Investigation of a Fault Tolerant and High Performance Motor Drive for Critical Applications

N. Ertugrul, MIEEE, W. L. Soong, MIEEE, S. Valtenbergs and H. Chye P NG

***Abstract*– This paper evaluates a fault-tolerant electric motor drive with redundancy for a potential all-electric aircraft (AEA), and investigates to increase the redundancy against partial or complete motor failures. A flexible motor configuration is proposed to increase the redundancy against motor failures. The paper highlights the importance of effectively simulating the system on computer, and the way in which the ideas and techniques used to simulate the system have been adapted to the physical prototype. The computer modelling section of the paper outlines the steps involved with simulating the complete system using an object orientated programming language, LabVIEW, and some simulation results are provided.**

***Index Terms*– Fault tolerant motor drives, Redundancy in electric motor drives, DSP based motor control, Brushless PM motors.**

I. INTRODUCTION

Within 10 km of an airport, especially in General Aviation (GA), the pollution from engine exhaust and the effects of aircraft noise are well documented [1]. Piston engine aircraft are the major contributor to these noise and exhaust levels. In addition, fatal aircraft accidents are not uncommon in GA, mainly due to the non-existent redundancy in case of an engine failure in single-engine aircraft

Some of the recent research activities in the area of alternative electrical energy generators are focused on looking at various fuels and techniques, and it is a very encouraging that the Fuel Cell technology is on the edge of a new era to make this aim a reality. It is clear that significant improvements in fuel cell specific mass and volume have been realised during the last decade. A seven fold increase in fuel cell energy density within the last five years indicates that an energy density of 0.5kWh/kg at low cost is now possible [2]. Therefore, the Fuel Cell technology has now reached a level where it is feasible to be used in propeller driven AEA by the help of the recent technological advances and developments in the area of power electronics, motor control.

There are very few applications reported so far on AEA [3], [4], which are mostly Unmanned Air Vehicles (UAVs). The first fault-tolerant motor drives were reported in [5]-[7]. Following these, a number of reports provided some comparative studies [8], investigated the effect of the numbers of phases [8], explored the fault detection methods in switched reluctance motor drives [13], and studied the fault-tolerant power electronic circuit topology to improve the reliability of the motors [6], [12].

However, none of the previous studies considered a fault-tolerant and modular motor drive operation for increased redundancy. In addition, there is a lack of control methodology of a practical drive, and not all possible faults, complete motor drive failure or motor and feedback device redundancy issues are considered in the earlier studies, which are crucial in AEA applications.

In this paper, the fault-tolerant motor drive suitable for a critical application, propeller driven AEA, is conceptualised and evaluated, and motor/drive simulation studies are presented.

II. FAULT-TOLERANT MOTOR DRIVE SYSTEM

It is recommended that the use of direct-drive multiple motors on the same shaft improves redundancy (Fig. 1). Moreover, an axial field version of the motor may provide a better utilisation of the power density and the space. Furthermore, high saliency interior Permanent Magnet (PM) motor designs generate low currents under winding short-circuit conditions. Due to the slim design of the segments, if a higher power rating is needed, another segment(s) can be added to the same shaft without any difficulty.

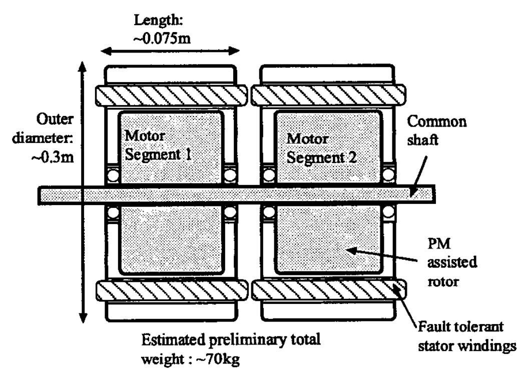

Fig. 1 Multiple segment/modular motor drive with redundancy. Note that most modern propeller driven aircraft with one or two seats require a maximum power of about 60kW-110kW. The dimensions given here are based on the preliminary calculations for a 80kW Brushless PM motor drive using cobalt-iron laminations.

