

Disturbance Free Operation of Fault-Tolerant Permanent Magnet Machines with diverse Fault Scenarios in Aircraft Applications

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Abstract—This paper examines thoroughly different types of fault in windings, and circuits interfacing fault-tolerant permanent magnet machines into a common DC bus. Analytical expressions that predict the system performance during a fault were derived. The failures either in the windings or driving circuits are normally accompanied with low frequency ripple components in the developed torque and the DC link voltage/current. Annotative, simple and robust techniques are advised for compensating torque ripples. The proposed controls were corroborated through comprehensive simulation work for wide range of operating speeds/load conditions.

Key words: Fault-tolerance, Permanent magnet, Open/Short circuit fault, Low frequency ripples, H-bridge inverter

I. INTRODUCTION

Aerospace industry requires application of fault-tolerant machines in different subsystems [1,2]. Fault-tolerance implies the ability of motor/generator set to continue functioning after developing a sustained fault in a satisfactory performance. This involves a slight reduction in the developed torque/generated power with minimal ripples level [3,4].

The conventional Permanent Magnet (PM) machines typically offer highest power to the mass ratio among different machine options; however their fault-tolerance capabilities are poor [5-8]. Thus, a radical change in the design and implementation of PM has to be advised, to compete in the area of safety critical applications [5-8].

Recently the fault-tolerance strategy has been adopted in PM machines. This is achieved by implementing the machine using the modular approach [5-8]. The modular approach implies that each phase in the machine is electrically, magnetically and thermally isolated from the remaining phases. Moreover, the phase has a high reactance of nearly 1 pu value. This is to limit the short circuit current to the rated level, which allows the machine operation with a sustained fault without exceeding the windings thermal limit. The fault-tolerant PM machine has typically a high phase number, which permits the machine introducing a reasonable amount of power/torque after losing one or more phases [5-8]. The modular approach is extended to the drive circuit; each phase of the machine is connected to a separate single-phase H-bridge converter. The converters are thermally and electrically isolated from each other. This is to ensure that the fault in a converter module is constrained not propagate

to the remaining modules/phases [7-8].

The operation of the fault-tolerant PM machines with failures either in windings or interfacing circuits is inadequately addressed in the literature [9-21]. The phase short circuit failure at the terminal was addressed in [10-12], while illustrating the advantages of the fault-tolerance design strategy of brushless DC machines in limiting the short circuit current to the rated value. However, the impact of this type of fault on the machine developed torque and/or the DC link current/voltage are not investigated.

The single turn short circuit was highlighted in [10,17,18]. It was shown experimentally in [10] that the single turn failure results in a current many times more than the rated value. Ref. [10] proposes a detection method for the single turn short failure; and it claims that the best remedy option is to shorten the entire phase.

A switch short circuit failure in an H-bridge module interfacing the brushless DC machine into the common DC bus was partly investigated in [19]. This failure resulted in unidirectional phase current, when inappropriate control strategy was taken. However, the impact of short circuited switch failure regarding the machine developed torque and/or the DC link voltage/current are not investigated in [19]. The author in [20] investigated only switch short circuit failure, and advised analytical expressions for the current during the fault. However, no attention was paid for the ripples in speed or to other types of fault in the driving circuits and the PM machine.

Ref. [21] analyzes the operation of multi-phase motor with an open circuit phase failure. The techniques proposed in [21] depend on the pre-fault states; and they are derived for specific phase numbers. Furthermore, the analysis has not paid attention to phase short circuit failure, or faults that are likely to develop in the driving circuits.

The operation of the fault-tolerant PM machine under different fault scenarios either in the machine windings or in the H-bridge circuits is thoroughly investigated. The behavior of the system during fault is analyzed. The remedy actions that eliminate/reduce the consequences of the fault are identified. Low frequency ripple component is normally produced in the machine developed torque and in the DC link voltage/current following the majority of faults; therefore analytical expressions are derived for the currents in unfaulted phases to suppress these unavoidable consequences.

II. FAULT-TOLERANT PM DRIVE

The analysis given below is valid irrespective of direction of the power into the machine; however for the purpose of demonstration a six-phase fault-tolerant PM motor is considered. Six single-phase H-bridges inverters are used to interface the PM motor into a common DC bus. The motor is proposed to drive the aircraft fuel pump [7], the machine parameters [7] are given in Table 1. The equivalent circuit of the PM motor drive is shown in Fig. 1.

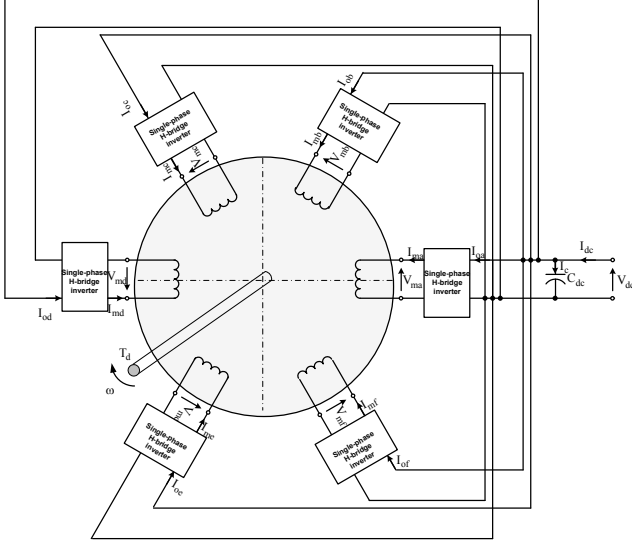


Fig. 1. Equivalent circuit of the PM motor driving the aircraft fuel pump

TABLE I
MACHINE PARAMETER [7]

Rated power	16kW
Number of phases	6
Number of poles	8
Operating speed	13000 rpm
RMS of motor back emf at operating speed	140.64 V
RMS rated current	19A
Per-phase inductance	1.28mH
Per-phase resistance	156mΩ
Phase separation	60°

The six-phase motor could be considered as two sets of three-phase system arrangement. Phases A, C and E constitute one three-phase system set, while the other set is composed of phases B, D and F. For each set, the developed torque has no ripple component. If an entire set was disabled, the motor torque will be halved; however it contains only pure DC component.

