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A Fault Tolerant Machine Drive Based on Permanent Magnet Assisted Synchronous Reluctance Machine

Bo Wang, Jiabin Wang, Antonio Griffo, Zhigang Sun, and Ellis Chong

Abstract — A fault tolerant machine drive based on permanent magnet (PM) assisted synchronous reluctance machine is proposed and investigated for safety critical applications. In order to achieve enhanced fault tolerant capability, the risk of the permanent magnet field that cannot be turned off under fault conditions is minimized without compromising the torque density and efficiency. This is achieved by employing a synchronous reluctance rotor topology with embedded permanent magnets. Three independent 3-phase windings are adopted and a segregated winding configuration is devised to ensure non-overlapping in the three 3-phase winding sets. Each 3-phase winding set is driven by a standard 3-phase inverter, which facilitates fast integration and cost reduction. The performance under various fault conditions has been evaluated by FE simulations. The results show that the proposed machine drive exhibits high performance as well as excellent fault tolerant capability under various faults, including open circuit, terminal short circuit, and inter-turn short circuit, etc.

Index Terms—Fault tolerant machine, permanent magnet assisted synchronous reluctance machine, multi-phase machine, non-overlapped winding configuration.

I. INTRODUCTION

FAULT tolerant machine and drives are capable of providing uninterrupted operation during fault conditions, therefore being attractive in safety critical applications, such as aerospace and electric traction [1, 2]. While electrical drives possess enhanced functionality, adaptability and controllability compared with the conventional mechanical, hydraulic, and pneumatic systems [3], relative low reliability of electric drive systems presents a restriction for their wide applications since an unexpected fault would cause serious consequences or economic losses. Thus, fault tolerance is an essential requirement for electrical drives to attain high availability.

To this end, various fault tolerant machine topologies and techniques have been investigated in literatures. The most straightforward approach is to adopt two or more machine-drive modules either in series or in parallel [4, 5]. However, use of multiple machine drives for redundant

operation requires large space and necessitates additional accessories to guarantee its operation in healthy and fault conditions, resulting in low power density and bulky size. Alternatively, fault tolerance may be achieved on a single 3-phase machine drive by employing a neutral connection to the midpoint of the DC link or to a fourth inverter leg [6]. Zero sequence current is utilized to generate the equivalent rotating magneto-motive force (MMF) if one phase is open-circuited. The neutral connection and zero sequence current can be eliminated by employing more than three phases in a single machine [7]. Depending on the number of phases, a multi-phase (number of phases > 3) machine may be capable of continuous operation when more than one phase has failed. The concept has been realized in both induction machines and permanent magnet machines [8-12]. Additionally, various control algorithms were proposed to achieve the maximum available torque, or minimum torque ripple [13-15] under fault conditions. It is worth noting that the majority of the above measures address the open circuit failure only.

In order to accommodate short circuit failure in the power electronic switches or phase windings, advanced fault tolerant drives were developed. Owing to its rugged, magnet-free rotor structure and concentrated windings, switched reluctance machine (SRM) is inherently fault tolerant [16, 17]. Each phase winding can be magnetically, thermally and electrically isolated. Due to low mutual coupling between phases, the short circuit current as a result of inverter failure or an inter-turn fault can be restricted in a safe region [18]. However, an SRM exhibits high torque ripple, undesirable noise and vibration, and poor torque density/efficiency.

In [19] a single layer fractional slot concentrated winding (FSCW) permanent machine is developed that facilitates electrical, magnetic, thermal, and physical isolations between phases. The slot opening is specially designed to obtain per-unit inductance. As a result, the terminal short circuit current is limited under a rated value. This methodology has also been extended to switched flux permanent machines with similar winding configuration [20]. However, due to the concentrated windings, very little reluctance torque can be exploited in this type of machine topology. The output torque of a FSCW PM machine relies on the PM field and, consequently, increase in torque capability leads to great flux linkage. The presence of strong PM field may pose a safety hazard to the machine as it cannot be turned off in the event of a fault [21]. In case of

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an inverter failure, the back electromotive force (emf) may be higher than the DC link voltage at high speeds and uncontrolled rectification via the diodes may occur. Excessive regenerative power which flows to the dc link capacitor may cause catastrophic failure to the drive system. Significant braking torque may also be imposed on the rotor causing huge stress to the mechanical system or sudden reduction in speed which may induce accidents in traction drives. Thus, the maximum back emf should be limited [22]. However, this is in conflict with the torque production. On the other hand, if the FSCW machine is required to operate in a wide constant power range, the VA rating of the inverter increases linearly with the speed, which in turn increases the overall size and cost of the drive. Further, the use of concentric windings also gives rise to sub- and high-order magneto-motive force (MMF) space harmonics which produce extra rotor loss. Hence, the magnets need to be segmented axially or circumferentially to avoid excessive rotor temperature. Manage and control of inter-turn short-circuit current in a FSCW PM machine are also very challenging [23, 24] because its magnitude may still be many times greater than a thermally sustainable value even after a terminal short circuit as the remedial action.

