Turn-Turn Short Circuit Fault Management in Permanent Magnet Machines

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ABSTARCT

This paper presents a systematic study on turn-turn short circuit fault and ways to manage them to provide a basis for comparison of the various options available. The possible methods to reduce the likelihood of the winding SC fault and the fault mitigation techniques related to such faults are discussed. A Finite Element (FE) analysis of a surface-mount Permanent Magnet (PM) machine under application of different mitigation techniques during a turn-turn fault is presented. Both machine and drive structural adaptations for different fault mitigation techniques are addressed. Amongst the investigated fault mitigation techniques, the most promising solution is identified and validated experimentally. It is shown that the shorting terminal method adopting vertical winding arrangement is an effective method in terms of the implementation, reliability and weight.

Key words — Inter-turn, short circuit, fault tolerance, fault mitigation, PM machine, safety, reliability.

INTRODUCTION

Permanent magnet (PM) machines are increasingly being used in safety critical systems such as fuel pumps, actuator, landing gear and starter generators in aerospace, and power steering, alternator and motor in automotive (Electric Vehicles) applications [1-4]. This is mainly due to their high power density and high efficiency. The key issue of the PM machines is that the permanent magnet field cannot be de-excited in the event of a fault. It influences the overall drive system safety, reliability and availability [5]. The safety of the system can be ensured by adopting fail-safe arrangement [6, 7]. By decreasing the failure rate of the components, the reliability of the system can be improved. To achieve high availability it is desirable for a system to continue to operate during a fault condition, this can be done using the concept of Fault Tolerance (FT) within the system [8, 9]. Such concept includes fast and accurate fault detection and isolation, as well as efficient remedial control strategies, in order to cope with any fault associated to the machine.

Electrical faults associated with the PM machines are winding Open Circuit (OC) faults and winding Short Circuit (SC) faults. Winding SC faults include turn to turn faults, phase to phase faults and phase to ground faults [10-14]. The likelihood of these faults' occurring can be reduced and also the faults can be managed by employing fault tolerant design practices. However, a winding turn-turn SC fault remains problematic since the fault is located within a slot and cannot be isolated from adjacent turns [15-17]. If remedial action is not taken during a turn-turn SC fault, the resulting fault current is likely to become excessively high due to the low impedance of the winding. The condition of high current can lead to catastrophic damage or fire which cannot be tolerated in safety-critical system, for instance, an aircraft fuel pump [4].

The main cause leading to a winding SC fault is deterioration of the insulation materials. In normal operation turns' insulation experiences mechanical, electrical and thermal stresses [18]. These stresses can be amplified by the following:

- voltage surges
- voltage rise rate (dv/dt) due to pulse width modulated switching [19]
- electrostatic partial discharge within the machine
- insufficient cooling
- poor maintenance

The level of deterioration depends on the insulation thickness and the operating environment. So the varying operating environment and manufacturing tolerances have a major impact on the likelihood of fault occurrence.

Insulation failure and thus, the SC fault can however be prevented by adopting better design, improved manufacturing processes, regular maintenance, adequate cooling, thicker insulation, operation under low temperature and lower switching frequencies. Although these prevention measures would be effective they also have disadvantages. Increased insulation thickness reduces the fill factor which results in increased winding losses. Operation at both DC and high frequencies introduces additional time harmonic losses. This inevitably results in further winding degradation. However, the insulation life can be extended further by condition monitoring of the insulation. This enables the machine to be controlled in accordance with operating conditions which decrease insulation degradation [20-22].

There are several techniques which have been proposed in the literature for monitoring the influence of the partial discharge [20, 23, 24] and the voltage surges [25, 26] on the winding insulation. Recently in [22] an effective methodology that employs a conductive coating coaxially embedded in between two insulation layers, has been proposed to monitor the state of the winding insulation and detect the presence of an incipient failure and thus able to predict winding faults. Although monitoring insulation and performing safe operation can be a solution to winding failure, if failure does occur then the system should be able to cope with such an event.

This paper presents a systematic study on the short circuit fault and ways to manage them to provide a basis for comparison of the various options available. The focus is given into the single turn-turn SC fault mitigation since this type of fault presents the worst case scenario as it leads to the highest short circuit current [17]. Using Finite Element (FE), a comparative study is carried out on a 12 slot-14 pole surface mount PM machine. Different machine structural adaptations are employed to adopt the fault mitigation techniques. The validity of the fault mitigation technique and their key challenges are addressed. A special attention is given to clarify their advantages/ disadvantages and the design trade-offs involved. Amongst the investigated fault mitigation techniques, the most effective solution has been identified and validated through experiment.

