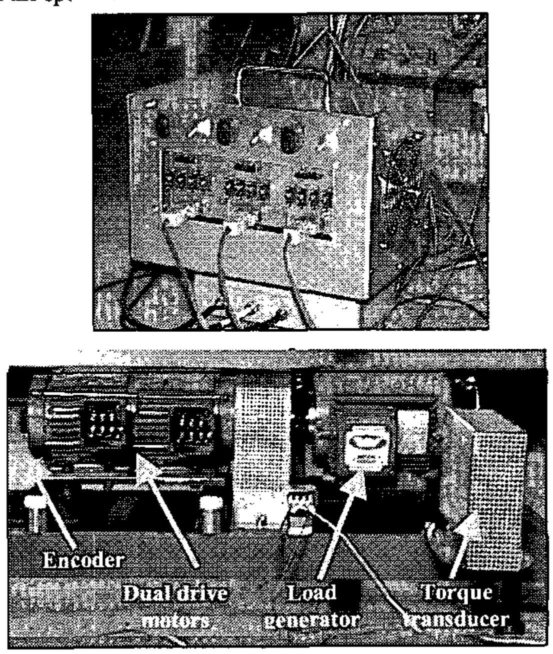
Fig. 3. A sample computer simulation result of the motor drive system at constant speed and operation under synthetic faults (Graph A : Rotor position; Graph B: Actual shaft speed; Region C: No fault, both motors develops equal torque; Region D: Phase 1 of Motor 2 is turned off; Region E: Motor 1 is switched off)

IV. Implementation of the Hardware and Experimental Results

The development and integration of the DSP based complete motor control including the implementation of a flexible inverter enclosure (Fig. 4a) have been completed. This arrangement can create some of the real time inverter faults.

A Realization of the Motor Segments

Fig. 4b illustrates the complete test setup used in the laboratory testing. In this study, the rotors of two 1.1kW induction machines are replaced with two surface-mounted permanent magnet (NdFeB) rotors, which were designed and built on a solid common shaft. In addition, the terminals of the stator windings of the motors are separated to allow the integration of isolated H-bridges. In the future study, an alternative motor design will be performed to accommodate all the specifications listed in Table I.



b

Fig. 4. Photos of the inverter enclosure (a) and complete dual motor drive and load generator with the torque transducer attached (b). The switches in the inverter box are included to introduce various synthetic faults while the motor drive is running (such as line-off, signal-off, and supply-off).

B DSP Based Control

Analog Devices ADMC401 motor control kit is used in this study to drive one of the motor module, which includes a 26 MIPS fixed point DSP core with a complete set of motor control peripherals that permits fast motor control in a highly integrated environment such as the motor drive being developed in this paper.

The rotor position is measured by using an encoder with 500 slots, which has two channels and one index pulse outputs, and which is also utilized to obtain the speed of the motor. The DSP generates the current commutation signals reference to the rotor position. Fig.5 illustrates the estimated rotor position and the back emf of phase 1 of Motor Segment 1. As expected, since the electrical position is p (number of pole pairs) times the mechanical position, the position resets every 2 cycles of the back emf.

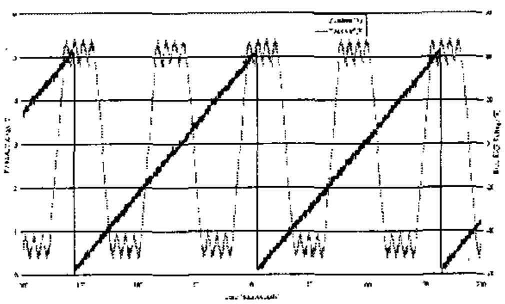


Fig. 5 Measured emf waveform of Phase 1 of Motor Segment 1 and rotor position

A comparison between the desired current and measured current in phase 1 of Motor Segment 1 is shown in Fig. 6, where the actual current is regulated using a PWM switching method reference to the desired current profile for torque ripple-free operation. Note that to obtain a torque ripple-free operation the command current should be generated reference to the shape of the actual back emf.

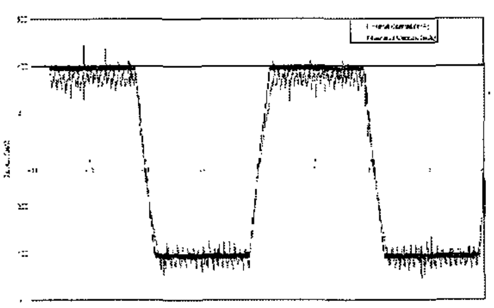


Fig. 6 The reference current (solid line) and the actual current of Phase 1 of Motor Segment 1.