Recently, PM assisted synchronous reluctance machine (PMA SynRM) has gained increasing interests as a viable candidate for electric traction due to reduced magnets usage, extended field weakening range and comparable performance with conventional PM machines[25, 26]. These unique characteristics are mainly attributed to the combined torque production mechanism, both the PM torque and reluctance torque. The reluctance torque enables use of less magnet material and results in low back emf which improves the machine's fault tolerant capability. The main disadvantage of this machine is that it usually employs distributed windings which are beneficial for exploiting reluctance torque. The use of the overlapped windings yields strong inter-phase coupling. And the coils of different phases may overlap in slots and in the end winding regions. Consequently, a fault in one phase could easily propagate to or affect other phases. For a conventional 3-phase machine drive, a single failure in any part of the drive will lead to a complete failure [27-29].

This paper aims to develop a new fault tolerant machine drive based on PMA SynRM topology. By employing appropriate winding configurations, the machine can be optimized to have high torque density while exhibiting fail-safe and fault tolerant characteristics. Detailed analysis is performed to examine its fault tolerant capabilities for various faults, such as open circuit, short circuit, and inter-turn short circuit.

II. FAULT TOLERANT WINDING CONFIGURATION FOR PMA SYNRM

Conventional 3-phase windings of a PMA SynRM are usually distributed as shown in Fig. 1 in order to produce a nearly sinusoidal MMF in the air gap albeit they are not conducive to fault tolerance. It is possible to reconfigure the windings as three isolated 3-phase sets for the purpose of

triple redundancy. Each 3-phase set is controlled by an electrically independent inverter. However, the windings of different sets are overlapped and bundled together which is prone to inter-phase short circuits. Strong magnetic coupling also exists between different 3-phase sets. An inter-turn short-circuit fault may occur in one 3-phase set, and its effect cannot be mitigated by turning off its inverter because of the mutual flux linkage produced by currents in other 3-phase sets. In addition, the heat produced by a faulty 3-phase set may spread to the other healthy sets via the overlapped windings.

In order to improve the physical, electrical and thermal isolations to provide enhanced fault tolerance for the PMA SynRM, a segregated triple 3-phase winding configuration is proposed as shown in Fig. 2. The conventional overlapped windings are divided into three separate 3-phase winding sets so that there is no overlapping between them, resulting physical and thermal isolation.

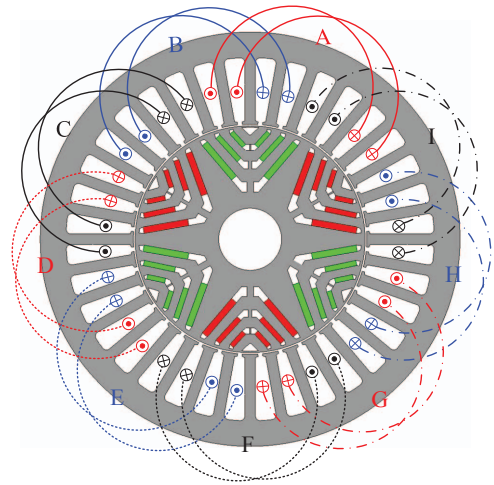


Fig. 1. PMA SynRM with original overlapped windings.

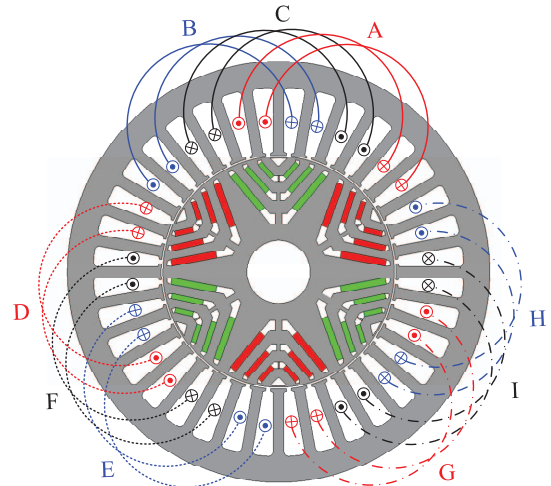


Fig. 2. PMA SynRM with segregated windings.

To obtain a symmetric 3-phase system for each 3-phase set, the go and return positions of the coils in phases C, F and I are modified whilst the induced voltages in phases C, F and I are unchanged. As a result, ABC, DEF and GHI each forms a balanced 3-phase winding. The electrical isolation is achieved by using three standard inverters to drive each 3-phase set. Since the distribution of the currents

in the slots is not affected by the new winding configuration, the performance of the machine in healthy conditions is exactly the same as the original one shown in Fig. 1. Thus, the all merits of the PMA SynRM, such as reduced magnet usage, low back emf, inherent large reluctance torque, high efficiency and high torque density are maintained. Most importantly, these segregated windings and independent inverters lead to excellent fault tolerance since the risk of fault propagation between different 3-phase winding sets is minimized and the three independent modules provide redundancy for various faults [30].