SC FAULT MITIGATION TECHNIQUES

As previously explained operation of a PM machine during the SC fault is challenging task due to the PMs' field. Different methods have been proposed to deal with this issue. The proposed methods can be categorized into following groups:

1) phase/machine terminals shorting [27, 28]
2) phase/machine terminal shorting whilst adopting vertical winding [17]
3) phase current injection [29]
4) mechanical shunts [30]
5) electrical shunts [31]
6) fuse wire/ switches technique [32]
7) mechanical design [33-36]
8) machine topologies [37-39]

The machine terminal shorting method, and phase current injection method, can easily be adopted within the drive system. The terminal shorting technique allows the shorted winding to share the total Magneto Motive Force (MMF) and thus reduces the SC fault current. The terminal shorting adopting vertical winding method improves the FT inherently by eliminating the influence of the fault location on SC fault current. The current injection method uses the healthy windings to reduce the flux linking with the shorted turns. The shunt mechanism limits the SC fault current by diverting the PM flux via the shunt magnetic pathway. An electrical shunt requires additional field windings while a mechanical shunt is triggered by mechanical movement. In the fuse wire or switches technique, an open circuit is formed which allows the fault to self-limit at the fusing current.

Different mechanical designs which include adjustable magnetic sleeves [33], misalignment between the stator and the rotor [34], variable air-gaps [35] and magnetic fluid [36] have been proposed for field weakening operation in the PM machine, these methods can also be considered for mitigation of the SC fault current. However, application of the mechanical methods de-fluxes not only the faulty phase winding but also the adjacent phase windings. As a result the machine cannot provide the performance required by the system. In such case redundancy needs to be introduced within the system, this further increases the system weight and volume.

Another methodology that could be considered for SC fault mitigation is a hybrid machine design which consists of both PMs and field windings. Those are memory motors [37], consequent pole PM machines [38] and doubly salient PM machines [39]. Although these machine topologies are possible solutions they have an inherently reduced efficiency and power density due to the additional losses caused by the field windings. In addition the design requires an additional space to accommodate the field winding. It would result in increased size and weight, thus reduced power density. So, the mechanical design and machine topologies proposed for field weakening are not considered as a turn-turn fault current limiting option. Herein methods that can easily be implemented within PM machines are considered. The following sub-sections will describe individually these SC fault current limiting methods in detail.

COMPARATIVE STUDY ON SC FAULT MITIGATION TECHNIQUES

This section presents a comparative study between five different fault mitigation techniques as discussed in the previous section. The study is carried out on a 6-phase, 12-slot/14-pole surface-mount PM machine (Fig. 1) designed for application of rotorcraft actuation. The specifications of the considered machine are given in Table I. The machine has single layer concentrated winding arrangement which has one coil per phase and 65 turns per coil. The initial machine is designed to have a high per unit inductance [17] and small mutual coupling between the phases. This facilitates the machine to limit the phase SC fault current to the rated phase current of the machine ($10A_{peak}$) avoiding interaction of adjacent phases. In addition the machine has been designed to handle the increased current loading during a fault and thus, continuous operation can be sustained.

2D FE analysis was carried out under different fault conditions whilst employing different fault mitigation techniques. In the analysis the non-linearity of the silicon steel laminations is taken into account. 3D influences are however neglected based on the machine’s relatively long stack and the short end-windings.

In order to effectively analyse turn-turn faults, an FE model that could specify the location of the fault geometrically and electrically is required. Such a model is build considering each individual turns' geometrical location and electrical connection of the winding arrangement. The geometrical representation of the turns and their location in the machine are shown in Fig.1. Thus, different turn-turn fault can be modelled and analysed. Within this work key focus will be on analysing a single turn-turn fault close to the slot opening region as this is the worst case scenario for turn-turn faults [40]. For clarity, such a condition of a single turn-turn fault is referred to as a worst-case SC (WSC) fault throughout the paper. The WSC fault analysis for considered surface mounted PM machine under different mitigation methodologies are detailed below.