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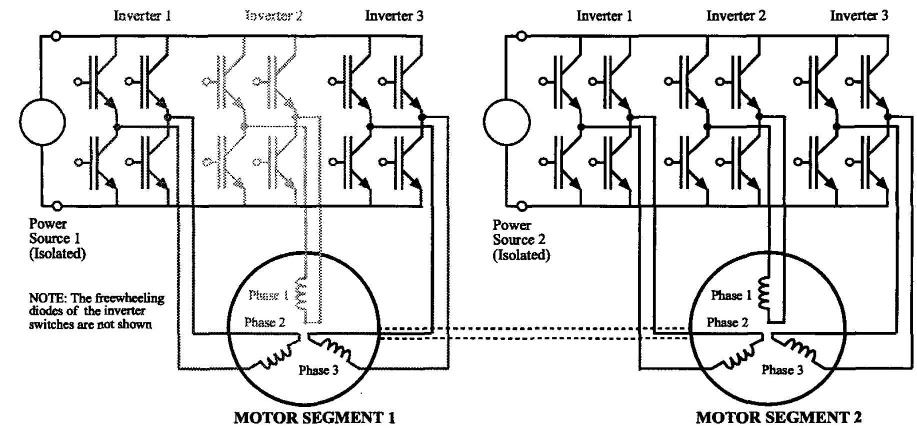


Fig. 2 An alternative motor/inverter configuration against the device and winding failure of two-segment motor.

In this proposed active redundancy system in Fig.1, either motor drive unit may sustain the function. Although the complexity of the 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 can provide sufficient power for safe flight and landing of the AEA.

A. Definition of a Fault-Tolerant System

In an AEA application, it was envisaged that a high performance and a complete fault-tolerant system can be obtained if all of the components in the motor drive system are made fault-tolerant individually. Although SR motors are inherently fault tolerant, they are not suitable as a direct motor drive in AEA applications where a low mass and a high efficiency are essential, and these motors have significantly less torque density and efficiency than their permanent magnet (PM) counterparts.

An alternative fault-tolerant motor configuration for Brushless PM motors can be obtained by separating the three-phase windings and driving each motor phase from a separate single-phase inverter (Fig.2). 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. As a result of this, the switching losses of the inverter will be reduced which in turn reduces the heat sink requirements, which also means less weight. Although there is a marginal advantage in increasing the number of phases of the motor under open-circuit fault [10], there is no overall benefit since the complexity of the drive circuit increases, which reduces the reliability. Therefore a three-phase modular PM motor configuration is selected

In the event of the failure of one motor phase, the reduction of the developed average torque can be compensated by overrating each phase by a fault-tolerant factor [7], which is a function of the number of phases.

It was found that the motor system (modular structure), which is suitable as a direct drive in an AEA application should have the specifications summarized below:

- Higher redundancy, by using identical motor segments on the same shaft,
- Higher efficiency design over the operating speed range to better utilise 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 neighbouring phases and to increase the thermal isolation,
- Higher winding inductance to limit the winding short-circuit current,
- Minimum weight and power loss design utilising Cobalt-Iron based laminations,
- Effective cooling to allow about 25% overloading capacity to be utilised during take off and climb.

B. Potential Faults in the Drive

As mentioned above, under any fault, the AEA should be able to continue to operate reliably and land safely. One way to achieve this is to make the overall system fault-tolerant. In a fault-tolerant motor drive, motor windings and modules should be physically, electrically and thermally isolated to prevent the faults spreading to the other sections of the motor. Furthermore, the motor windings should not be magnetically coupled to limit the winding short circuit currents.

Unlike previous studies on fault-tolerant motor drives, the potential faults that can occur in an electric motor drive system should not be restricted to certain types only, and because of the safety considerations, all possible faults must be considered in an AEA application. Therefore, the fault scenarios, which may occur in a high-performance motor drive are identified and listed below:

- 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 (can also be use for speed sensing) failure
- Combination of the above faults

To address the such faults in the drive, various methods and technologies can be implemented, which are explained below.

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) are 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 limited by the increased self-inductance of the windings in the design stage [7],[16]. 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. However, the type of power sources anticipated in actual implementations (fuel cell) can be designed to eliminate such faults. The solution is to use multiple and electrically isolated power sources for every critical section of the drive instead of a single supply. It should be noted here that it is easy to observe and detect any fault in an electric power source.

Failure of position sensors (which can also be used for speed sensing) can be avoided by using multiple position sensors, together with an indirect position detection method [16], [17], operating simultaneously.

The design of a complete modular motor drive system is a relatively complex task as there is a wide array of design factors, which need to be considered. A diagram of the main components of the drive system is shown in Fig. 3. Therefore, it is important to design the motor and drive together in an integrated manner. This means that for optimum performance, the motor, power electronic circuits, control circuits and algorithms, and measuring circuits should be considered together, and not in isolation.