In case of an open-circuit fault in an inverter switch or the windings, the faulty 3-phase winding set can be simply deactivated by opening all the switches in that set, and the remaining two healthy 3-phase sets are capable of continuous operation in a balanced manner, with about one third reduction in output torque or power. If a short circuit failure occurs in an inverter switch or in one 3-phase winding, a terminal short circuit can be applied on the faulty set by closing the entire bottom or the top switches of the 3-phase inverter. Since the PM flux in the machine is quite low, the short circuit current is restricted below or close to the rated value. And if an inter-turn short circuit takes place, the current of the faulted turn can be alleviated by applying terminal short circuit to nullify the flux in short-circuited turns. Thus, owing to the winding separation, a fault in one 3-phase system can be isolated and the other two 3-phases can continue operation to generate torque or power. The magnets are better protected by the rotor core, but even if in an unlikely event that magnets are partially demagnetized, the reduction in torque capability will be insignificant since the magnet torque only accounts for $\sim 30\%$ torque in this type of machines. The low back-emf of the machine also means that in the event of inverter or control failure, the effect on the drive is benign with no uncontrollable rectification even at high speed. This inverter fail-safe feature is very attractive in many applications.

It follows that the PMA SynRM machine with this novel segregated winding configuration exhibits good performance as well as excellent fault tolerance. The segregated windings are realized with no penalties and no additional cost. Only a winding reconfiguration is required for forming multiple 3-phase winding sets with minimum mutual coupling and each 3-phase set can be driven by a standard 3-phase inverter. Separating a 3-phase winding into multiple 3-phase sets is also conducive to reducing the current in each 3-phase set, spreading heat in the inverter switches and hence facilitating machine-inverter integrations, particularly for high power drives. Although the proposed winding segregation is primarily aimed for PMA SynRM, it is also applicable to the other machines with distributed windings to enhance the fault tolerance, such as synchronous reluctance machines, surface mounted PM machines, synchronous wound field machines and induction machines [31]. The number of 3-phase modules can be selected according to application requirements. It should be noted that while the proposed winding

segregation is not new, its exploitation in PMA SynRM to achieve desirable fault tolerance has not been reported in literature to date.

III. PROTOTYPE DESIGN

A prototype machine has been designed to assess the performance of the proposed fault tolerant machine against the design specification given in Table I. The stator and rotor cores employ 0.2mm Cobalt-iron lamination and the machine is oil cooled to enhance torque density. The machine requires a wide constant power operation range from 4000rpm to 19200rpm and the PMA SynRM is particular suitable for deep field weakening owing to its low characteristic current defined as the ratio of PM flux linkage to the d-axis inductance. To address the redundancy requirement, triple 3-phase modules offer a good compromise between the fault tolerance and overall complexity. Thus, a PMA SynRM with 36 slots and 6 poles was selected for the design study.

Table I
DESIGN SPECIFICATION OF THE MACHINE

Specification	Symbol	Value
Base speed	ω_b	4000 rpm
Maximum speed	ω_m	19200 rpm
Rated power	P_r	40 kW
Peak power	P_p	50 kW
Rated torque at base speed	T_r	95.5 Nm
Peak torque at base speed	T_p	119.4 Nm
Rated torque at maximum speed	T_{rm}	19.9 Nm
Peak torque at maximum speed	T_{pm}	24.9 Nm
Nominal DC link voltage	V_{dc}	270 V
Ambient temperature	T_{amb}	100 °C
Maximum winding temperature	$Temp_r$	180 °C
Cooling medium	-	Aeroshell oil
Redundancy	1	Triple or quadruple

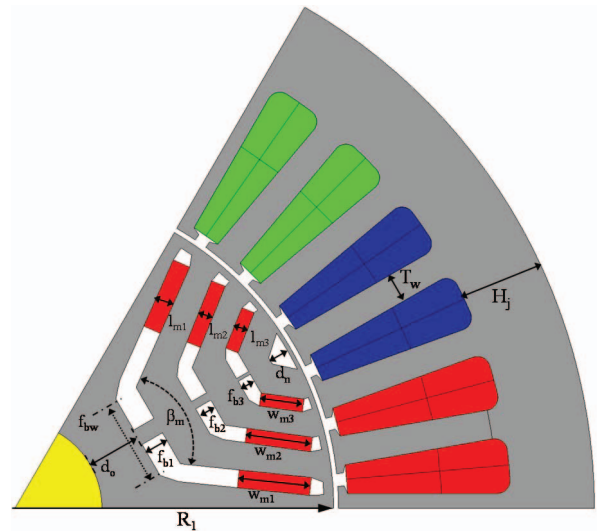


Fig. 3. Optimization geometry parameters of PMA SynRM.