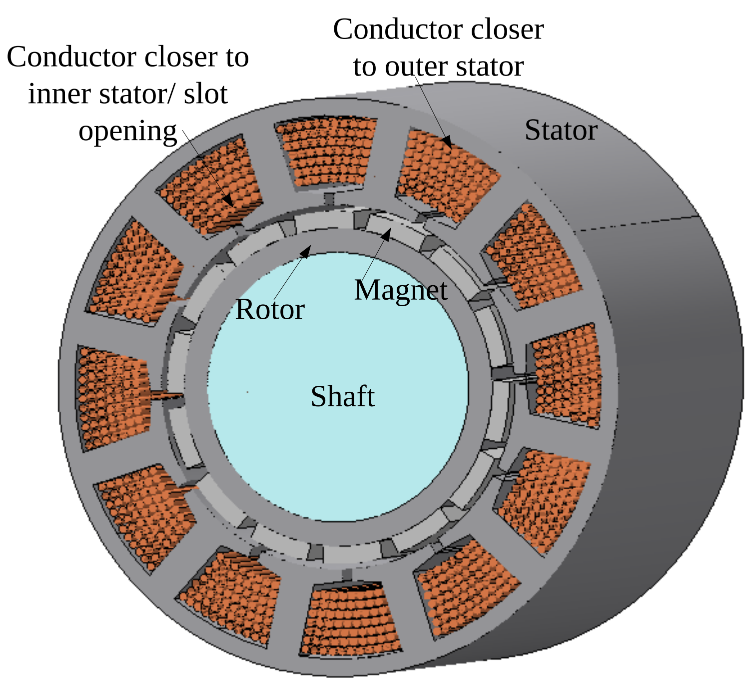


Fig. 1. Cross sectional view of 12 slot 14 pole studied PM machine

TABLE I

Specification of the six phase FT PM Machine

Outer Diameter	100mm
Axial length	100mm
Split ratio	0.6

Rated Speed	2000 rpm
Rated Output Power	2070 W
Rated Current	7.07 A
Back-emf	45.75 V
Phase Resistance	0.22529 Ω
Phase Inductance	0.0043 H

A. Terminal Shorting

This method has been proposed for PM machines in [27, 28] where, a separate H-bridge inverter for each phase was used to isolate the phase windings electrically and control them under SC fault. The respective faulty phase is short-circuited through the H-bridge converter switches (T_1 and T_3 are ON while T_2 and T_4 are OFF) as shown in Fig.2. In order to avoid imbalance between the phases, this method has also been implemented for double star connected PM machines with two separate three-phase voltage source inverters [41]. When a fault occurs, a star connected phase will be short-circuited while the remaining star connected phases are used to provide the required performance. In fact under faulted operation the field produced by the PM is shared almost equally among the turns of the faulty winding, and thus the current will be limited. However, phase inductances should be designed sufficiently high to limit the SC current to a safe value [6].

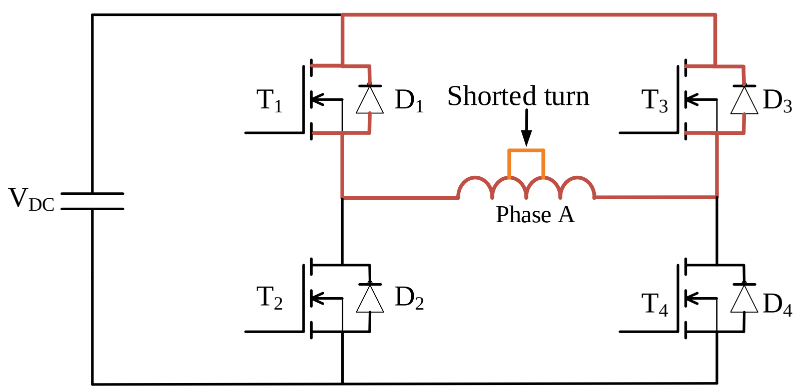


Fig. 2. Illustration of terminal shorting control strategy when each phase is separately controlled through an H-bridge inverter

If the adopted machine is designed to have a 1 per unit inductances [40], this implies that the SC current will be limited to the machines' rated current value in case of a full phase short. For such a machine two single turn faults located at the extremes of the slot will be investigated. One in the slot topmost position (close to the core back) and one at the bottom of the slot(close to the slot opening) as shown in Fig. 1. The resulting fault currents in the shorted turn after shorting the machine terminals are shown in Fig. 3.

As can be seen from the results, the fault current in the outer most turn is twice the rated current ($10A_{peak}$). As expected the inner most turn fault is the worst case scenario and the current induced in a turn is significantly (more than four times) higher than the rated phase current. This is mainly due to the slot leakage inductances associated to the faulty turn which changes with its location. As a result the SC current with respect to the fault location varies [17]. In order to overcome this higher magnitude of SC current, the PM machine must be designed with approximately four times higher inductances or able to withstand higher currents. In each case this would result in a poor machine weight and performance. If this method is opted for, one needs to carefully trade of the fault tolerant capability against machine weight and performance.