Power processing and control units suggested in this project provide many other challenging integration and control issues, such as:

- Development of a supervisory system as a backup, and for condition monitoring that may be based on embedded flux, temperature and vibration sensors.
- Implementation of electromagnetic torque sharing and torque control (which can be achieved by using a look up table method that can utilise the actual back emf waveforms)

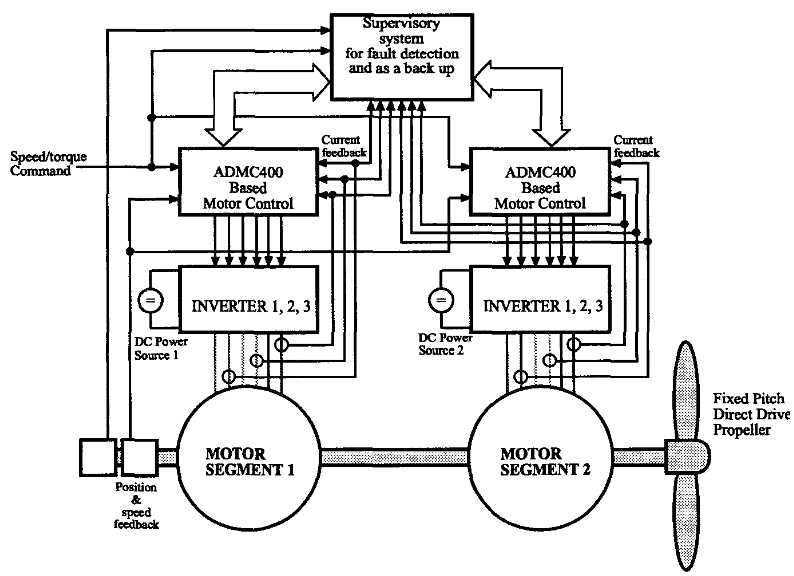


Fig. 3 The block diagram of proposed multiple motor/drive for AEA.

III. Computer Modelling of the Drive

In this study, a computer simulation model of the system have been developed, which provides a useful tool to study the drive in detail, which also allowed to observe the system's reaction to synthetic faults.

A. System Equations of the Two Segment Motor

The motor segments are assumed to be balanced and has identical resistance, R and equivalent winding inductance, L. Hence the terminal voltage, v for each phase is given by

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

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, the trapezoidal approximation, which obeys the rule given below. Note that the other integration methods (such as Simpson's or the Runge-Kutta methods) may provide more accurate results. However, they are mathematically intensive and hence not used here.

$$\int_{t_1}^{t_2} f(t)dt = \Delta t(\frac{1}{2}f_1 + \frac{1}{2}f_2) \qquad (2)$$

Here f(t) is the time dependent function of the current, Δt is the time step in seconds, and f_1 and f_2 are the values of the function at two consecutive time steps.

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

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

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

$$T_{e(total)} = \frac{(e_{a1}i_{a1} + e_{a2}i_{a2} + e_{a3}i_{a3}) + (e_{b4}i_{b4} + e_{b5}i_{b5} + e_{b6}i_{b6})}{\omega} \qquad (4)$$

In each motor segment, each back emf must be out of phase with the adjacent phase by 120°, which is calculated using the following relationship.

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} E_m \sin(\theta_e) \\ E_m \sin(\theta_e - \frac{2\pi}{3}) \\ E_m \sin(\theta_e - \frac{4\pi}{3}) \end{bmatrix} \qquad (5)$$

As can be seen in the above equation, 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 (see Fig. 9). Furthermore, the phase currents must be regulated reference to the corresponding back emfs.

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

$$T_{e(total)} = J\frac{d\omega}{dt} + B\omega + T_L \qquad (6)$$

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

B. Computer Modelling and Simulation Results

A simplified computer simulation block diagram is illustrated in Fig. 4. The computer simulation provides the user with a choice between Hysteresis or PWM current control. Hysteresis current control uses a bandwidth centred upon the desired current waveform. The actual current is constantly measured, and at the instant the actual current becomes equal to the hysteresis bandwidth limit, the status of the terminal voltage is changed to control the current using the inverter switches. The PWM method, however, employs a fixed sampling frequency and thus constant time step to sample the actual current produced by the motor. The inverter is only switched at the instant when the current is sampled, according to whether the actual current is above or below the reference current value.