The conventional PM motor has low per unit inductance; therefore the phase terminal voltage is almost in phase with the motor generated voltage. However, in the fault-tolerant PM motor, the high phase inductance introduces reasonable angle between the terminal and the generated voltages of the motor, as shown in phasor diagrams, Fig. 2. In these phasor diagrams, the fundamental components of the generated voltage, terminal voltage and current are drawn. The phase current is also assumed to be in phase with the generated voltage.

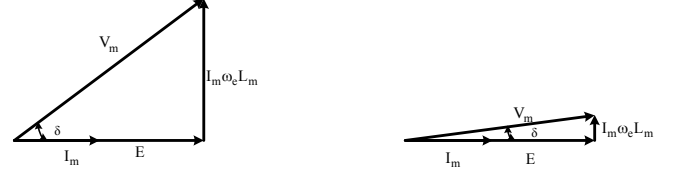


Fig. 2. Phasor diagrams, left: fault-tolerant, right: conventional PM motor for the same value of the per unit current and the generated voltage

The implication of this phenomenon in the fault-tolerant PM motor is the difficulty of simultaneous compensation of low frequency ripples in the motor developed torque and the DC-link in case of fault. However, employing a large DC capacitor reduces the ripple in the DC-link to acceptable levels.

Many faults are possible to occur within the windings or in the drive circuit of the PM drive. In this paper, only the principal faults are addressed. These are divided into: electromagnetic faults in the windings; and electronic faults in the drive circuits. The machine winding faults are likely winding short/open circuit at the terminal and turn-to-turn short circuit. While the faults in H-bridges could be power device short/open circuit in a module.

III. ANALYSIS OF THE FAULTS IN THE MACHINE WINDING

The electric machines are naturally exposed to adverse conditions of heat and vibration; which progressively results in deterioration and eventual breakdown of the windings and the insulation; thus a variety of faults are developed. The major faults within the windings are:

1. Winding open circuit,
2. Winding short circuit at the terminals,
3. Winding short circuit (single-turn/turn-to-turn).

These faults are addressed comprehensively in the following.

A. Winding open circuit

The open circuit winding failure has serious consequences as the remaining phases have to be overrated to maintain the same torque level as pre-fault state; otherwise the net torque is reduced by factor of number of faulted phases to the total number of motor phases. Moreover, significant low frequency ripple components are produced in the developed torque and the DC-link voltage/current.

The ripples in the DC-link, as mentioned before, could be reduced by deploying large DC-link. Meanwhile, the torque ripples unless compensated, stress the mechanical system composed from the motor and the load. An innovative solution is advised here for suppressing torque ripples. The values of the currents in unfaulted phases that compensate torque ripples are derived.

For the purpose of analysis a conceptual two-phase system is reproduced from the six-phase motor, Fig.1, and shown in Fig.3. The phases are marked 1 and 2. The phase separation between the two windings is 2ϕ , where the angle ϕ can have any value between 0 and π , $\phi = 0 \rightarrow \pi$. This is to generalize the analysis for any arbitrary system; irrespective of the position/order of the faulty phase provided that the number of the remaining healthy phases

is even.

The following assumptions are considered to simplify the analysis:

1. The inertia of the machine is sufficiently high such that the machine mechanical speed ω_m is constant over a fundamental period.
2. The inverters have sufficiently high switching frequency, such that the phase currents i_{m1} and i_{m2} are sinusoidal.
3. Motor phases are identical; thus the phases have the same inductance L_m .
4. The phase resistance is ignored
5. The output filter capacitor C_{dc} is large enough so that the output voltage V_{dc} is purely DC.
6. The inverter output voltages are modulated using Sinusoidal Pulse Width Modulation (SPWM) .

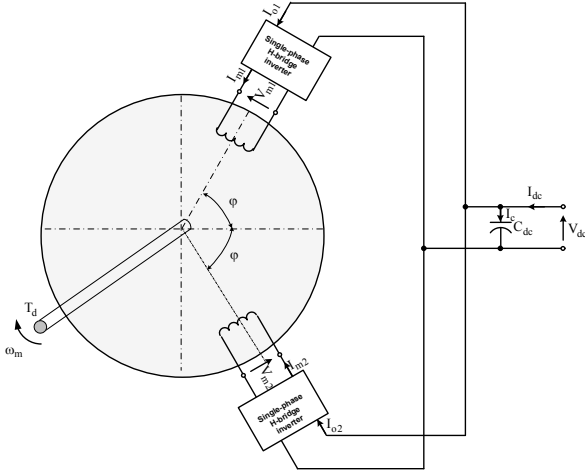


Fig. 3. Conceptual Two-phase PM drive

The developed torque T_d is computed by neglecting the losses and equating the instantaneous input and output powers,

$$T_d = \left(\frac{e_1 i_{m1} + e_2 i_{m2}}{\omega_m} \right) \quad (1)$$

e_1 and e_2 are the back emfs of phases 1 and 2 respectively. Separating the develop torque into average and low frequency ripple components; the average T_{dav} and low frequency ripple T_{dr} components are given by,

$$T_{dav} = \frac{E}{\omega_m} (I_{m1} \cos(\theta_1) + I_{m2} \cos(\theta_2)) \quad (2)$$

$$T_{dr} = -\frac{E I_{m1}}{\omega_m} \exp(j(\varphi - \theta_1)) - \frac{E I_{m2}}{2\omega_m} \exp(j(-\varphi - \theta_2)) \quad (3)$$

$$= -\frac{E}{\omega_m} (i_{m1} r + i_{m2} \bar{r})$$

where $r = e^{j\varphi}$. The capital letters represent the RMS values. The bar over a variable denotes the complex conjugate. Equation (3) gives the low frequency torque ripples in arbitrary two-phase system. The component T_{dr} has twice the value of the supply voltage frequency.