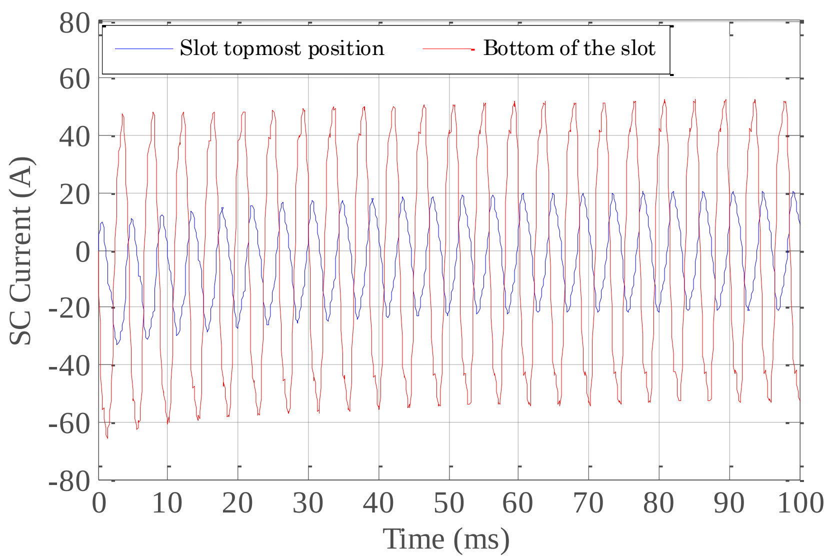
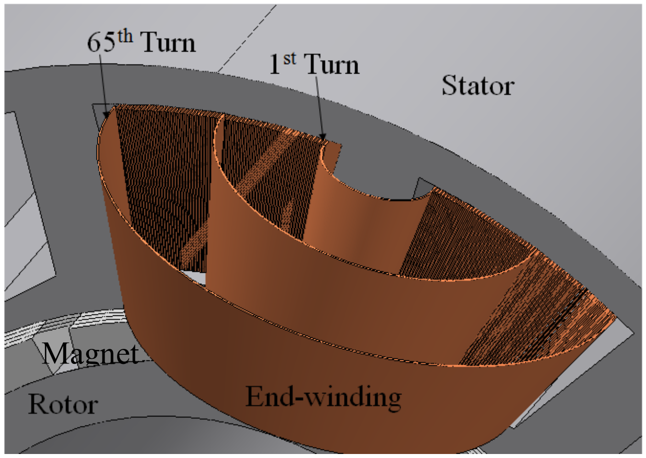


Fig. 3. A single turn-turn SC fault current after the application of the shorting the terminal scheme

B. Terminal shorting whilst adopting a vertical winding

The terminal shorting method with a machine adopting vertical winding [17] was proposed for mitigating SC faults independent of their position within the slot. The considered vertical winding arrangement is shown in Fig. 4a. Different winding fault locations will be considered to illustrate the key features of this solution. The results obtained for three fault locations are shown in Fig. 4b. The locations 1, 2 and 3 indicate the fault at 1st turn, 33rd turn and 65th turn respectively.



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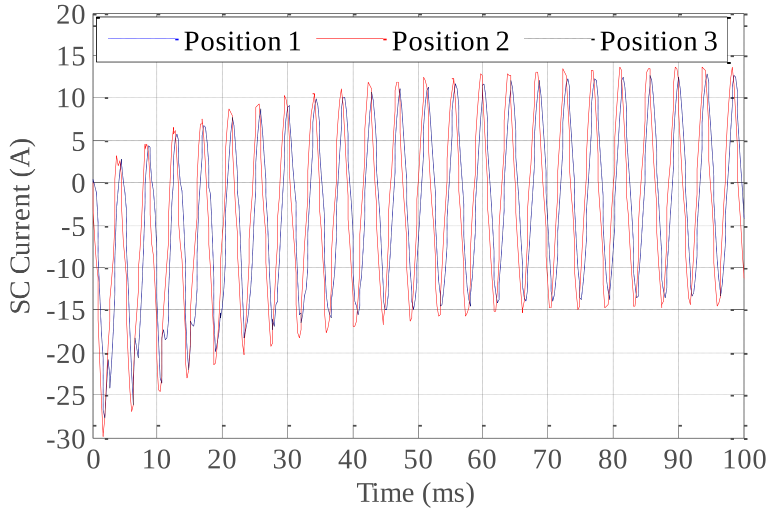


(b)

Fig. 4. (a) Schematic of the vertical winding and illustration of winding's fault location in the slot, and (b) a turn SC fault current for different fault location of vertical winding

As can be seen in Fig. 4b, similar SC fault currents are obtained for each of the considered fault locations. The results show that the SC current in the shorted turn is limited to the rated value regardless of its position in the slot. It is worth mentioning here that the possible SC fault that can occur in vertical winding is a single turn fault. This is due to the physical arrangement of the concentric coil. In a real machine one would expect a small reduction in the resulting SC current for the outer turns as their end winding (hence turn resistance) would increase accordingly. This winding structure has the main disadvantage of increased AC loses but on the positive side it also reduces the winding effective thermal resistance in the radial direction. Such a winding is thus more beneficial for low speed/ low frequency applications.