Compared with a conventional 3-phase PMA SynRM, only the windings are reconfigured. Hence, the machine can be designed as a conventional 3-phase machine by exploiting its periodicity. 1/6 of the machine geometry as shown in Fig. 3 was used in FE based design optimization. The multiple embedded layers and cutout in the rotor lead to enhanced reluctance torque production capability, whilst ensuring good structural integrity and manufacturability of

the rotor. The magnets in the rotor are placed on the sides of the rotor flux barriers. This topology is conducive to reduction of the magnet usage for a given flux linkage compared with other magnet configurations (e.g. single blocks in the middle of the flux barrier or a combination of middle and side blocks in the flux barrier). This can be attributed to the flux-focusing effect which enhances the flux in the airgap. In addition, the magnets are placed closer to the airgap leading to less flux leakage [32].

Table II
OPTIMIZED DESIGN PARAMETERS

Parameter	Symbol	Value
Stator radius	R_s	90 mm
Back iron thickness	H_f	10.25 mm
Tooth width	T_w	5.1 mm
Rotor radius	R_r	51.75mm
Magnet thickness	l_{mt}	2.8 mm
Magnet width	w_{mt}	14.88 mm
Middle flux barrier thickness	f_{bt}	2.9 mm
Middle flux barrier width	f_{bw}	10.64 mm
Magnet layer's angular span	β_m	157.6 °
Magnet layer's depth	d_0	9.83 mm
Turn number per coil	TN	8

The geometry parameters to be optimized are shown in Fig. 3. The machine has been optimized against the design specifications, the thermal and mechanical constraints to maximize the efficiency at the base speed rated torque using the finite element (FE) based technique as described in [33]. The fault tolerance of the machine was examined after the optimization, some fine tuning was conducted to satisfy the various objective and constraints listed in Table I. The final optimized parameters are listed in Table II.

IV. PERFORMANCE EVALUATION

In this section, the performance of the optimized machine at healthy condition is evaluated and its fault tolerant capability to various faults is also examined via FE simulation. All the evaluations are conducted at the base speed 4000rpm unless otherwise stated. And, for the sake of discussion, the faults, including open- and short-circuit fault, and inter-turn short circuit, are assumed to occur in the ABC 3-phase winding set.

A. Back emf

Initially, the machine under no load condition was evaluated. The phase flux linkage and line-to-line back-emf are shown in Fig. 4 and Fig. 5, respectively. Since the flux linkages and back-emfs in all three 3-phase sets are identical, only the waveforms for the ABC set are shown. It is observed that the PM flux linkage in the machine is relatively low which means that in case of a short circuit fault, no excessive current would be induced. The maximum line-to-line back emf voltage at 19200rpm is 284V, slightly larger than the DC link voltage. Consequently, in the case of an inverter failure at the maximum speed, negligible power would flow back to the DC link. This is a special merit for this PM assisted synchronous reluctance machine since the torque production mainly relies on the reluctance torque rather than the PM torque.

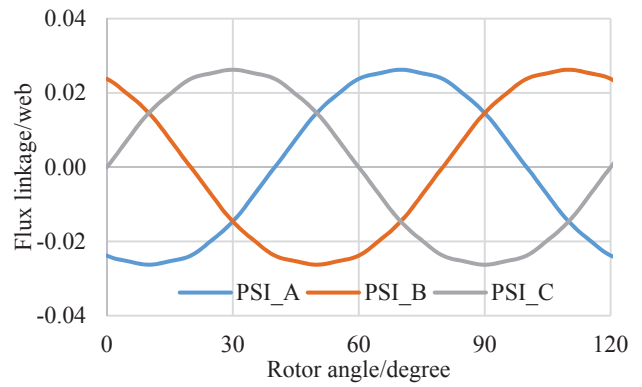


Fig. 4. Phase flux in no load condition.

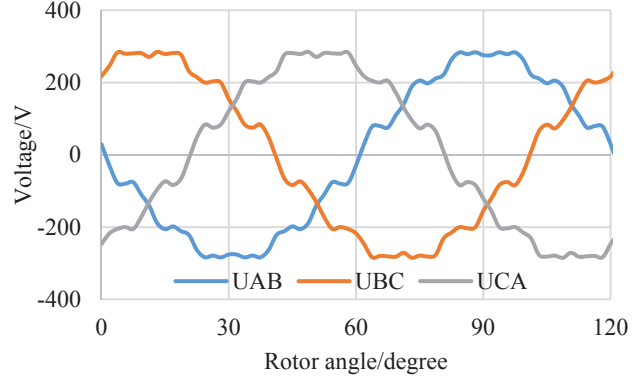


Fig. 5. Line-to-line back emf at 19200 rpm.

B. Healthy Operation

When operating in healthy condition with the rated current excitation, namely, 118.5A at 52.5° γ angle in all the three 3-phase winding sets, the resultant torque waveform at the rated power of 40kW is shown in Fig. 6. The machine outputs an average torque of 95.5Nm at the rated operating point with 16.8% torque ripple which is mainly due to the 6th and 12th harmonic produced by the interaction of the rotor saliency and stator slotting. Fig. 7 shows the 2D flux distribution under the rate conditions. It is evident the distribution repeats 3 times periodically over 360 degrees. Thus, the flux linkages of the three 3-phase sets are also identical under healthy conditions. By way of example, Fig. 8 shows the flux linkage waveforms of the ABC set. While distortions due to space harmonics and magnetic saturation are visible, the waveforms exhibit the 3-phase symmetry.