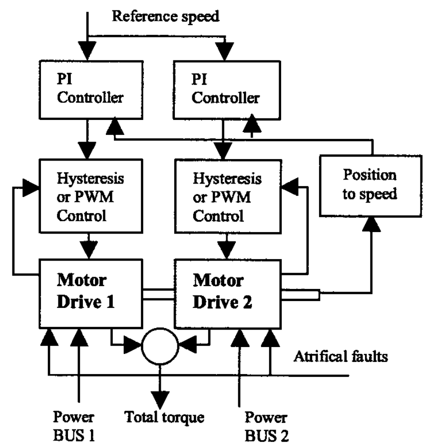


Fig. 4 Simplified block diagram of the simulation

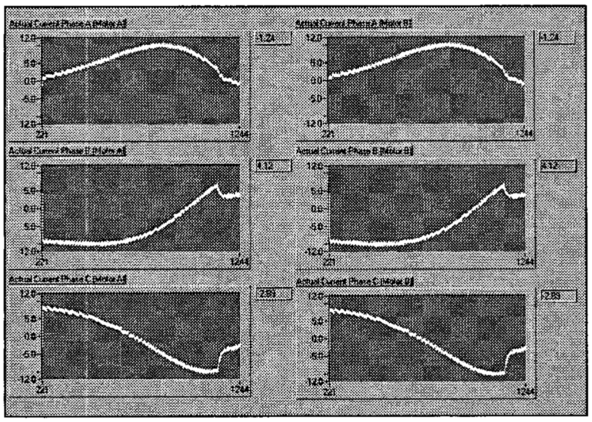
As shown in the simulation block diagram (Fig. 4), the proportional integral (PI) controller for each machine is responsible for current regulation. A number of user controls are provided in the "Global" user panel, which accommodates the complete motor and system parameters, current control types, faulted winding parameters and saving data options.

The dual motor system is required to be highly fault tolerant. The simulation must therefore provide a means to test the fault tolerance of the system. The virtual instruments used in the simulation have been designed to provide as much isolation between phases as is possible. The "Faults" virtual instrument designed in LabView allows any of the six motor phases to be short-circuited or open circuited. It also facilitates the complete shut down of one of the two motors. The "Faults" virtual instrument also allows the user to vary the two motors' back emf constants and specify the machine parameters for phases that become short-circuited.

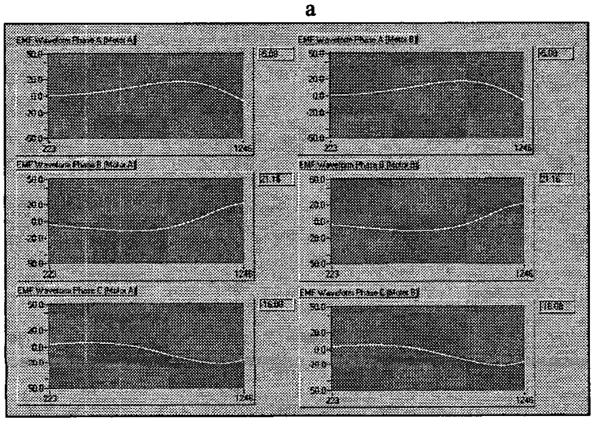
The switches included in the "Faults" virtual instrument can be adjusted by the user as the system is running, and allows the user to watch the result of the synthetic faults in real time.

A number of results from the dual motor drive computer simulation is given here to demonstrate the operation of the fault tolerant motor drive.

Rather than concatenating all of the waveform graphs into a single "Global" user interface and creating in a cluttered front panel, two sub virtual instrument in LabView were created to allow the user to view the EMF waveforms and actual currents in each of the six motor phases. As shown in Fig.5, it is evident that the motor segments generates identical and in-phase current waveforms and back emf waveforms.



a



b

Fig. 5 Current (a) and back emf (b) waveforms under the settings: sinusoidal back emfs and sinusoidal current excitation of the motor drive.
First column: Phase 1, 2, and 3 of Motor A respectively
Second column: Phase 1,2, and 3 of Motor B respectively

Fig. 6 illustrates the starting performance of the motor drive. The point at which the machine reaches steady state is evident is in the figure, as the current amplitude drops off when the rotors stop accelerating.

In the result given in Fig. 7, the drive was accelerated from standstill until it reaches to a steady state speed of 500rpm, and then two faults were introduced. As seen in the figure, the torque reduction due to the absence of the phase current in Motor 2 is compensated by the increase in the torque produced in Motor 1.