C. Current Injection

The current injection scheme is an alternative fault mitigation method proposed for an open slot, bar wound, large PM machine in [29]. The method relies on the principle of nullifying the flux associated with the faulty turn so as to suppress the SC current by forcing an adequate predetermined current wave shape in the remaining heathy turns. Here this technique is adopted for mitigation of the turn-turn SC fault when the machine adopts conventional round conductors such as that shown in fig.1. The current to be injected can be obtained from the differential equations (1) and (2). It is worth highlighting here that the mutual coupling between phases is assumed to be very small due to the coil arrangement and the machine geometry itself.

$$V_1(t) = I_1(t) R_h + L_h \frac{dI_1}{dt} + L_m \frac{dI_s}{dt} + e_1(t) \qquad (1)$$

$$0 = I_s(t) R_s + L_s \frac{dI_s}{dt} + L_m \frac{dI_1}{dt} + e_2(t) \qquad (2)$$

where,

- e_1: electromotive force (emf) in the healthy (N_h) turns
- e_2: emf in the shorted (N_s) turns
- I_1: phase current
- Is: induced current in the shorted (N_s) turns
- Lh: self-inductances of healthy (N_h) turns
- Ls: self-inductances of shorted (N_s) turns
- Lm: mutual inductance between N_h and N_s turns

From (2), the optimal current to inject into the healthy winding in order to cancel the SC current (I_s = 0) can be expressed by

$$I_1(t) = -\int_0^t \frac{e_2(t)}{L_m}\,dt \quad = \quad \frac{\Psi_{sc}}{L_m} \tag{3}$$

where, Ψ_{sc} is the no-load flux linkage in the shorted turn. Using Fourier expansion of e_2, (3) can be re-written as

$$\begin{aligned} I_1(t) &= -\int_0^t \frac{\sum_{n=1}^{\infty} C_n \sin(n\omega t) + S_n \cos(n\omega t)}{L_m}\,dt \\ &= \sum_{n=1}^{\infty} \frac{C_n \cos(n\omega t) - S_n \sin(n\omega t)}{n\omega L_m} \end{aligned} \tag{4}$$

The SC fault current can be therefore nullified by injecting the current estimated by (4).

Fig. 5 shows the resulting current induced in a shorted turn (located at the bottom of the slot) after injection of the predetermined phase current for the machine considered. The obtained results clearly show that the WSC current can effectively be limited but not completely cancelled. This remaining current might be due to an inadequate no load e_2(t) used in (3) as this last is affected by the armature reaction field when the optimal current (4) is injected. A solution to overcome this problem consists to calculate the optimal current in an online recursive way by estimating Ψ_{sc}; this is clearly an inextricable task. Also it is worth noting that injecting a current with inaccurate harmonic components or less precision in the desired current waveform would result in excessive current in the shorted turn. Superimposing the respective current harmonics with enough precision is the key challenge in this method.

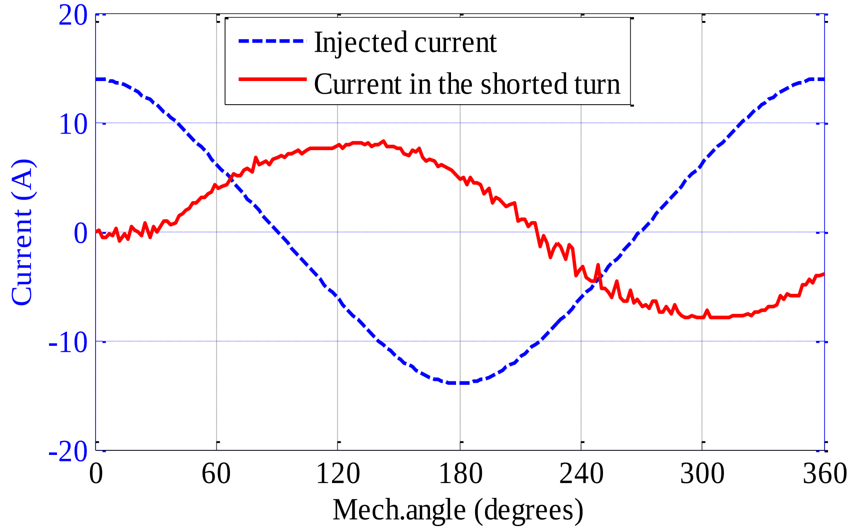
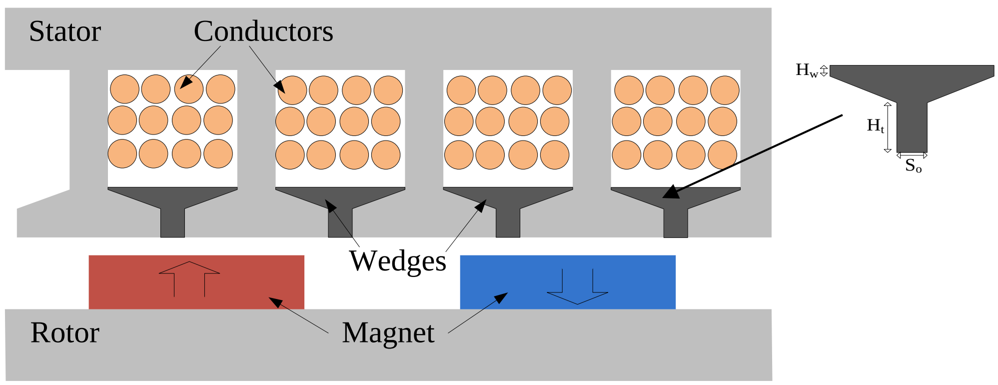