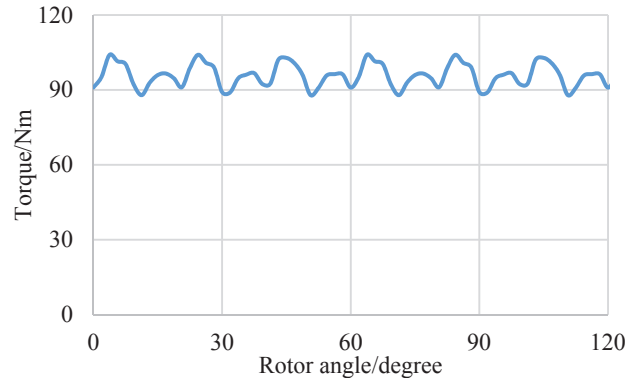


Fig. 6. Torque in healthy condition.

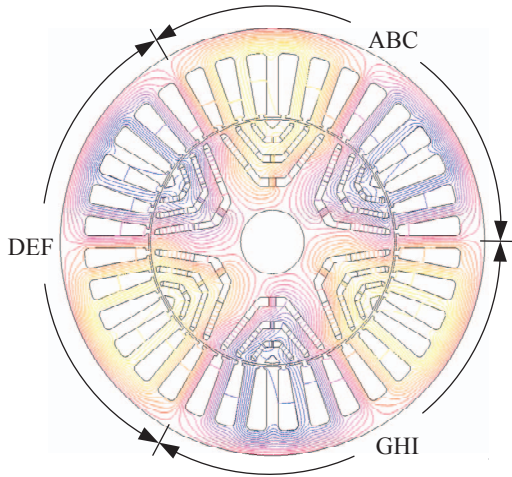


Fig. 7. Flux distribution in healthy condition.

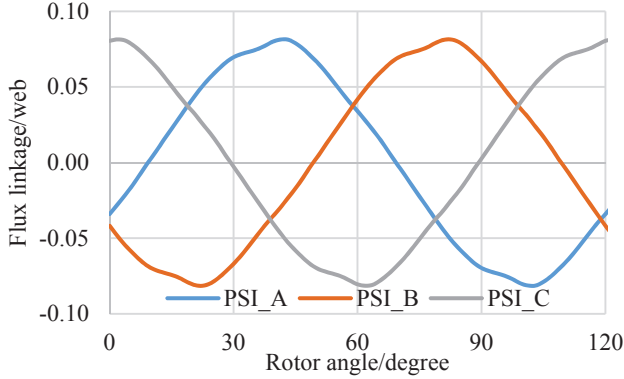


Fig. 8. Phase flux linkage in healthy condition.

C. One Set Open Circuit

In case of a winding open circuit, switch open-circuit failure or control failures the faulty set of 3-phase winding should be deactivated by opening all the inverter switches. The currents in the faulty set become zero, leading to one set open-circuit failure mode. The remaining two 3-phase sets are excited by the same currents and resulting torque waveform is shown in Fig. 9. The average torque of the machine is 54.6Nm, slightly lower than 2/3 of the rated value. In addition to the 6th and 12th harmonic torque ripples, a 2nd harmonic torque ripple is clearly visible in the torque waveform. This is caused by the electromagnetic unbalance resulting from the open-circuit fault, which is evident from the flux distribution shown in Fig. 10 under the open circuit condition of the ABC set.

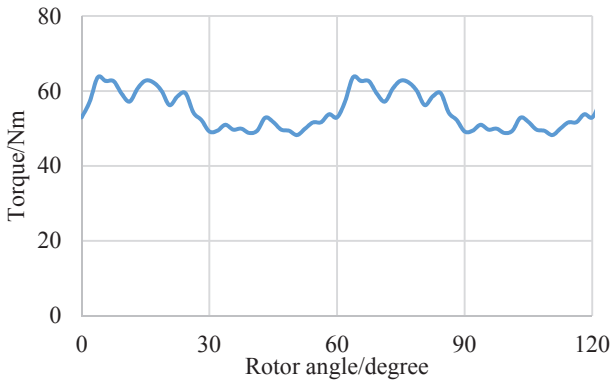


Fig. 9. Torque with set ABC open circuited.

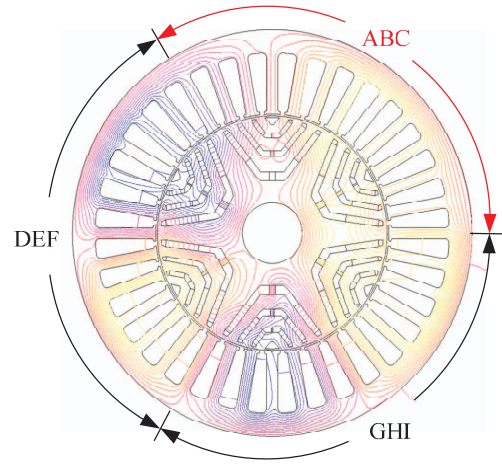


Fig. 10. Flux distribution with ABC set open-circuited.

