Fault diagnosis and tolerant control for power converter in SRM drives

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Abstract: Switched reluctance motors (SRMs) are considered a competitive technology for more electric aircraft and automotive applications due to their excellent fault-tolerant capabilities and robust configuration [1]. However, due to harsh operational environment and repetitive duty cycles, power switching devices in SRM drives are susceptible to failure, particularly in transient of speed up and braking in automotive applications [2]. Therefore, in such applications, high system reliability and fault tolerance is of paramount importance.

Furthermore, unlike other machines, the occurrence of fault in one phase does not affect the remaining phases, owing to the magnetic independence nature of motor phases. However, their electromagnetic performances are deteriorated and the rotor is subjected to unbalanced force. Therefore, to prevent the drive system from secondary failures, strategies for immediate detection and remediation of faults are necessary.

In SRM drives, power converter is the most vulnerable part and most prone to failure. The converter faults are classified into open- and short-circuit faults [3]. Its fault diagnosis has been researched intensively, such as in [4–8]. For instance, the work proposed in [4] uses dc bus current and [5] uses phase current to identify open-circuit and short-circuit faults. The strategy explored in [6] uses freewheeling and bus current to localise the power transistor faults. Other analytical methods such as genetic algorithm-based artificial neural network (ANN), fast Fourier transform, and fuzzy logic are proposed in [7, 8]. In general, the existing methods use additional sensors that increase the cost and complexity of the drive system and the analytical methods are hard to be implemented as real-time detection.

In order to achieve fault-tolerant operation, software and hardware approaches can be employed. For example, ANN, genetic algorithms, and the time dynamic models are developed in [9] for normal and abnormal condition control of the SRM. For the fault-tolerant SRM structure, increasing the number of phases is a common approach [10, 11]. Dual channels are also introduced to enhance the reliability of the SRM drive systems [12]. In [13], a modular stator structure is developed to bypass the faulty winding.

The fault-tolerant strategies for power transistor faults are discussed in [14–16]. Hu et al. [14] proposed a flexible fault-tolerant topology, composed of single-phase bridge and a relay network based on asymmetric converter. The topology developed in [15] added two switching devices to the conventional asymmetric converter. The strategy adopted in [16] regulates turn-on angle of previous and turn-off angle of subsequent phase when an open-circuit fault occurs and state of switching devices are changed in the case of short circuit, but this strategy may not work if simultaneous fault occurs in both transistors on the same leg. The modular structure fault-tolerant topology proposed in [17] can only save 1/2 winding in the faulty phase. In addition, it also requires three half-bridge legs for the fault-tolerant operation.

Hence, this paper proposes a new fault-tolerant topology that can ensure the continuity of machine operation when a fault occurs in one phase or faults occur in two phases. Moreover, the proposed fault diagnostic algorithm does not require additional sensors. It extracts the fault features from the fundamental current by injecting a high-frequency (HF) voltage signal into the upper switches of the converter. The effectiveness of the proposed strategy is verified through thorough simulation results based on a three-phase 12/8 SRM drive system.

1 Introduction

Switched reluctance motors (SRMs) are becoming an attractive technology for automotive applications and more electric aircraft industry owing to their excellent fault-tolerant capabilities and robust configuration [1]. However, due to harsh operational environment and repetitive duty cycles, power switching devices in SRM drives are susceptible to failure, particularly in transient of speed up and braking in automotive applications [2]. Therefore, in such applications, high system reliability and fault tolerance is of paramount importance.

Furthermore, unlike other machines, the occurrence of fault in one phase does not affect the remaining phases, owing to the magnetic independence nature of motor phases. However, their electromagnetic performances are deteriorated and the rotor is subjected to unbalanced force. Therefore, to prevent the drive system from secondary failures, strategies for immediate detection and remediation of faults are necessary.

In SRM drives, power converter is the most vulnerable part and most prone to failure. The converter faults are classified into open- and short-circuit faults [3]. Its fault diagnosis has been researched intensively, such as in [4–8]. For instance, the work proposed in [4] uses dc bus current and [5] uses phase current to identify open-circuit and short-circuit faults. The strategy explored in [6] uses freewheeling and bus current to localise the power transistor faults. Other analytical methods such as genetic algorithm-based artificial neural network (ANN), fast Fourier transform, and fuzzy logic are proposed in [7, 8]. In general, the existing methods use additional sensors that increase the cost and complexity of the drive system and the analytical methods are hard to be implemented as real-time detection.

In order to achieve fault-tolerant operation, software and hardware approaches can be employed. For example, ANN, genetic algorithms, and the time dynamic models are developed in [9] for normal and abnormal condition control of the SRM. For the fault-tolerant SRM structure, increasing the number of phases is a common approach [10, 11]. Dual channels are also introduced to enhance the reliability of the SRM drive systems [12]. In [13], a modular stator structure is developed to bypass the faulty winding.