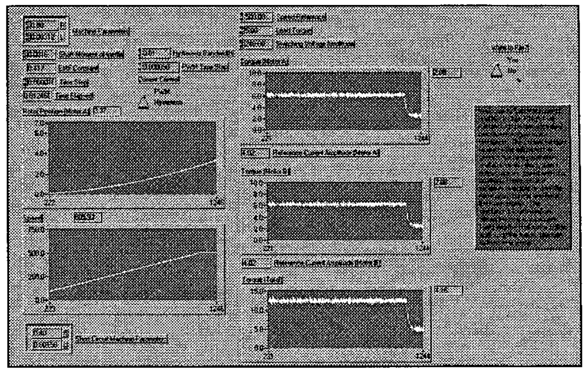


Fig. 6 Global virtual instrument user interface showing the dual motor pair accelerating from standstill to reach a steady state speed of 500rpm.

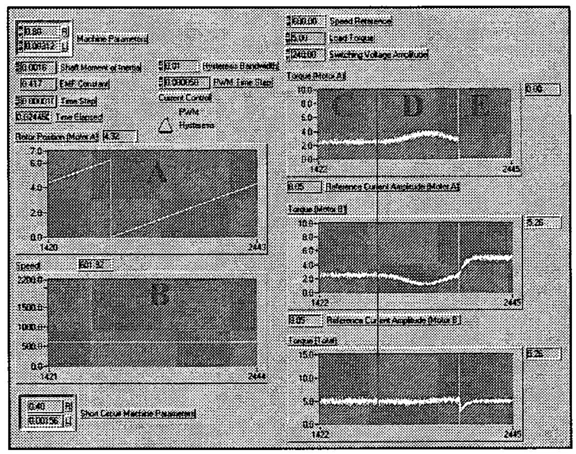


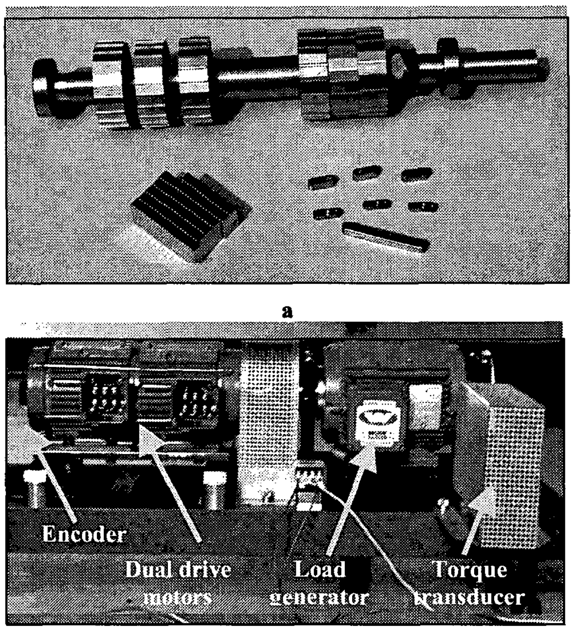
Fig. 7 Front panel of the Global Virtual Instrument demonstrating the constant speed and the operation under artificial faults (Graph A : Rotor position; Graph B: Actual shaft speed; Region C: No fault, both motors develops equal torque; Region D: Phase 1 of Motor 2 is turned off; Region E: Motor 1 is switched off)

IV. CONSTRUCTION OF THE LABORATORY SYSTEM

Fig. 8 illustrates a two-motor arrangement, which is designed for the laboratory testing. However, this limited-scale laboratory demonstration setup is still under investigation. Therefore, the hardware development section of the system is briefly explained here.

A. Realisation of the Dual Motor

In this study, due to the simplicity of manufacturing and efficiency, a three-phase surface-mounted Brushless PM motor is selected as a prime mover. To construct a test system, two 1.1kW, 50Hz induction machines are utilised. Firstly, the terminals of the stator windings of the motors are separated to allow the integration of H-bridges. Then the original squirrel cage rotors are replaced with two identical rotors with permanent magnets that have been designed and constructed on a solid shaft. Each rotor has three axial segments with NdFeB magnets. In order to retain the magnets to the rotor segments, fibreglass roving was used to bind the rotor segments. Special keyways are also added to the segments and to the shaft to allow either step skewing one stator slot pitch or for unskewing.



a

b

Fig. 8 Hardware components of the dual motor and the experimental setup.
a) Rotor shaft showing three rotor slices per motor (top), the collection of magnets before they have been attached to the rotor cores (bottom left) and the keys used to offset and fix the rotor slices (bottom right)
b) Complete dual motor drive and load generator with the torque transducer attached

Fig. 9 is given to demonstrate the identicalness of the back emf waveforms of the two motor segments.