To find the current values that result in zero torque

ripples, it is insufficient to equate T_{dr} to zero; and an additional equation is mandatory to allow explicit solution for i_{m1} and i_{m2} . This equation could be obtained by considering the total complex power S associated with the motor generated voltages :

$$S = P + jQ = \frac{E \bar{i}_{m1}}{2} + \frac{E \bar{i}_{m2}}{2} \quad (4)$$

where P and Q are the total active and reactive powers that flow in the considered two-phase system and are associated to currents and back emfs of the phases. Rearranging (4) to express i_{m2} in terms of \bar{S} and i_{m1} , then substituting the obtained i_{m2} into (3) after equating it to zero and rearranging,

$$0 = -\frac{E}{\omega_m} \left(i_{m1} r + \bar{r} \left(\frac{\bar{S}}{E} - i_{m1} \right) \right) \quad (5)$$

Solving (5) for i_{m1} ,

$$i_{m1} = \frac{-\bar{S} \bar{r}}{E(1 - \bar{r}^2)} \quad (6)$$

and i_{m2} is given by,

$$i_{m2} = \frac{\bar{S}}{E(1 - \bar{r}^2)} \quad (7)$$

Equations (6) and (7) shows that the currents producing zero torque ripples for an arbitrary two-phase winding arrangement have equal magnitude and are load and speed dependent. A particularly desirable solution is one that minimizes the copper losses. The value of the total reactive power that minimizes copper losses in (6) and (7) could be given by,

$$\frac{d}{dQ} (|i_{m1}|^2 + |i_{m2}|^2) = 0 \quad (8)$$

Substituting (6) , (7) and (4) into (8), and differentiating with respect to Q , the total reactive power Q for minimum copper losses is equal to zero. Thus, one phase acts as source for the reactive power, while the other acts as a sink.

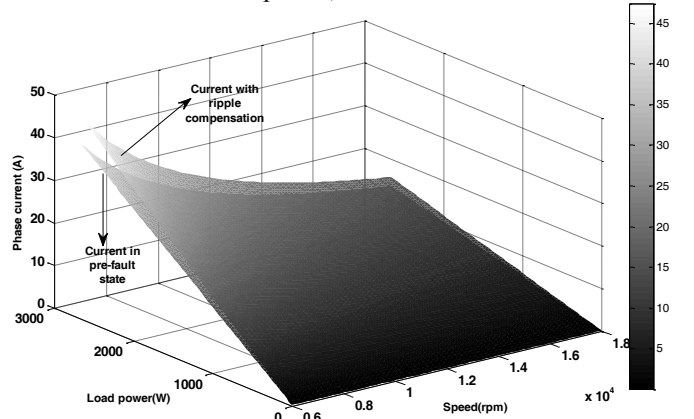


Fig. 4. Phase current for torque ripple compensation and pre-fault state under different speed and load levels for open circuit winding failure, $\varphi = \pi/3$.

Fig. 4, shows the magnitude of the pre-fault current and

that computed from (6) at different load and speed levels. In the pre-fault state, the phase terminal current is in phase with back emf to reduce losses in the winding and the associated H-bridge circuit.

Fig. 4 shows that currents of the unfaulty phases have to be increased by 13% to eliminate torque ripples due a phase open circuit failure. In order to validate the derived analytical expression, the fault-tolerant PM drive is simulated in Saber environment. The PM motor in the pre-fault state is controlled such that the phase terminal current is in phase with the generated voltage.

The torque ripples from simulation and (3) are illustrated in Fig. 5.

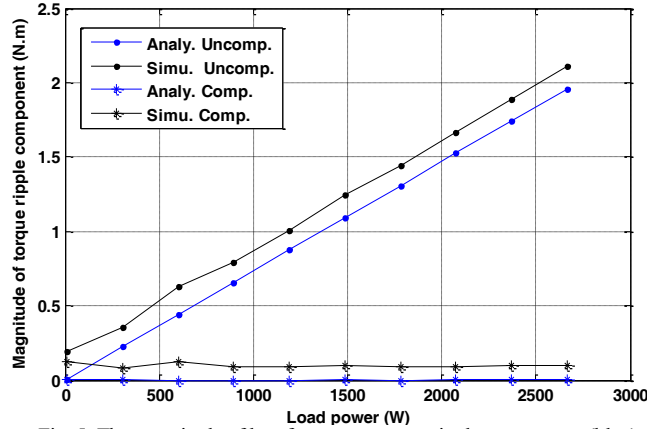


Fig. 5. The magnitude of low frequency torque ripple component: (blue) analytical expression, (black) simulation, (dotted) during open circuit phase failure, (stars) compensated at different load levels and normal speed

The torque ripples from simulation are higher than the calculated, as shown in Fig.5; this is attributed to the ignored losses in the analytical expressions.

Fig. 5 shows that the advised technique reduced the torque ripple by around ten folds, particularly at rated power. This will be significant for medium and large size machines.

The dynamic performance of the drive under concern for an open circuit fault in a phase is investigated in the following. Phase 2, while the machine was running loaded with full load at base speed, is subjected to open circuit failure at 0.1sec. The inverters were openly controlled; and the terminal voltages are modulated using SPWM strategy according to the mentioned operating point. This extends even during the fault. In, the post-fault state, the modulation strategy of phases 4 and 6 are modified according to (6) and (7), while phases 1, 3 and 5 was running with same control in the pre-fault and fault states. The developed torque and drive speed under these circumstances are shown in Fig. 6.

The focus is in on machine transient response following the phase open circuit phase, thus the starting with ignored in Fig. 6. Also, the high frequency switching ripples were removed from Fig. 6, to show obviously the low frequency ripples that result from phase open circuit failure.

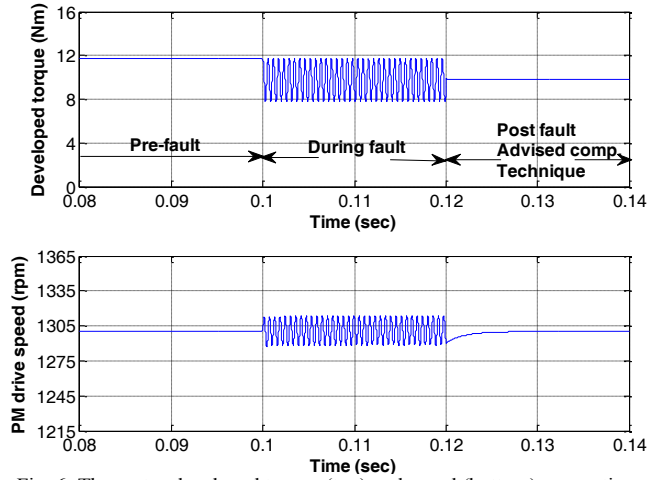


Fig. 6. The motor developed torque (top) and speed (bottom) versus time for pre, during and post the fault with the advised compensation technique for a phase open circuit fault

Fig. 6 reveals that the developed torque and speed experiences following a phase open circuit fault 33.34% and 0.2% ripples respectively. This probably stresses the motor, load and the coupling system. As, the machine has a sufficient inertia, the ripples in the speed are reduced. The drive speed is nearly constant at 13000rpm.