The fault-tolerant strategies for power transistor faults are discussed in [14–16]. Hu et al. [14] proposed a flexible fault-tolerant topology, composed of single-phase bridge and a relay network based on asymmetric converter. The topology developed in [15] added two switching devices to the conventional asymmetric converter. The strategy adopted in [16] regulates turn-on angle of previous and turn-off angle of subsequent phase when an open-circuit fault occurs and state of switching devices are changed in the case of short circuit, but this strategy may not work if simultaneous fault occurs in both transistors on the same leg. The modular structure fault-tolerant topology proposed in [17] can only save 1/2 winding in the faulty phase. In addition, it also requires three half-bridge legs for the fault-tolerant operation.

Hence, this paper proposes a new fault-tolerant topology that can ensure the continuity of machine operation when a fault occurs in one phase or faults occur in two phases. Moreover, the proposed fault diagnostic algorithm does not require additional sensors. It extracts the fault features from the fundamental current by injecting a high-frequency (HF) voltage signal into the upper switches of the converter. The effectiveness of the proposed strategy is verified through thorough simulation results based on a three-phase 12/8 SRM drive system.

2 Power converter fault classification

An asymmetric power converter, as shown in Fig. 1, is widely used in SRM drive systems owing to its fault tolerance, phase isolation, and stability performance. The power switches of the converter are key, but vulnerable components and most prone to failure. The typical faults are classified into open- and short-circuit fault of the upper and lower switches.
In SRM drives, soft switching mode is normally employed such that the upper switch keeps switching and the lower switch is constantly turned on during the phase turn-on region.

3 Proposed fault diagnostic algorithm

Fig. 2 shows the current control loop of the SRM drive control strategy with HF voltage signal injection. The sinusoidal HF voltage signal has the following specifications:

\[ V_{HF} = V_i \sin(\omega t) \]  
\[ V_{sum} = V_{ref} + V_{HF} \]

where \( V_{HF} \) and \( V_{ref} \) are the magnitudes of HF voltage and reference voltage, respectively. The pulse width modulation (PWM) signals generated from \( V_{sum} \) (sum of \( V_{HF} \) and \( V_{ref} \)) and a carrier signal are injected into the upper switches of the power converter. Subsequently, HF current components will be introduced to the phase currents. The resulting HF current is filtered from the difference of measured current and reference current through a band-pass filter. The frequency of the filtered HF current is calculated using zero crossing detection technique, the block diagram of the process is shown in Fig. 3. Open- and short-circuit faults are analysed by monitoring the variation in frequency and amplitude of the filtered HF current. In addition, the change in amplitude of the fundamental current is also used as fault signature using two empirically opted threshold values for open-circuit (\( k_o \)) and short-circuit (\( k_s \)) faults, respectively

\[ k_o = 1.35i_{ref} \]  
\[ k_o = 0.7i_{ref} \]

3.1 Open-circuit fault diagnosis

Table 1 summarises the fault signatures for open-circuit fault of upper and lower switches. For instance, when an open-circuit fault occurs in the upper switch of phase A, the frequency and amplitude of the filtered HF current dramatically reduce, as the HF voltage signal is injected into the upper switches. In addition, the fundamental current drops below the threshold \( k_o \) and a fault is detected in the upper switch.

However, in the case of open-circuit fault in the lower switch, the fundamental current drops below the threshold \( k_o \) but the frequency and amplitude of the HF current does not reduce quickly since, the upper freewheeling current still have considerable HF current components. Hence, the faulty switch is localised.

3.2 Short-circuit fault diagnosis

The fault signatures for short-circuit fault of power switches are depicted in Table 2. When the upper switch is short circuited, the faulty switch continuously excited and the fundamental current of the faulty phase quickly increases to a very large value and the frequency and amplitude of the filtered HF current reduces to zero, as there will be no HF current components in the phase current.

On the other hand, when a short-circuit fault occurs in the lower switch, no detrimental effect is observed until turn-off angle of the faulty phase. Since, in soft switching mode, the lower switch remains closed in the phase turn-on region. The frequency and amplitude of HF current reduce to zero during demagnetisation, while the fundamental current still has higher amplitude than reference current, and hence a fault in the lower switch is detected.