Fig. 5. Resultant current in the outermost shorted turn after the application of the current injection

D. Mechanical Shunt

This method proposed in [30] is triggered by a spring loaded mechanism acting on the magnetic wedges to decouple the rotor flux from the windings via the slot wedges as shown in Fig. 6a. Under healthy operation the slot-opening region is open allowing magnetic coupling between the stator winding and the rotor magnetic flux. Under fault, the slot-opening is shorted via magnetic wedges. Hence, a large portion of the magnet flux is shorted through the magnetic wedges; consequently the coupling between the stator winding and the magnets flux is reduced significantly. In fact it is obvious that the wedge's height (H_w as shown in Fig. 6a) has a significant influence on the magnitude of the SC current since the flux generated by the PM is shorted via the wedge. Thus, the wedge has to be designed with an adequate height to limit the SC current to a desired value. To investigate this influence, different heights of the mechanical shunt are considered under a turn-turn SC fault conditions. The obtained WSC current for different heights of the shunt is given in Fig. 6b.

The results show that the mechanism effectively limits the WSC fault current; however, it requires the wedge to have an optimal height as expected. In the case considered here, the required optimal height is 1.9 mm to maintain the WSC current to the rated phase current value. The key concern is reliability of the spring loaded mechanism which could jam or increase the risk of losing parts into the airgap. Apart from the reliability of the triggering mechanism, another disadvantage of this method is that it requires a significant slot opening height to restrict the WSC current. This consequently results in a reduced slot fill factor and thus increased copper loss.



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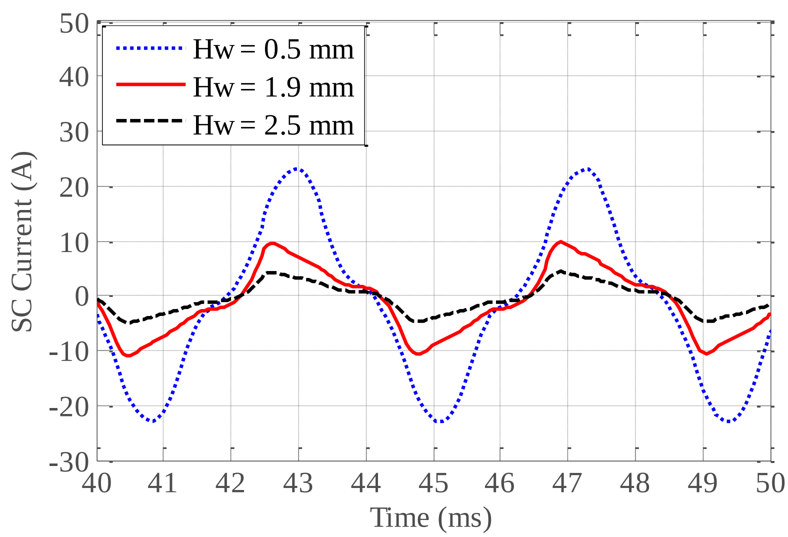


(b)