The advised compensation techniques in (6) and (7) successfully suppress the torque and speed ripples, Fig. 6. The developed torque during the post fault state is around 9.8Nm. This is attributed to the value of active power P , (4) used in the simulation; it was set to 5.4kW, which is corresponding to the rated power of two phases. However, in the future work, the active power P will be adjusted according to the load requirement, as the drive will be closed loop controlled.

The values of the phase current in pre-fault and post-fault states are shown in Fig. 7 from simulation and analytically. The currents are obtained for different load levels at nominal speed

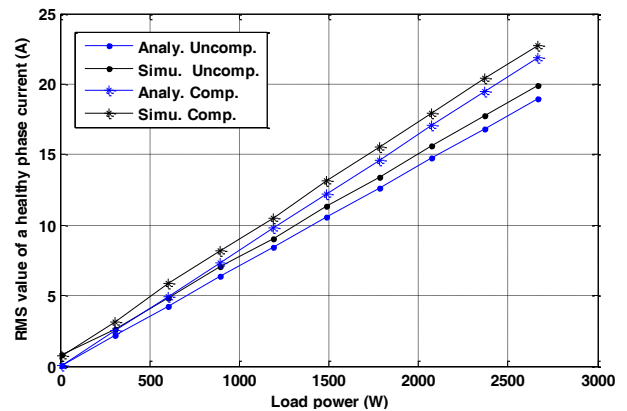


Fig. 7. The RMS value of a healthy phase current : (blue) analytical expression, (black) simulation, (dotted) during open circuit phase failure, (stars) compensated, at different load levels and nominal speed

Again, the simulation gives higher values than the analytical expressions, even for the current magnitudes.

The current in the healthy phase has to be increased by 13% compared to pre-fault state to reduce the torque

ripples. However, the net average torque is reduced by the percentage of number of faulty phases to the total phase number. For our demonstration case, the net average torque in post-fault state is around 83.3% from its value in pre-fault state, Fig. 6.

B. Winding short circuit failure at the terminal (phase to ground)

The design strategy of the fault-tolerant PM drives prevents the phase-to-phase short circuit failure, as each phase is placed around single tooth; then all phase windings are physically separated. However, there is still possibility for phase to ground short circuit failure. The drive is designed to have 1.pu leakage reactance, which limits the current of the faulty phase to the rated value to avoid thermal stress of the windings. Yet, the short circuit failure of a phase in the drive results in reducing the developed torque and introducing a significant ripple component in the drive torque/speed, which may deteriorate the performance of the fuel pump and hence jeopardize the flight.

Similarly to the open circuit phase failure, the values of the currents in the unfaulted phases that suppress low frequency torque ripple component are derived here.

A conceptual three-phase system with a shorted phase is shown in Fig. 8. The assumptions applied for analyzing the case of open circuit phase failure are valid here. The current in the shorted phase is given by,

$$i_{msc} = j \frac{E}{\omega_e L_m} \quad (8)$$

ω_e is the electrical frequency in rad/sec. Equation (8) indicates that the shorted phase produce no average torque/power, as current is 90° lagging the phase generated voltage. Therefore, equation (2) still gives the average developed torque for short circuit failure.

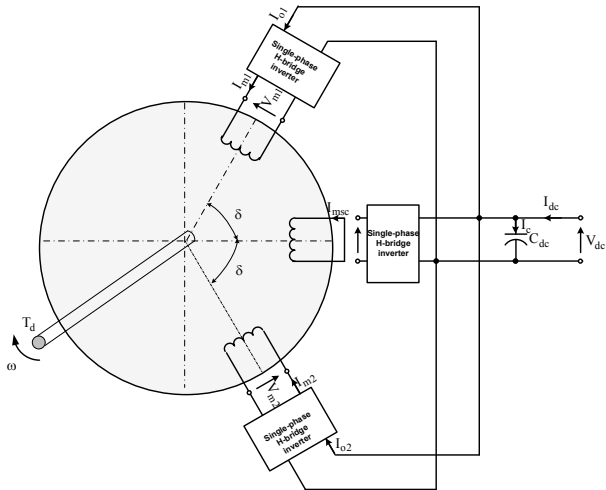


Fig. 8. Conceptual Three-phase with a shorted phase

Torque ripple component under phase short circuit failure is given by,

$$T_{dr} = -\frac{E}{\omega_m} (i_{m1} r + j \frac{E}{\omega_e L_m} + i_{m2} \bar{r}) \quad (9)$$

Again, rearranging (4) to express i_{m2} in terms of \bar{S} , and i_{m1} , then substituting the obtained i_{m2} into (9) after equating it to zero and rearranging,

$$0 = -\frac{E}{\omega_m} (i_{m1} r + j \frac{E}{\omega_e L_m} + \bar{r} \left(\frac{\bar{S}}{E} - i_{m1} \right)) \quad (10)$$

Solving (10) for i_{m1} ,

$$i_{m1} = \frac{-\bar{S} \bar{r}^2}{E (1 - \bar{r}^2)} - \frac{j E \bar{r}}{\omega_e L_m (1 - \bar{r}^2)} \quad (11)$$

and i_{m2} is given by,

$$i_{m2} = \frac{\bar{S}}{E (1 - \bar{r}^2)} + \frac{j E \bar{r}}{\omega_e L_m (1 - \bar{r}^2)} \quad (12)$$

The values of i_{m1} and i_{m2} that produce no torque ripple component in case of phase short circuit failure are given by (11) and (12). These expressions are load and speed dependent. The current magnitudes (11) and (12) here are unequal compared with (6) and (7).

Again equation (8) is used to give the value of the reactive power Q that minimizes the copper losses. Substituting (11), (12) and (4) into (8), then differentiating with respect to Q , the total reactive power Q for minimum copper losses is equal to zero, similarly to the previous case. Similarly to open circuit fault, one phase acts reactive power source, while the other is a sink.

The magnitude of the pre-fault current and that computed from (11) at different load and speed levels are shown in Fig.9. In the pre-fault state, the phase terminal current is in phase with back emf.