Table 1 Analysis of filtered HF current and fundamental current under open circuit of phase

| Switching devices state | High-frequency current | Phase current |
|-------------------------|------------------------|--------------|
| \( S_1 \)            | \( S_2 \)           |              |
| frequency             | amplitude             |              |
| open-circuited constant ON | \( \omega \) rad/s | zero            |
| open-circuited \( <k_o \) | less amplitude | than normal |

Table 2 Analysis of filtered HF current and fundamental current under short circuit of phase A

| Switching devices state | High-frequency current | Phase current |
|-------------------------|------------------------|--------------|
| \( S_1 \)            | \( S_2 \)           |              |
| frequency             | amplitude             |              |
| short-circuited constant ON chopping | \( \omega \) rad/s | zero            |
| short-circuited \( \omega \) rad/s until turn-off angle | normal until turn-off angle | \( >k_s \) |
| after turn-off angle |                        |              |
4 Proposed fault-tolerant topology

In order to sustain the driving operation after fault, a new fault-tolerant converter topology, without changing the traditional asymmetric converter, is proposed as shown in Fig. 4. The fault-tolerant topology is composed of four additional power switches with a relay network. When a fault is detected in any switch, the

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**Fig. 4** Proposed fault-tolerant topology

**Fig. 5** Fault-tolerant operations under open- and short-circuit fault
- a) Open-circuit fault of the upper switch
- b) Open circuit of the lower switch
- c) Short circuit of the lower switch
- d) Upper and lower switches simultaneous short-circuit fault

**Fig. 6** Fault-tolerant operation under hybrid faults in two phases

**Fig. 7** Fault-tolerant operation under open circuit of the lower switch at 500 rpm speed
- a) Phase A current
- b) HF current
- c) Frequency of filtered HF current
- d) Total torque
- e) Speed
- f) Short/open-circuit fault flag of upper and lower switch
corresponding relay is turned ON and the faulty switch is replaced by the healthy switch, to ensure the continuity of machine operation.

4.1 Open-circuit fault tolerant

Figs. 5a and b show the fault-tolerant operations for open-circuit fault of upper and lower power switches, respectively. When an open-circuit fault occurs in the upper switch, relay $R_1$ is turned ON and the faulty switch $S_1$ is replaced by $S_7$. Likewise, when the lower switch is faulted, $S_8$ is connected through $R_4$.

4.2 Short-circuit fault tolerant

When a short-circuit fault occurs in the upper or lower switch, the diagnostic algorithm detects the fault, immediately, the faulty switch is blocked and the healthy switch $S_7$ or $S_8$ continues driving operation through relay $R_1$ or $R_4$, respectively. In the case of simultaneous fault in both switches, as shown in Fig. 5c, $R_1$ and $R_4$ simultaneously turned ON and healthy switches $S_7$ and $S_8$ maintain driving operation. When hybrid fault occurs in phases $A$ and $B$, as shown in Fig. 6, relays $R_1$, $R_2$, $R_4$, and $R_5$ replace faulty switches with $S_7$, $S_8$, $S_9$, and $S_{10}$ to ensure the continuity of machine operation.

5 Simulation results

The presented simulations were performed using a three-phase 12/8 SRM model in Matlab/Simulink. The amplitude and frequency of the injected HF voltage signal were opted 90 V and 4 kHz, respectively. Moreover, the frequency of the carrier signal of the PWM generator was opted 20 kHz. Various power converter faults are simulated, and the corresponding fault detection and fault-tolerant operation are presented as below.
5.1 Open-circuit fault diagnosis and tolerant control

Figs. 7 and 8 show the results of fault diagnosis and tolerant control for open-circuit fault in the upper switch and lower switch at 500 rpm speed. Open-circuit fault is introduced at \( t = 0.082 \) s in both cases. As expected, no HF current is observed right after fault when the upper switch is open circuited while there is still HF current with low amplitude, in the case of lower switch open-circuit fault. When the fault is detected, the respective fault flag changes to 1 and immediately, tolerant control strategy is applied to minimise the impact of fault on machine driving operation.

5.2 Short-circuit fault diagnosis and tolerant control

The simulation results for short-circuit fault diagnosis and tolerant control operation in upper and lower switches are shown in Figs. 9 and 10. In both cases, short-circuit fault is simulated at \( t = 0.084 \) s. As expected, when the fault is detected, immediately fault-tolerant control strategy is operated to maintain the driving operation. In order to validate the robustness of the proposed strategy under different operating conditions, upper switch and lower switch short-circuit faults are simulated at 1500 and 1000 rpm, respectively. It can be noted that the proposed algorithm can detect and locate the fault accurately and promptly. In addition, the tolerant control topology can sustain the machine operation after occurrence of faults.