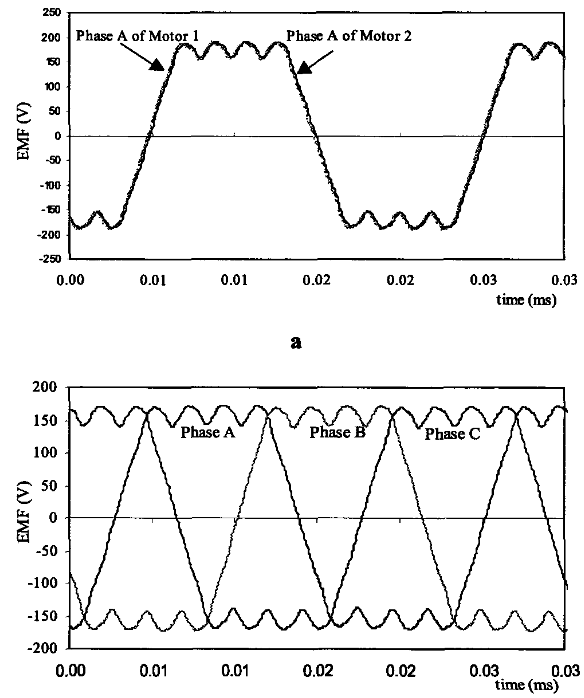
Six H-bridge power modules were built to control the six windings of the dual motor configuration. Each inverter module utilises IGBTs as switching devices, and accommodates fast recovery diodes, driver chips (IR2110), and an opto-coupler configuration to isolate each inverter, which ensures that a malfunction somewhere in the system does not propagate to the other sections.

B. Digital Signal Processor Control System

Three Analog Devices ADMC401 evaluation kits were chosen to built the fault-tolerant motor controller (see Fig. 3). This evaluation kit 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 dual motor drive being developed as part of this project.

The DSP core of the ADMC401 houses a 2K x 24 bit internal program RAM, a 2K x 24-bit internal program ROM and a 1K x 16-bit internal data RAM. The various RAMs and ROM can be booted from a number of internal and external sources, and the program ROM includes features that allow software debugging though the chip's serial port.

Also included in the ADMC401 are a number of specialised motor control peripherals. A high-performance, 8-channel, 12-bit ADC system with dual channel simultaneous sampling ability across 4 pair of inputs is well suited to interfacing with the various transducers and sensors included in the drive system. The evaluation kit also includes a three-phase, 16-bit, PWM generation unit suitable for the production of current control signal as demonstrated by the LabView simulation.



a

b

Fig. 9 Measured back emf waveforms of the dual PM motor.
a) Comparison of the back emfs (a phase error of 3° electrical is measured, which is due to the small error in aligning of the stator slots.
b) Three -phase back emfs of Motor 1.

Other notable components of the DSP evaluation kit include: an encoder interface unit for position sensor feedback; twelve lines of digital IO, and an interrupt controller that manages all peripheral interrupts.

A Hewlett Packard three channel encoder is mounted on the dual motor system's main shaft. The encoder generates three separate square waveforms (Ch A, Ch B and Index pulses), which can be fed into the digital signal processor, which requires information concerning the rotor position to generate the switching signals for the inverters.

The content of the ADMC401 software stages are as follows:

- Stage one: three phase sine wave generation module
- Stage two: analog to digital conversion module
- Stage three: rotary encoder module
- Stage four: main control module

V. Conclusions and Future Work

The design and implementation of the various components of the fault tolerant drive system is explained.

The detailed electrical model of the motor drive was given. There is a considerable amount of flexibility provided by the computer simulation, as it enables the machine parameters to be adjusted to simulate almost any permanent magnet machine pair.

As demonstrated, the development of the complete computer simulation provides a useful tool to study the drive in detail, which allows the user to observe the system's reaction to synthetic faults, and also allows to facilitate the tuning of the speed controller.

It is believed that the recommended electric motor configuration, power electronics circuits and control technologies can be utilised as enabling technologies to be utilised in various critical applications where the fault-tolerance is important, such as AEA and pump drives in nuclear power stations.

The future work in this project will include the integration and realisation of the DSP based control using the dual motor configuration, which is currently under investigation.

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