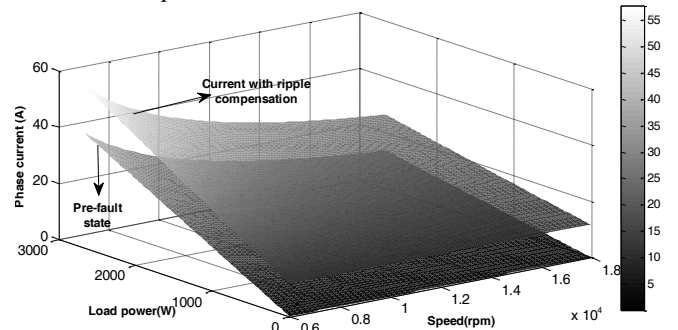


Fig. 9. Phase current for torque ripple compensation and pre-fault state under different speed and load levels for open short winding failure, $\phi = \pi/3$.

Torque ripple compensation following phase short circuit failure requires tremendous increase in the currents of the healthy phases particularly at light loads, which may yield thermal stress for these phases. This increase is inevitable due to the current in the shorted phase.

A revision for the design philosophy of the fault-tolerant PM motor should be carried out. Since, the claimed benefits of introducing high per unit inductance for limiting the current under short circuit failure are overwhelmed by the ripples produced in the developed torque and DC link. Moreover, the torque ripples compensation technique as shown in Fig. 8 results in currents in healthy phases that are approximately twice the rated current, which stress these

winding significantly.

The magnitudes of the torque ripples and current in a healthy phase with and without torque ripple compensation are shown in Figs. 10 and 11.

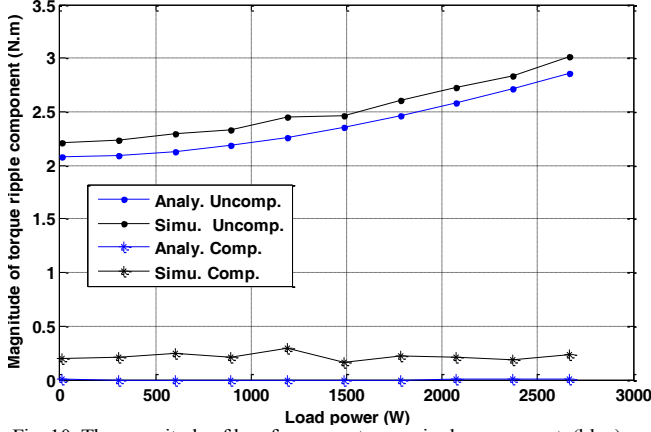


Fig. 10. The magnitude of low frequency torque ripple component : (blue) analytical expression, (black) simulation, (dotted) during open circuit phase failure, (stars) compensated, at different load levels and normal speed

The short circuit failure of a phase results in a significant torque ripples even under no/light load conditions. This is attributed to the current in the shorted phase. Fig. 10 shows that there are adequate correlation between the simulation and analytical expressions.

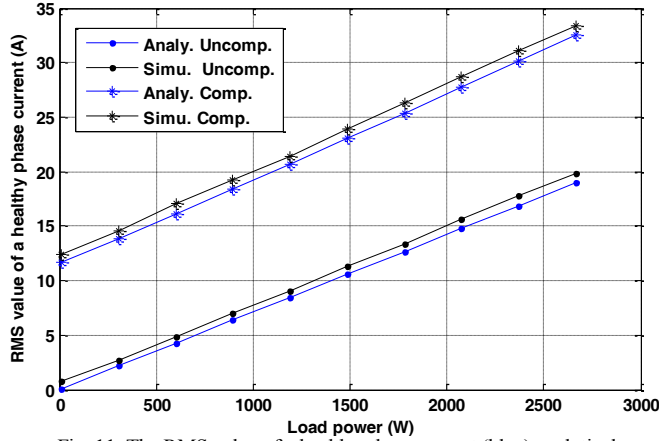


Fig. 11. The RMS value of a healthy phase current (blue) analytical expression (black) simulation, (dotted) during open circuit phase failure (stars) compensated at different load levels and normal speed

The currents in the healthy phases have to contain a component that neutralizes the torque ripple produced from the shorted phase. The value of this component is load independent; it depends only on the shorted circuit current, as shown in Fig. 11. For, the system under consideration, this component is found to be around 50% of the current in the shorted phase.

Again, the transient response of the drive under concern for a short circuit fault in phase 4 is investigated in the following. While the machine was loaded by rated load at nominal speed, phase 4 develops short circuit fault at the terminals. The inverters were openly controlled; and the terminal voltages are modulated using SPWM strategy

according to the mentioned operating point. This extends even during the fault. In the post-fault state, the modulation strategy of phases 2 and 6 are modified according to (11) and (12), while phases 1, 3 and 5 was running with same control in the pre-fault and fault states. The developed torque and drive speed under these circumstances are shown in Fig. 12.

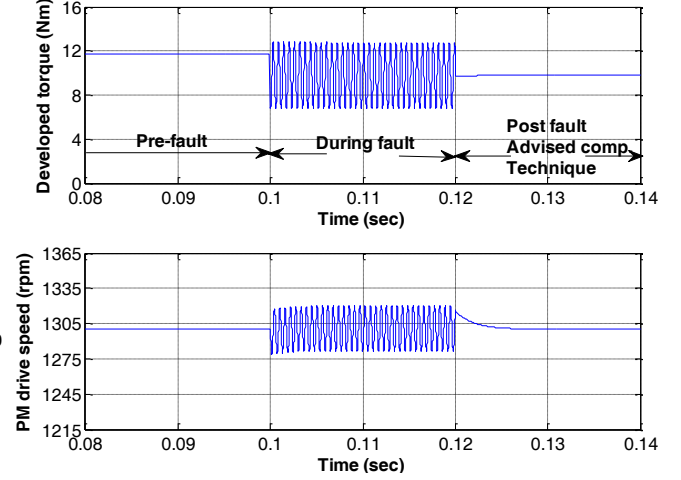


Fig. 12. The motor developed torque (top) and speed (bottom) versus time for pre, during and post the fault with the advised compensation technique for a phase short circuit fault

The phase short circuit fault has more severe consequences than that of open circuit one, as shown from Figs. 6 and 12. The ripples in the developed torque and speed during the phase short circuit failure are increased to 51.5% and 0.35% respectively, which eventually degraded the performance of the drive system. Fig. 12 shows that the machine speed settles at around 13000rpm.