6 Conclusion

In this paper, a new fault-tolerant topology is proposed to enhance the reliability of the SRM drive systems for more electric aircraft and automotive applications. The introduced topology is composed of four additional power switches with a relay network based on the conventional asymmetrical half-bridge power converter. Fault-tolerant topology can still sustain driving operation when a fault occurs in one phase or faults occur in two phases. In addition, a fault diagnostic algorithm based on HF signal injection is proposed that, unlike other methods, does not require additional sensors. Open- and short-circuit faults are analysed by monitoring the variation in frequency and amplitude of the injected HF current along with the fundamental current with the occurrence of fault. Simulation results demonstrate the effectiveness of the proposed scheme under wide range of mechanical operating conditions. The introduced strategy can improve the reliability and cost efficiency of the SRM drive system for electric aircraft technology and other automotive applications.

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8 References

[1] Yang Z., Shang F., Brown I.P., et al.: ‘Comparative study of interior permanent magnet, induction, and switched reluctance motor drives for EV and HEV applications’, IEEE Trans. Transp. Electrific., 2015, 1, (3), pp. 245–254
[2] Fahimi B., Emadi A., Sepe R.B.: ‘A switched reluctance machine-based starter/alternator for more electric cars’, IEEE Trans. Energy Convers., 2004, 19, (1), pp. 116–124
[3] Pei X., Nie S., Kang Y.: ‘Switch short-circuit fault diagnosis and remedial strategy for full-bridge DC–DC converters’, IEEE Trans. Power Electron., 2015, 30, (2), pp. 996–1004
[4] Gameiro N.S., Marques Cardoso A.J.: ‘A new method for power converter fault diagnosis in SRM drives’, IEEE Trans. Ind. Appl., 2012, 48, (2), pp. 653–662
[5] Marques J.P., Estima J.O., Gameiro N.S., et al.: ‘A new diagnostic technique for real-time diagnosis of power converter faults in switched reluctance motor drives’, IEEE Trans. Ind. Appl., 2014, 50, (3), pp. 1854–1860
[6] Hao C., Shengli L.: ‘Fault diagnosis digital method for power transistors in power converters of switched reluctance motors’, IEEE Trans. Ind. Electron., 2013, 60, (2), pp. 749–763
[7] Gan C., Wu J., Yang S., et al.: ‘Fault diagnosis scheme for open-circuit faults in switched reluctance motor drives using fast Fourier transform algorithm with bus current detection’, IET Power Electronics, 2016, 9, pp. 20–30
[8] Arkadan A.A., Du P., Sidani M., et al.: ‘Performance prediction of SRM drive systems under normal and fault operating conditions using GA-based ANN method’, IEEE Trans. Magn., 2000, 36, (4), pp. 1945–1949
[9] Belfore L.A.II, Arkadan A.: ‘A methodology for characterizing fault tolerant switched reluctance motors using neurogenetically derived models’, IEEE Trans. Energy Convers., 2002, 17, (3), pp. 380–384
[10] Heinen M.D., Niessen M., Heyers C., et al.: ‘Development and control of an integrated and distributed inverter for fault tolerant five-phase switched reluctance traction drive’, IEEE Trans. Power Electron., 2012, 27, (2), pp. 547–554
[11] Labak A., Kar N.C.: ‘Designing and prototyping a novel five-phase pancake-shaped axial-flux SRM for electric vehicle application through dynamic FEA incorporating flux-tube modeling’, IEEE Trans. Ind. Appl., 2013, 49, (3), pp. 1276–1288
[12] Ding W., Liu Y., Hu Y.: ‘Performance evaluation of a fault-tolerant decoupled dual-channel switched reluctance motor drive under open-circuits’, *IET Electr. Power Appl.*, 2014, 8, (4), pp. 117–130

[13] Ruba M., Voorel I.-A., Szabo L.: ‘Modular stator switched reluctance motor for fault tolerant drive systems’, *IET Electric Power Appl.*, 2013, 7, (3), pp. 159–169

[14] Hu Y., Gan C., Cao W., ET AL.: ‘Flexible fault-tolerant topology for switched reluctance motor drives’, *IEEE Trans. Power Electron.*, 2016, 31, (6), pp. 4654–4668

[15] Gameiro N.S., Cardoso A.J.M.: ‘Fault tolerant power converter for switched reluctance drives’. Proc. 18th Int. Conf. Electrical Machines, Algarve, Portugal, September 2008, pp. 1–6

[16] Ro H.S., Kim D.H., Jeong H.G., ET AL.: ‘Tolerant control for power transistor faults in switched reluctance motor drives’, *IEEE Trans. Ind. Appl.*, 2015, 51, (4), pp. 3187–3197

[17] Hu Y., Gan C., Cao W., ET AL.: ‘Central-tapped node linked modular fault-tolerance topology for SRM applications’, *IEEE Trans. Power Electron.*, 2016, 31, (2), pp. 1541–1554