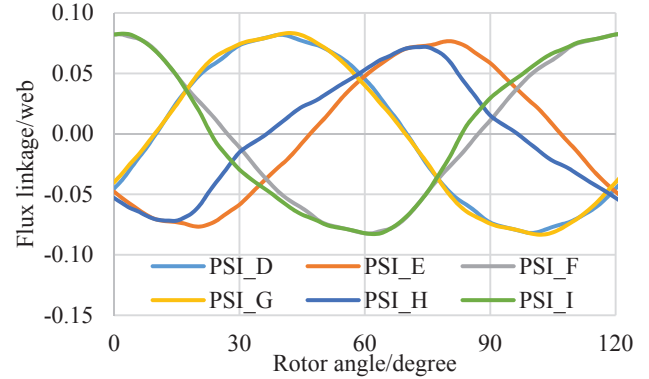


Fig. 11. Healthy phase flux with ABC set open-circuited.

As will be seen, the flux in the region occupied by the ABC set is mainly produced by the rotor magnets and differs from those in the other regions. Hence the flux linkage waveforms of the DEF and GHI sets shown in Fig. 11 are no longer balanced. The amount of distortion in the flux linkage waveforms due to the unbalance is different in different phases. The distortions in phases D and G are very small while slightly more distortions are seen in phases E and H. This is mainly attributed to the leading and trailing end effects relative to the direction of rotation similar to those in a linear machine. However, the phase flux linkages in the open-circuited ABC set, as shown in Fig. 12, are heavily distorted. This indicates that mutual coupling still exists in the three 3-phase winding sets of the machine.

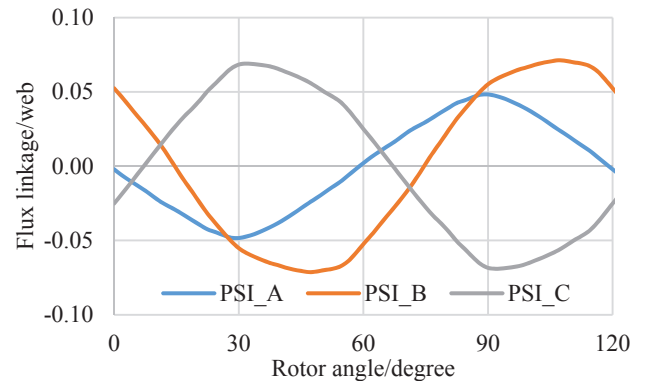


Fig. 12. Faulty phase flux with ABC set open-circuited.

D. One Set Short Circuit

If a switch in the inverter or the phase winding is short-

circuited, that particular inverter should turn-on all its top or bottom switches to create a terminal short circuit for the faulty set. The healthy sets are still excited by the inverter for continuous operation similarly to the case of the one set open-circuit fault. The resultant short-circuit phase currents are shown in Fig. 13 and their RMS values are lower than the rated due to the fact that the PM flux in the machine is relatively low. Hence, no excessive heat will be produced in the faulty set and the machine will be safe to continue operating. Such low short-circuit current is an inherent property of this type of machines and no penalty was required in the machine design to achieve this. It is observed that the short circuit currents in each phase of the ABC set are asymmetrical. This is attributed to the mutual coupling between the healthy sets and the faulty set since they are not completely magnetically isolated.

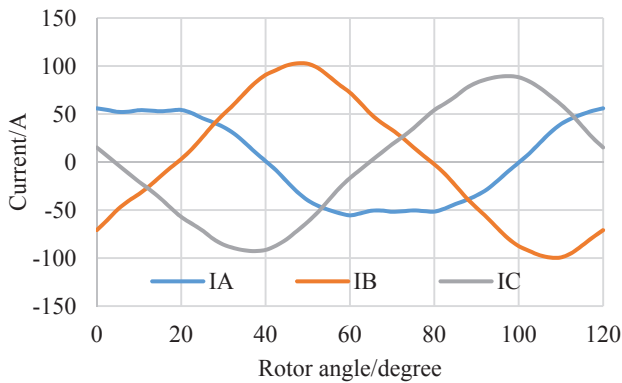


Fig. 13. Short circuit currents.

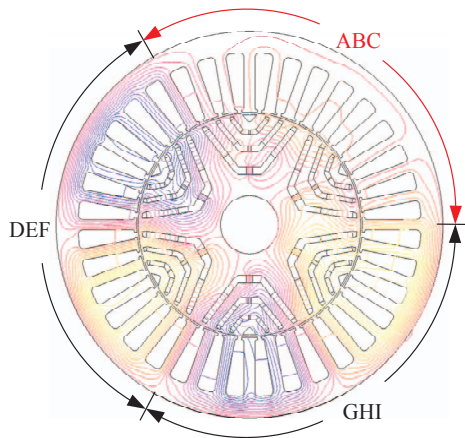


Fig. 14. Flux distribution when ABC set is terminally short-circuited.