Fig. 12 corroborates the viability of the proposed compensation technique (11) and (12) in suppressing torque ripples following to short circuit phase failure. Again, the developed torque during the post fault state is settled at 9.8Nm. This is attributed to the value of active power P , (4) used in the simulation; it was set to 5.4kW, which is corresponding to the rated power of two phases. However, in the future work, the active power P will be adjusted according to the load requirement, as the drive will be closed loop controlled.

C. Winding single-turn short circuit

Particular emphasis is directed into single turn short circuit failure, as this fault could not be detected easily, and its possibility is quite high.

For simplicity, consider a phase that has n turns and R_m resistance. k turns of the phase winding develop a short circuit fault. The current flows in the shorted turns is given by,

$$i_{tsc} = \frac{E(k/n)}{R_m(k/n) + j\omega_e L_m(k/n)^2} \quad (12)$$

Neglecting the resistance, the current i_{tsc} in the shorted turns is (n/k) times the phase short circuit current i_{msc} , (8).

Obviously, the most severe case is a single shorted turn, where parameter k is equal to 1. However, for single-turn or group of turns short circuit failure, the resistance has a comparable value to the inductance; thus it could not be ignored. Ref. [10] claims that for this type of fault, the resistance term is dominant, but the fault current is still significantly large even compared with phase short circuit current; which eventually causes very high localized heating.

This fault could be physically explained through realization that the MMF of the shorted turns is trying to produce a flux component; which neutralizes the whole flux linkage of the phase.

The detection of the single turn/turn-to-turn short is still under ongoing research, a technique was advised in [10] for detecting single turn short circuit failure. It is based on monitoring the PWM harmonic current. The single turn fault, as claimed in [10], has impact on phase current at PWM frequency. However, this technique is complicated, expensive and unreliable due to the difficulty of differentiating between the harmonics resulted from single turn failure or those from switching strategy. The advised remedy action for this fault once detected is shortening the entire phase through the H-bridge converter, as the fault-tolerant PM machines are designed to accommodate phase short circuit only. In this scenario, a compromise has to be carried out between the windings thermal stress and the torque ripples.

IV. ANALYSIS OF THE DRIVE CIRCUIT FAILURES

The faults in drive circuit result in quite different performance from those corresponding to winding failures; regarding the phase current. The major faults that occur in the drive circuits are device short and open circuit. These will be addressed comprehensively in the following sections.

A. Device short circuit failure

A power device short circuit failure results in unidirectional current with significant DC component, when inappropriate control action is taken. This failure was partly investigated in [19] neither with mathematical manipulation nor with comprehensive discussion of the remedial strategies. In the following, this fault is thoroughly analyzed.

The per-phase equivalent circuit of an H-bridge module and motor phase is shown in Fig. 13, where switch 4 is short circuited. The fault may be due to internal defects in the switch. The PM motor is modeled as sinusoidal AC voltage source in series with the resistance and inductance.

In the following analysis, the switching frequency is assumed sufficiently high and SPWM modulation strategy is used; thus inverter current could be considered sinusoidal. The motor back emf is taken as a reference.

Switches 1 and 2 conduct the positive half cycle of the current before the fault; however, during the fault triggering switch 1 results in a shoot-through that possibly damages the switching devices and the DC link. Obviously the degrees of freedom are limited with a short circuited switch in the drive circuit.

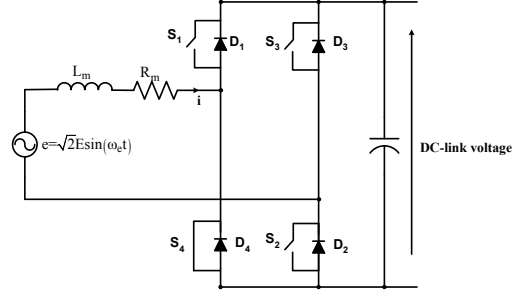


Fig. 13. Per-phase equivalent circuit of the PM drive with a short circuit fault in switch 4

The conventional control strategy for short circuit switch fault, Fig.13, is to block all gate signals. Blocking the gate signals causes the current to circulate between the motor phase, switch 4 and diode 2. The voltage across the phase winding is the emf; therefore the current is given by,

$$i_m = \frac{\sqrt{2}E}{\sqrt{(\omega L_m)^2 + R_m^2}} \sin(\theta) e^{-\frac{t L_m}{R_m}} + \frac{\sqrt{2}E}{\sqrt{(\omega L_m)^2 + R_m^2}} \sin(\omega_e t - \theta) \quad (13)$$

where, $\theta = \tan^{-1} \left(\frac{\omega_e L_m}{R_m} \right)$. It is apparent that the phase current i_m in (13) has a DC component.

The phase current continues to build during the whole positive half cycle of the motor back emf. During the negative half cycle of the motor emf, the current is large and positive; therefore, the current still flows through diode 2 and switch 4 applying negative voltage across the phase winding, which reduces the current. If the current tries to reverse, diode 3 and switch 4 conduct; however the current will be driven back to zero, as this combination connects the motor to the DC-link in such way to reduce the current. Therefore, the current is likely to settle around the zero until the next positive half cycle of the motor emf begins.

It could be concluded that inappropriate control strategy following to a device short circuit failure results in a sustained DC component in the inverter output current.

Fig. 14 shows the inverter output currents calculated from (13) and simulated for the machine parameters reported in Table 1.

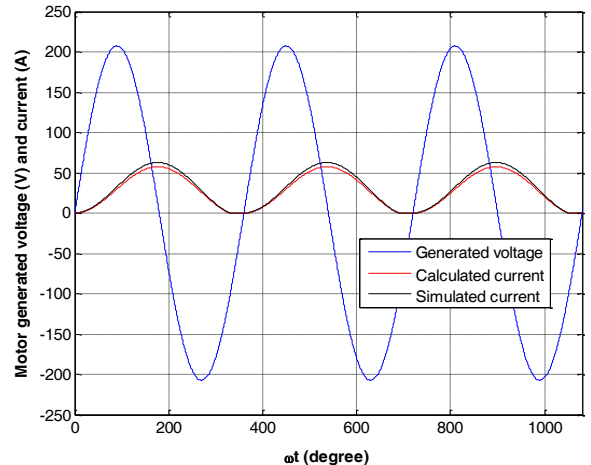


Fig. 14. Motor voltage and current, voltage (blue), current calculated (red), current simulated (black) during the short-circuit fault of a H-bridge switch

The DC component is apparent in the inverter current; this component could saturate the machine and results in excessive iron losses. Fig. 14 shows that equation (13) predicts the current during the fault. The current during the fault is also around two times rated current.

