

# Remedial Strategies of the Faults in the Drive Circuit of Aircraft Fuel Pump

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## Abstract

This paper presents a thoroughly analysis for a failure of switching device in H-bridges supplying a fault-tolerant permanent magnet motor that drives aircraft fuel pump. Expressions are derived to predict the inverter current during the fault. The paper also discusses all the possible remedial actions and highlights the most suitable one.

**Key words:** Fault-tolerance , Permanent magnet motor, H-bridge inverter.

## I. INTRODUCTION

Aerospace applications require a fault-tolerant drive that be able to continue operating in an adequate manner after developing a sustained fault [1-3]. A satisfactory performance implies that the drive during/post the fault has minimal torque ripples while providing nearly the same torque level as pre-fault state [4, 5].

The switched reluctance machines have been considered for these high performance applications due to their inherent fault tolerant performance [1, 2, 6], as each phase is fed from a separate H-bridge. However, the SR machines have relatively reduced power density compared to other machine types [7].

The Permanent Magnet (PM) machines typically offer higher power to mass ratio than the SR machines; however their fault-tolerant capabilities are poor [1, 2, 6-10].

Recently the fault-tolerance strategy has been introduced into the PM machines. This is achieved by implementing the machine using the modular approach [1, 6-10]. 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. 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 not propagate to the remaining modules/phases [1, 6-10].

A six-phase fault-tolerant PM machine driven from six single-phase H-bridges inverter is proposed to drive the aircraft fuel pump[1,7],the machine parameters [1] are given in Table1.

TABLE I  
Machine Parameter [1]

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°

Many faults are likely to occur in the windings of the PM machine or in the drive circuit. The principal faults within the PM machine as: winding short/open circuit at the terminal and turn-to-turn short circuit are adequately covered in [1, 2, 6, 7,9]. However, the faults in the drive circuit (H-bridge) such as: power device short/open circuit is not satisfactorily addressed. References [1,7] provides experimental results for short-circuit device in H-bridge drive. These graphs show that the current in the faulted phase is unidirectional with significant DC component, However, neither mathematical manipulation nor comprehensive discussion of the remedial strategies is introduced in [1, 2, 6, 7].

Therefore, the aim of this paper is to examine thoroughly the short-circuited switch in the drive circuit of the PM motor used to drive the aircraft fuel pump and to introduce expressions, which predict the phase current during the fault with a reasonable degree of accuracy. Moreover, this paper discusses all the possible remedial actions and highlights the most suitable one.

## II. POWER DEVICE SHORT CIRCUIT FAULT

The per-phase equivalent circuit of the PM drive is shown in Fig. 1, 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. The motor phase is connected to single-phase H-bridge inverter.

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

Switches 1 and 2 conducts the current positive half cycle

before the fault; however, during the fault triggering switch 1 results in a shoot-through that possibly damages the switching device and the DC-link. Obviously the degrees of freedom are limited with a short-circuited switch in the drive circuit.

The conventional control strategy for short-circuit switch fault, Fig.1, is to block all gate signals.

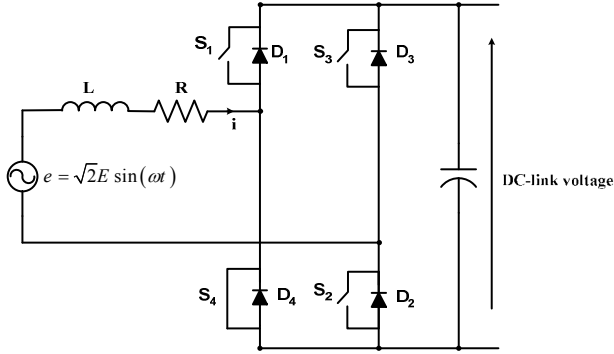


Fig. 1 Per-phase equivalent circuit of the PM drive with a short circuit fault in switch 4

Blocking the gate signals causes the current to circulate between the motor phase, switch 4 and diode 2 placing a short circuit on the machine phase. This case is depicted in the equivalent circuit, Fig. 2,

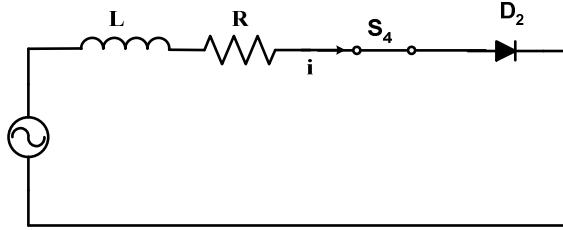


Fig. 2 Current path during the fault

The voltage across the phase winding is the emf; therefore the current is given by,

$$i = \frac{\sqrt{2}E}{Z} \sin(\theta) e^{-\frac{t}{\tau}} + \frac{\sqrt{2}E}{Z} \sin(\omega t - \theta) \quad (1)$$

where,  $Z = \sqrt{(\omega L)^2 + R^2}$ ,  $\theta = \tan^{-1}\left(\frac{\omega L}{R}\right)$ , and  $0 \leq t \leq \frac{\pi}{\omega}$ .