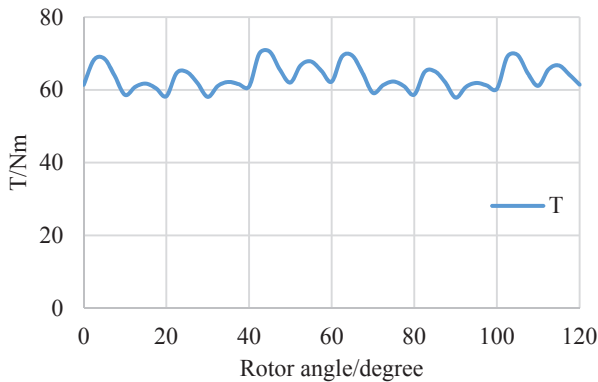


Fig. 15. Torque with one set short-circuit.

The flux distribution under the short circuit condition is shown in Fig. 14. As can be seen, the flux in the region

occupied by the short-circuit ABC set is almost nullified by the short-circuit currents. The flux density in this region is quite low. In contrast, the flux-density distribution in the other region is almost as normal. The torque waveform under the short circuit condition is plotted in Fig. 15 with an average torque of 63.5Nm, slightly higher than 2/3 of the rated and that in the open circuit case. The torque ripple is also lower than the open circuit case, and the main ripple are also the 2nd and 12th harmonics. These results confirm that the terminal short-circuit fault can be accommodated.

E. Inter-turn Short Circuit

An inter-turn short circuit fault in a phase winding is known as the worst fault scenario, especially for a single turn fault. Excessively large current is induced in the faulty turn due to extremely low impedance. Consequently the temperature of the faulted turns increases rapidly which may spread quickly and cause catastrophe failure. The predicted single turn fault current without any mitigation is 9 pu as shown in Fig. 16 under the same operating condition as previously stated. Therefore, fast fault detection and mitigation strategy should be in place to reduce to current to a sustainable level by application of terminal short circuit.

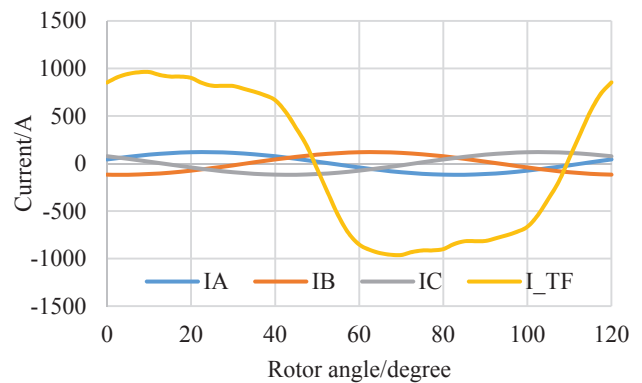


Fig. 16. Phase currents and short-circuit currents in single turn fault.

In order to limit the fault current to an acceptable level, terminal short circuit was applied via the inverter of the faulty 3-phase set to nullify the flux in the fault part. Consequently, the fault current was reduced to a much lower value. However, the investigations show that the fault current is dependent on the location where a single turn fault occurs, coils A1, A2, B1, B2, C1, and C2 as shown in Fig. 17, and on the currents (both magnitude and phase angle) in the healthy DEF and GHI sets.

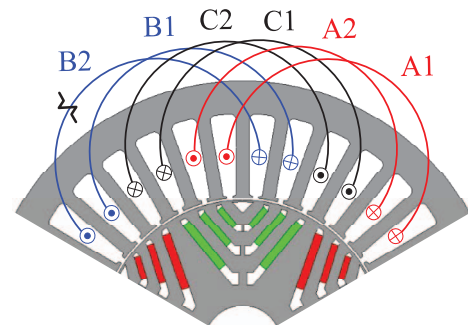


Fig. 17. Turn fault location.

In order to guarantee safe operations under any fault scenario, therefore, the worst fault case requires to be identified. In order to find the maximum fault current after

applying the terminal short circuit, the turn fault currents are evaluated by a fast prediction method assuming a single