As mentioned before that there are limited options for the short circuit switch fault. Triggering the complementary switch, the switch in the same leg, is not desirable option as it causes shoot-through that damages the DC link and the switching elements.

Activating the diagonal switch, the switch in opposite location in the healthy leg, transfers the current from diode 2. However, this strategy increases the magnitude of the current significantly, as the DC link now is adding to the motor emf.

Activating the switch in the same position in the healthy leg continuously seems to be the available option, as this short circuits the whole motor phase, which removes the sustained DC component from flowing into the phase winding. However, the situation reverts to the phase short circuit failure with its consequences. Additionally, continuously triggering of the switch in the faulty phase increases the conduction losses due to 360° conduction. The proposed control strategy is shown in Fig. 15,

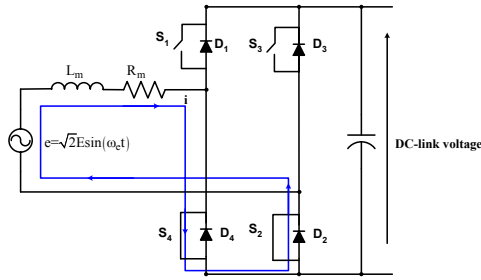


Fig. 15. The proposed control strategy, the current path

The current path in the proposed control action is shown in Fig. 15.

The instantaneous developed torque and speed are plotted in Fig.16 for pre, during and post fault states. In developing Fig. 16, the high frequency harmonics in the developed torque/speed are ignored, as the machine has sufficient inertia.

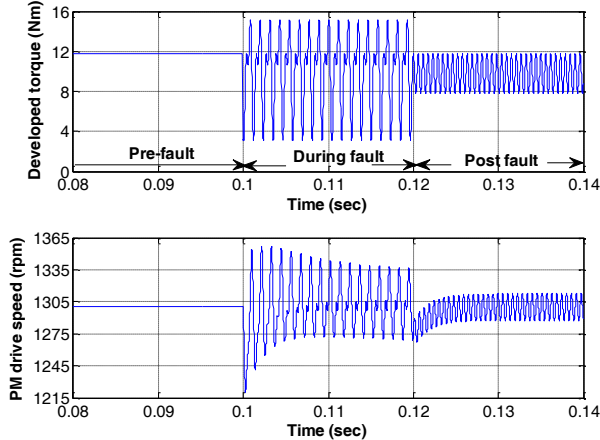


Fig. 16. The motor developed torque (top) and speed (bottom) versus time for pre, during and post the fault with the advised compensation technique for a switch short circuit fault

In the pre-fault state, when the six phases are running normally, the instantaneous developed torque is ripple free and has the value of 11.73Nm. However, when a device in an H-bridge develops a short-circuit fault and inappropriate control action was taken, large ripples are present in the instantaneous developed torque and drive speed, Fig. 16. These ripples could be destructive for the load and the motor mechanical parts. These ripples are reduced significantly with the proposed control strategy. The proposed control technique, however, reduces the torque capability, Fig. 16, where the average value of the developed torque in the post-fault state is around 9.8 Nm as compared with 11.73 Nm in the pre-fault state. The advised remedy strategy for torque ripple compensation under short circuit phase failure could then be employed.

Again, a compromise should be carried out between thermal stress in the healthy phases due to the proposed technique and the allowed level of ripples in the torque and the speed.

Comparing Figs. 6, 12 and 16 reveals that a switch short circuit failure results in significant ripples either in torque or speed than other fault types. Thus, this type of fault should be promptly diagnosed .

B. Device open circuit failure

If a switch in an H-bridge fails to close, while the remaining switches are still operating according to the pre-fault switching strategy; a unidirectional current circulates between the phase and the H-bridge. Again equation (13) predicts the phase current in the fault state. The recommended remedy option for this failure is to block the gate signals from other switches, as this disconnects the phase from the H-bridge and the DC link, which resembles phase open circuit failure. Then, the torque ripples resulted from deliberately opening the faulty phase could be compensated using the technique proposed in this work.

V. CONCLUSIONS

The following conclusions are drawn:

1. The fault-tolerant PM is designed with high per unit inductance to limit phase short circuit current to the rated value. This philosophy has the disadvantages of difficulty of compensating ripples in the developed torque and the DC link simultaneously.
2. Generally the ripples in the DC link are attenuated by deploying large DC capacitor.
3. Open circuit failure of a phase results in significant ripple component in the developed torque and the DC link. Innovative strategy is proposed for compensating the low frequency torque ripples; this technique has the merits of simplicity, robustness and generality. Since it could be applied irrespective to motor size, number of phases, speed, load or operating condition. Further, it is independent on pre-fault state, as it requires only sensing load power. Although, the proposed compensation scheme is derived for two-phase system; however it

could be applied for a drive with arbitrary phase number provided that the number of healthy phases after open circuit phase(s) is even.

4. A simple and innovative technique was proposed for compensating torque ripples in case of phase short circuit failure. This technique is independent on pre-fault state. Moreover, it could be applied for motor with any phase number, as if the number of healthy phases is even.
5. For the compensation of the low frequency torque ripples resulted from a phase short circuit failure, the current in the healthy phases is composed from two components. One component is load independent, and nearly equal to half of the phase short circuit current. It is aimed to neutralize the ripples resulted from the short circuit current.
6. The most hazardous fault is single turn short, as the current circulates in the shorted turn is around the number of turns times the rated current, which could causes permanent damage for the phase. A detection technique was discussed; however this method has the disadvantages of complexity and unreliability. Therefore, simple and inexpensive detection methods for this fault have to be developed.
7. The optimal control strategy for single turn/turn-to-turn short is to shorten the entire phase.
8. A sustained DC component in the phase terminal current is resulted due to a switch open circuit failure or inappropriate control action in case of a switch short circuit failure. This is attributed to the free-wheeling of the anti-parallel diodes. The presence of these diodes actively prevents the current in the faulted phase from reversing. The sustained DC component reduces the drive torque capability, saturates the machine irons and increases the losses.
9. The available remedy for the short circuited switch is continuously gating the switch in the same position in the healthy leg to intentionally shorten the whole phase. This allows the DC component of the current to decay. However, this implies that the control system and gate circuits remain functioning and available during the fault.
10. For open circuited switch, the recommended control action is to disable all gate signals of the healthy switches in the faulty H-bridge, which resemble open circuit of the faulty phase. Again, this is possible, if the control system and gate circuits are still operating.