Two uncommon test results are given in Fig. 7 and Fig. 8, which illustrate the voltage and the current of phase 3 of Motor Segment 1. In both operating conditions, the actual currents failed to reach the reference current of 2A. Note that due to the high induced voltages (EMF) at the operating speeds, the current is limited by the back emf only. The peak value of the induced voltage is measured 7.9 V at 60 rpm for the motor designed.

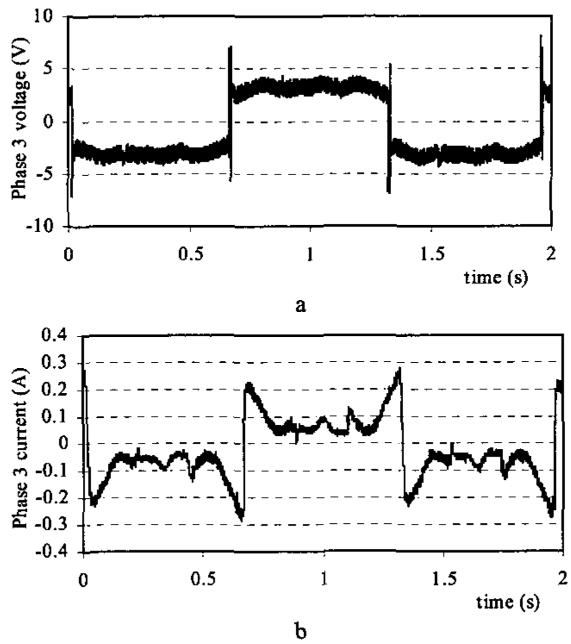


Fig. 7 The measured voltage and the current of phase 3 of Motor Segment 1. $V_{dc} = 4.95$ V.

The current conduction interval is 180° electrical in Fig. 7. In Fig. 8, however, the current conduction interval is very narrow, which is due to the higher back emf. Note that the current conduction occurs when the back emf is less than the applied dc voltage minus the inverter drop.

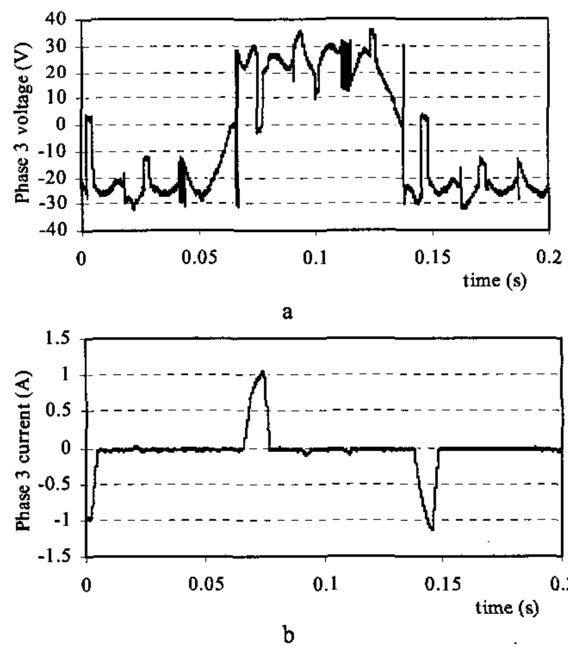


Fig. 8 The measured voltage and the current of phase 3 of Motor Segment 1. $V_{dc} = 29.5$ V.

Furthermore, note that there is a significant voltage ripple on the dc link voltage, which is due to the ripples on the single-phase bridge rectifier and the back EMF waveforms.

The future tests will consider three separate battery supplies to power the inverter bridges separately.

V. Conclusions

A comprehensive description of a fault tolerant motor drive is given and a simulation model is developed using the detailed electrical model of the motor drive, which can allow the user to vary the motor parameters and/or to introduce synthetic faults.

To verify the results and to study real time problems, a complete hardware system is developed and tested. However, absence of a suitable rotating torque transducer has prevented us to demonstrate the dynamic torque profiles under normal and faulty conditions.

The future studies will extend the discussions further and will present various experimental results including real-time shaft torque and the system performance under faulty conditions.

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