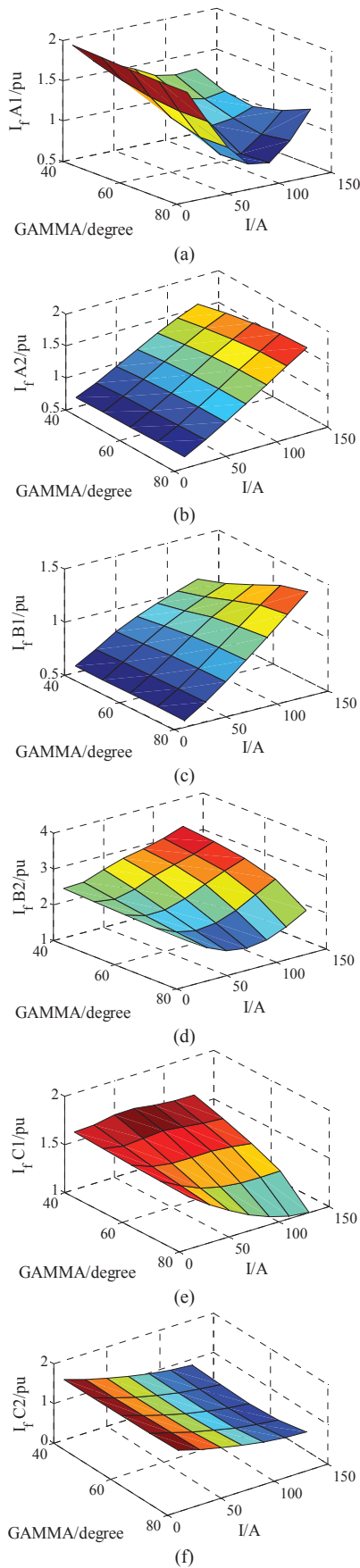


Fig. 18. Turn fault current variations in coils with magnitude and gamma angle of currents in healthy sets (a) A1 (b) A2 (c) B1 (d) B2 (e) C1 (f) C2.

turn fault occurs in each of the 6 coils. Thus, turn fault current variations in each of the 6 coils with the current magnitude and phase angle in the healthy sets were scanned and the results are shown in Fig. 18. It is seen that the turn fault current variations with the magnitude and gamma angle of the currents in the healthy sets exhibit different trends in different coils. The fault currents are around 1~2pu for coils A1, A2, B1, C1 and C2 which are quite sustainable for the machine. Detailed thermal analysis shows that the heat produced by the fault current can be easily contained and the machine is capable to continue operation for a long time. However, the fault current in B2 coil is found to be the highest with the maximum value around 3~4pu. It can also be seen that the fault current increases with the current amplitude and decreases with the gamma angle. Therefore, the worst operation condition is the maximum current and minimum gamma angle which is the rated operating point.

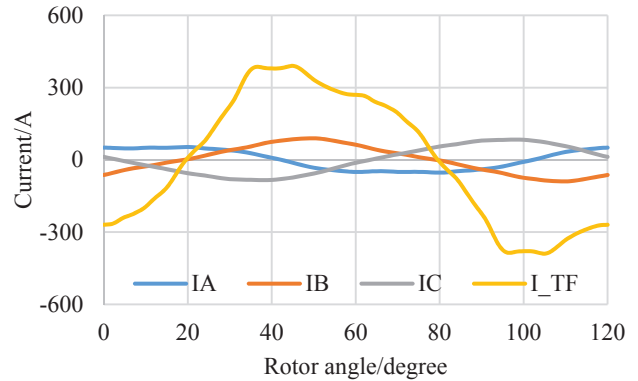


Fig. 19. Currents in turn fault with terminal short circuit.

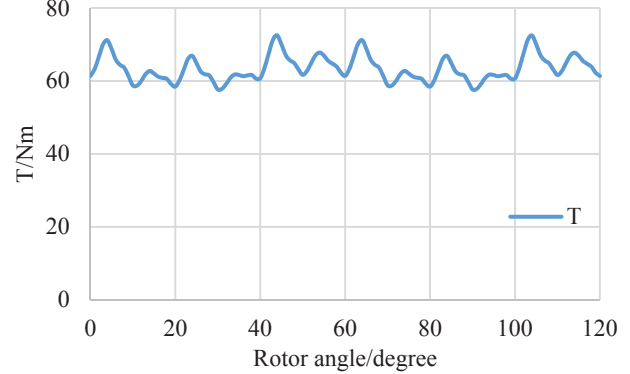


Fig. 20. Torque in turn fault scenario with terminal short circuit.

As a result, the performance of the worst case, single turn fault in B2 coil in motoring mode, has been further examined in details at the rated operating point. Terminal short circuit is applied on the faulty set to reduce the turn fault current. The resultant currents in the 3 phases and in the fault turn are illustrated in Fig. 19. The phase currents in the healthy part of the ABC windings are almost the same as those in one set terminal short circuit while the turn fault current is 3.2pu which is thermally sustainable for the single turn fault since the current in the healthy part of the coil is lower than the rated value. The output torque is similar to the one set terminal short-circuit case as shown in Fig. 20. The average output torque is around 2/3pu. The 2nd and 12th harmonics are still the main harmonics in the torque ripple. Thus, the machine is capable of continuous

operation under the single turn fault and can still outputs 2/3 rated torque.

It should be noted that the maximum turn fault current occurs in B2 coil when the machine is operating in motoring mode. If the machine is operating in generating mode, the worst turn fault case will occur in A1 coil.

V. CONCLUSION

In this paper, a fault tolerant machine drive based on PMA SynRM with segregated windings has been described and a prototype machine with triple redundancy has been optimally designed. Its performance in healthy and various faulty conditions are evaluated by FE simulations. The results show that the proposed machine exhibits excellent performance in healthy conditions and good fault tolerant capability under various fault scenarios, including a single turn short circuit fault in the worst location. In addition, the machine can be designed without any penalties, achieving both high performance and fault tolerant capability. The prototype machine is currently under construction and experimental results will be reported in future.

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