REFERENCES

- [1] Jones, R. I. "The More Electric Aircraft: the past and the future?" IEE Colloquium on Electrical Machines and Systems for the More Electric Aircraft, pp. 1-4, 1999.
- [2] Mecrow, B. C.; Atkinson, D. J.; Jack, A. G.; Green, S. and Haylock, J. A. "THE NEED FOR FAULT TOLERANCE IN AEROENGINE ELECTRIC FUEL CONTROL SYSTEM," *IEE Electric Power Applications*, vol. 20, pp. 1-5, 1999.
- [3] Argile, R. N.; Mecrow, B. C.; Atkinson, D. J.; Jack, A. G. and Sangha, P. "reliability analysis of fault tolerant drive topologies," in the Proceeding of The 4th IET International Conference on Power Electronics, Machines and Drives, 2008, PEMD 2008, pp. 11-15, 2008.
- [4] White, R. V. and Miles, F. M. "Principles of fault tolerance," in the Proceeding of Eighth Annual Applied Power Electronics Conference and Exposition, 1996, APEC '96, pp. 18-25, 1996.
- [5] El-Refaie, A.M., " Fault-tolerant permanent magnet machines: a review" *IET Electric Power Applications*, vol. 5, No. 1, pp. 59-74, 2011.
- [6] Mohammadpour, A. ; Gandhi, A. ; Parsa, L. "Design and control of fault-tolerant permanent magnet machines " IEEE Workshop on Electrical Machines Design Control and Diagnosis (WEMDCD), 2013, pp. 108-116, 2013.
- [7] Jack, A. G.; Mecrow, B. C.; Haylock, J. A. and Coles, J. "Fault-tolerant permanent magnet machine drives," *IEE Electric Power Applications*, vol. 143, pp. 437-442, November 1996.
- [8] Mitcham, A. J.; Antonopoulos, G.; and Cullen, J. A. "Favorable slot and pole number combinations for fault-tolerant PM machines," *IEE Electric Power Applications*, vol. 151, pp. 520-525, 9 September 2004.
- [9] Bianchini, C. ; Fornasiero, E. ; Matzen, T.N. ; Bianchi, N. and Bellini, A. " Fault detection of a five-phase Permanent-Magnet machine" 34th Annual Conference of IEEE Industrial Electronics, 2008. IECON 2008, pp. 1200-1205, Orlando, USA, 10-13 Nov., 2008.
- [10] Jack, A. G.; Mecrow, B. C.; and Haylock, J. A. and Atkinson, D. J. "Operation of Fault Tolerant Machines with winding Failures " *IEEE Transactions on Energy Conversion*, vol. 14, pp. 1490-1495, December 1999.
- [11] Dwari, S. ; Parsa, L. " Optimum Fault-Tolerant Control of Multi-phase Permanent Magnet Machines for Open-Circuit and Short-Circuit Faults " Twenty Second Annual IEEE Applied Power Electronics Conference, APEC 2007, pp. 1417-1422, 2007.
- [12] Pang, Y. ; Zhu, Z.Q. ; Chen, X.J. and Channon, S. " Design concept of short-circuit fault-tolerance permanent magnet machine " 5th IET International Conference on Power Electronics, Machines and Drives (PEMD 2010), pp. 1 – 4, Brighton, UK , 19-21 April, 2010.
- [13] Shamsi-Nejad, M.-A. ; Nahid-Mobarakeh, B. ; Pierfederici, S. and Meibody-Tabar, F. " Fault Tolerant and Minimum Loss Control of Double-Star Synchronous Machines Under Open Phase Conditions" *IEEE Transactions on Industrial Electronics*, vol. 55, no. 5, pp. 1956-1965, 2008.
- [14] Zhigang Sun ; Jiabin Wang ; Howe, D. ; Jewell, G. "Analytical Prediction of the Short-Circuit Current in Fault-Tolerant Permanent-Magnet Machines " *IEEE Transactions on Industrial Electronics*, vol. 55, no. 12, pp. 4210-4217, 2008.
- [15] Mohammadpour, Ali and Parsa, Leila , "Post-fault control technique for multi-phase PM motor drives under short-circuit faults" Twenty-Eighth Annual IEEE Applied Power Electronics Conference & Exposition (APEC) , 2013, pp. 817-822, 2013.
- [16] Jia-dan Wei and Bo Zhou " Fault tolerant strategies under open phase fault for doubly salient electro-magnet motor drives" International Conference on Electrical Machines and Systems, 2007. ICEMS, pp. 1569-1573, Seoul, South Korea, 8-11 Oct. 2007.
- [17] Chai, J. ; Wang, J. ; Sun, Z. and Howe, D. " Analytical prediction of inter-turn short-circuit current in fault-tolerant permanent magnet brushless machines " 4th IET

Conference on Power Electronics, Machines and Drives, 2008. PEMD 2008, pp. 1-5, 2008.

- [18] Wei Tang ; Guohai Liu and Jinghua Ji " Winding turn-to-turn faults detection of five-phase fault-tolerant permanent-magnet machine based on parametric model " 15th International Conference on Electrical Machines and Systems (ICEMS), 2012, pp. 1-6, 21-24 Oct. 2012.
- [19] Jack, A. G.; Mecrow, B. C.;and Haylock, J. A. "A comparative study of permanent magnet and switched reluctance motors for high-performance fault-tolerant applications," *IEEE Transactions on Industry Applications*, vol. 32, pp. 889-895, July/August 1996.
- [20] A. A. AbdE lahfez" Remedial strategies of faults in Aircraft fuel pump" *Journal of Electrical Engineering, JEE*, vol. 13, no. 1, pp. 10-14, 2013.
- [21] Jen-Ren Fu and Lipo, T.A."Disturbance-free operation of a multiphase current-regulated motor drive with an opened phase" *IEEE Transactions on Industry Applications*, vol. 30, No. 5, pp. 1267-1274, Oct. 1994.