The phase current continues to build during the whole positive half cycle of the motor back emf; at the end of the half cycle, the current could be obtained by setting  $\omega t = \pi$  in (1),

$$I_1 = \frac{\sqrt{2}E}{Z} \sin(\theta) e^{\frac{\pi L}{\omega R}} + \frac{\sqrt{2}E}{Z} \cos(\theta) \quad (2)$$

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. The phase current  $I$  is still given by (1) during the negative half cycle; where  $t$  in this case is  $\frac{\pi}{\omega} \leq t \leq \frac{2\pi}{\omega}$ . Thus, (1) gives the inverter current over the whole cycle.

Equation (1) indicates that the current declines gradually during the negative half cycle and approaches zero before the end of the back emf cycle.

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.

Normally, the DC offset in the current decays naturally to zero due to the losses. However, for a short-circuit switch fault in H-bridge inverter supplying PM motor the presence of the diodes prevents the current from going negative and forces it to be zero. Therefore, a DC component is sustained in the inverter output current, as the circuit reset each cycle and as shown in references[xxx].

Fig. 3 shows the inverter output currents calculated from (1) and simulated for the machine parameters reported in Table 1.

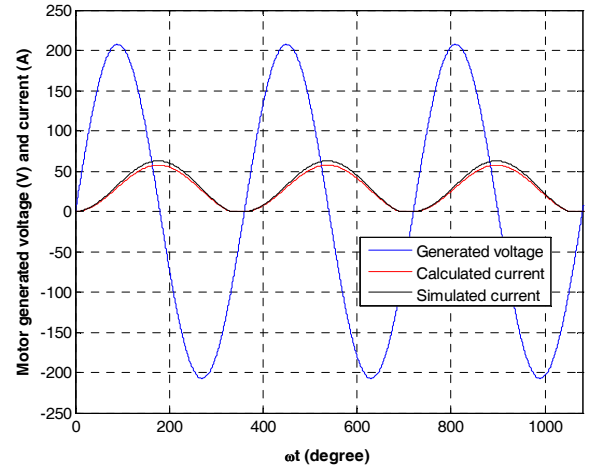


Fig. 3 Motor voltage and current, voltage (blue), current calculated (red), current simulated (black) during the short-circuit fault of a H-bridge switch

### III. REMEDIAL STRATEGIES OF POWER DEVICE SHORT-CIRCUIT FAULT

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 best option, as this short-circuited the whole motor phase, which removes the sustained DC component from flowing into the phase winding. For this kind of fault-tolerant drive as mentioned before the short-circuit current is no more than the rated current; thus short-circuiting the motor phase deliberately ensures that the thermal limits of the phase windings are not exceeded. However, continuously triggering of the switch in the healthy phase increases the conduction losses due to 360° conduction. The proposed control strategy is shown in Fig. 4,

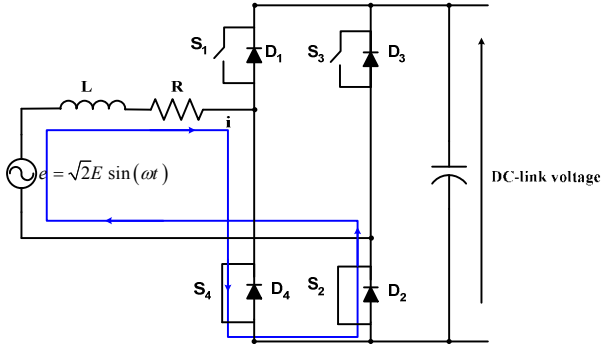


Fig. 4 The proposed control strategy, the current path (blue)

The current path in the proposed control action is shown in blue in Fig. 4.

Fig. 5 shows the motor back emf and the current calculated and simulated after deploying the proposed control strategy.