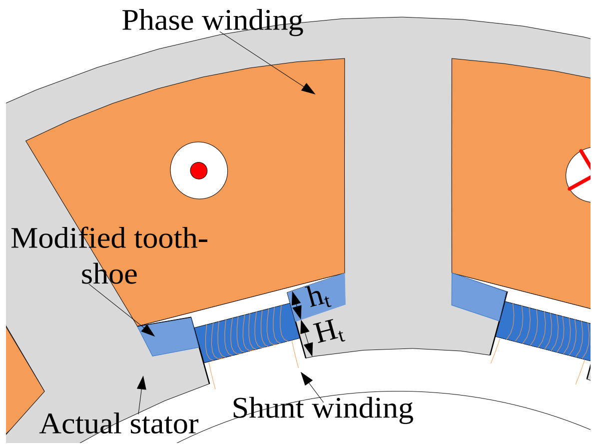
Fig. 6. (a) Shunting the flux via slot opening - mechanical shunt structure and (b) worst-case SC current waveform under a turn-turn fault for different wedge heights

E. Electrical Shunt

Similar to mechanical shunt, the electrical shunt method [42] is triggered by an auxiliary winding (called "control winding") which is placed in the slot opening region. In normal operation, the control winding is energized and thus a coupling between the stator and the rotor is formed due to saturation of the wedges placed at the slot openings. Under faulty condition the supply is disconnected, consequently the flux produced by the magnet is shorted through the slot openings.

Fig. 7a shows an arrangement of the electrical shunt adopted in the slot opening of the considered machine. The shunt has a number of turns wound around a magnetic core. Similarly to the mechanical shunt, the electrical shunt also requires an optimal height of the tooth-shoe to shunt the flux effectively. In this analysis, WSC current is investigated for different values of the tooth shoe height (h_t) in addition to the initial tooth height (H_t). The obtained WSC current for different tooth-shoe heights is given in Fig. 7b.

It is evident from the results that the design requires an additional shunt modification as its height significantly influences the magnitude of the WSC current. The main drawback of this method is that the shunt winding requires an additional space in the slot which reduces the effective fill factor. This must be considered at the design stage as additional copper loss will result due to the additional coils and due to the reduction of the available slot area for the main winding.



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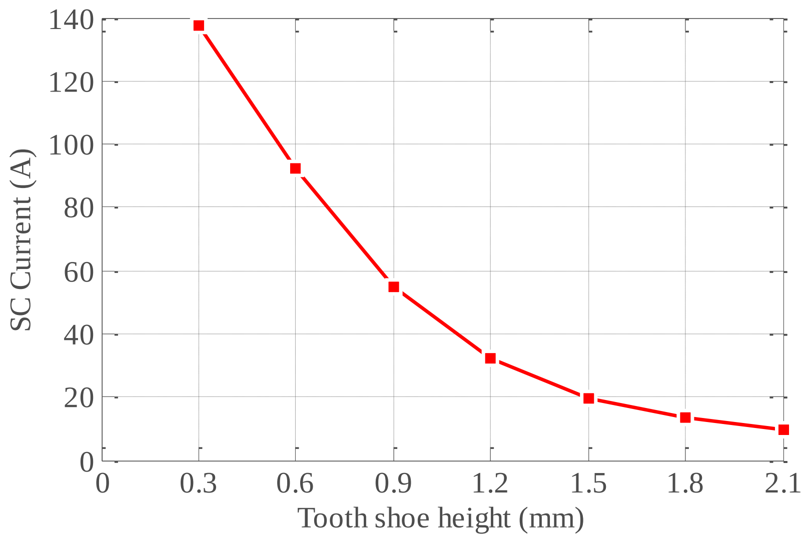


(b)

Fig. 7. (a) Arrangement of electric shunt and tooth height in the region of slot opening and (b) magnitude of WSC current vs. tooth shoe height

This method also reduces the generated torque during normal operation unless the slot opening regions are subjected to an MMF which drives the magnet flux through the main coils. To confirm the required level of MMF to achieve the required torque of the machine under consideration, FE simulations are carried out for different numbers of Ampere-turns. It is worth highlighting that although inserting a higher number of Ampere-turns (> 100 At) within the slot (compared to the initial slot which has 650 At) is not realistic, several unrealistic conditions in the simulation are also considered to predict the MMF requirement for the machine to develop the required torque. The torque obtained for different MMFs is presented in Fig. 8.