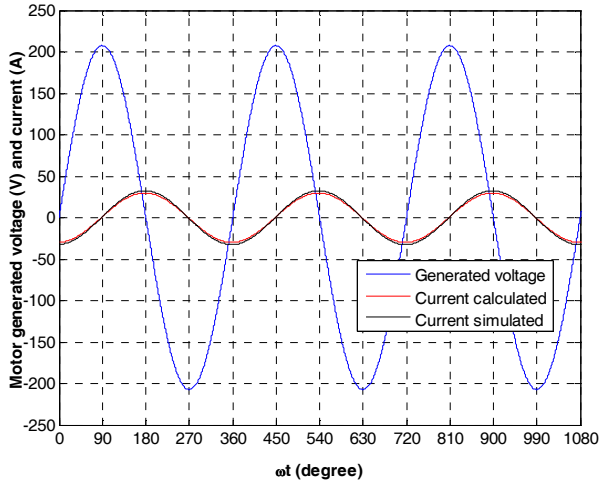


Fig. 5 Motor voltage and current, voltage (blue), current calculated (red), current simulated (black) with the proposed control strategy

The current lags the back emf by nearly  $90^\circ$  as shown in Fig. 5, which is attributed to the high phase inductance. Therefore, the average braking torque produced by the faulted phase is nearly zero. This is shown in Fig. 6, where the instantaneous developed torque is plotted for pre, during and post fault states. In developing Fig. 6, the high frequency harmonics are ignored, as machine has sufficient inertia.

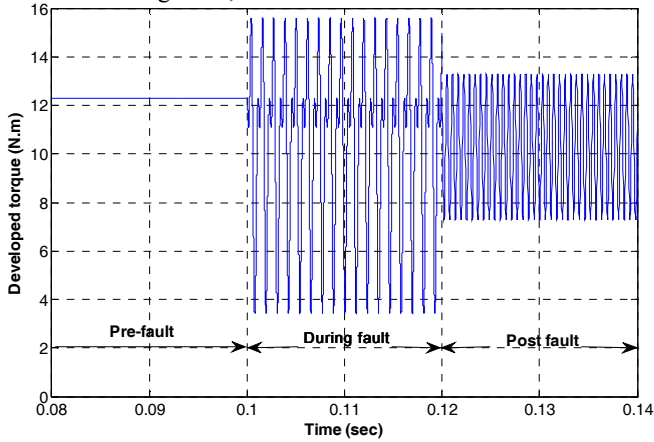


Fig. 6 The motor developed torque for pre, during and post the fault

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, Fig. 6. 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. 6, 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.

A switch failure in an H-bridge inverter supplying the fuel pump affects the common DC-side. Accordingly, the DC current contains a significant low order harmonics. This current component degrades the supply, and necessitates a bulky capacitor to be inserted between the supply and the inverter. The DC-link current for the system under concern is shown in Fig. 7, the high frequency switching harmonics are ignored in developing this Figure, to allow good comparison between low frequency and DC components of the supply current.

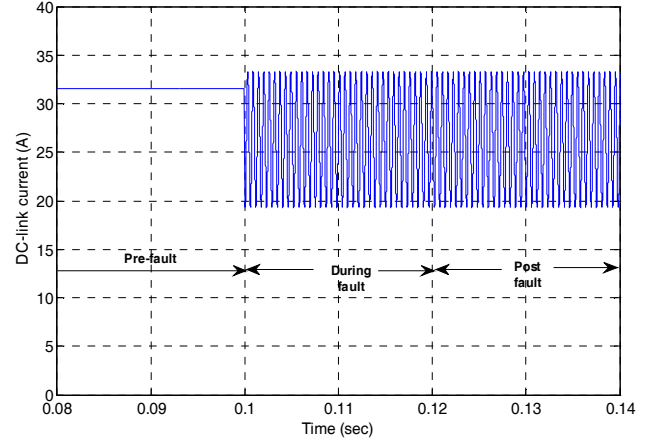


Fig. 7 DC-side current for pre, during and post the fault

Fig. 7 shows that when the H-bridge inverters operate, the current circulates between the supply and the inverters is pure DC, 32A, and during/post fault this current contains low frequency ripple component.

#### IV. CONCLUSIONS

The following conclusions could be extracted:

1. The failure of a switching element in H-bridges supplying fault-tolerant PM drive results in sustained DC component in the faulted phase.
2. The sustained DC component reduces the drive torque capability, saturates the machine irons and increases the losses.
3. The inappropriate control action may worsen the situation, for example disabling all gate signals prevents the DC component of current from decaying as would naturally occur in normal AC circuit. This is attributed to the free-wheeling diodes, the anti-parallel diodes. The presence of

these converter diodes actively prevents the current in the faulted phase from reversing.

4. The optimal remedy for the short-circuited switch is continuously gating the switch in the same position in the healthy leg to intentionally short-circuit the whole phase. This allows the DC component of current to decay. However, this implies that the control system and gate circuits remain healthy and available in the event of a faulted switching element.

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