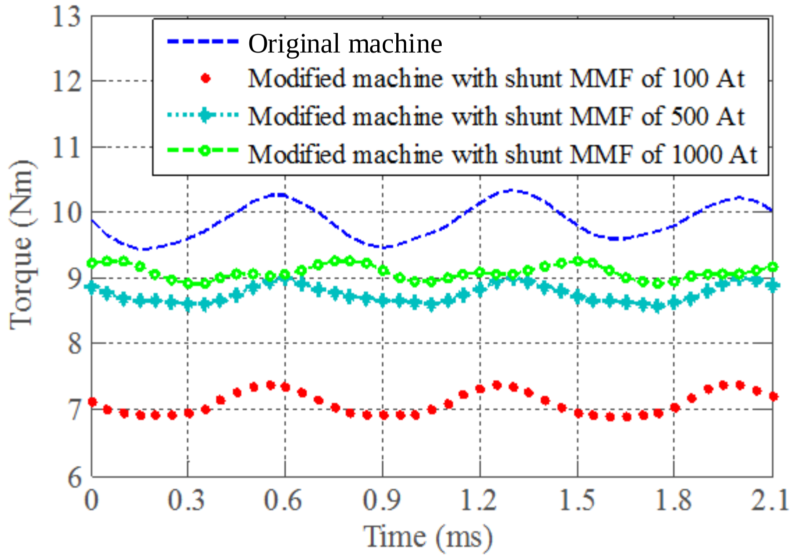


Fig. 8. Torque vs. shunt winding MMF (At - Ampere turns) under normal operation

From results, it can clearly be seen that the control winding would require a significantly high number of Ampere-Turns to produce the required torque. In addition to the extra copper losses generated by the control winding, torque reduction under normal operation is the main concern of this control methodology.

COMPARATIVE SUMMARY OF THE DIFFERENT SC FAULT MITIGATION TECHNIQUES

Table II compares the WSC current, active weight of the machine and generated losses for different fault mitigation methods. In the analysis the windings end effects and the requirement of additional cooling for the electrical shunt mechanism due to implementation of control windings are not considered; copper eddy current losses are however accounted for. The losses generated in the auxiliary winding of the electrical shunt are also taken into account where MMF of 100 At (N x I = 10 x 10) is used considering the availability of the space in the slot.

TABLE II

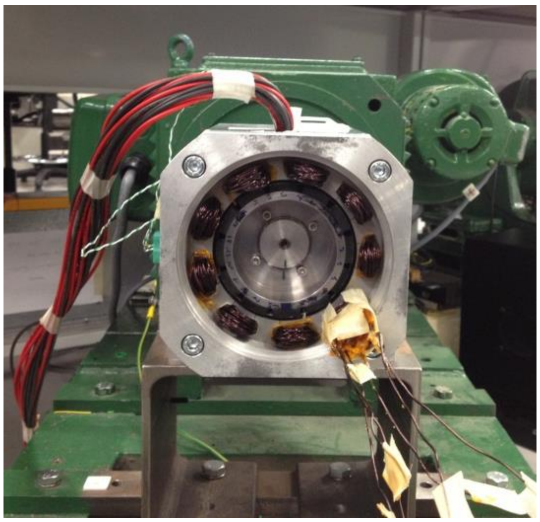
Comparison between different fault mitigation methods

Methods	WSC current (A)	Weight (kg)	Winding losses at rated operation (W)	Torque (Nm)	Torque under fault (Nm)
Terminals shorting with conventional winding	52.65	4.06	58.61	9.98	8.14
Terminal shorting with vertical conductor winding	12.37	4.06	72.09	9.98	8.25
Current injection	8.12	4.06	60.29	9.98	8.42
Electrical shunt	10	4.92	104.75	7.35	6.73
Mechanical shunt	10	4.87	69.50	9.98	8.34

As previously discussed, the vertical winding generates slightly higher losses than the conventional type of winding; but it has a better WSC limiting capability. The current injection method has a the best WSC limiting capability without affecting performance; however as mentioned earlier implementation of this method is not simple and the resulting WSC current will still be critical unless the injected current magnitude and its phases are precise. Despite being less reliable and heavier, the shunting methods lead to a better WSC current limiting capability than the first two control methods. It allows shunting completely the PMs' flux while adopting the required shunt height. However torque reduction and additional winding losses are inevitable in the electrical shunt mechanism whilst a mechanically actuated shunt requires a reliable triggering mechanism in the event of fault. Hence, considering all these facts amongst the investigated fault mitigation topologies it can be concluded that the vertical winding is the preferred method as it is easy to implement, is more reliable and does not incur additional weight. In the next section details of the effectiveness of the vertical winding method via an experiment will be presented.

AN EFFECTIVE SC FAULT MITIGATION TECHNIQUE EXPERIMENTATION

To validate the concept of the vertical winding, a 12-pole/ 18-slot PM machine is wound with vertical conductor. In addition a similar prototype with conventional round conductor is used for comparison. The experimental prototypes are shown in Fig. 9a,b and associated FE flux density plots are presented in Fig.9c,d respectively. The machines' specifications are detailed in Table III.



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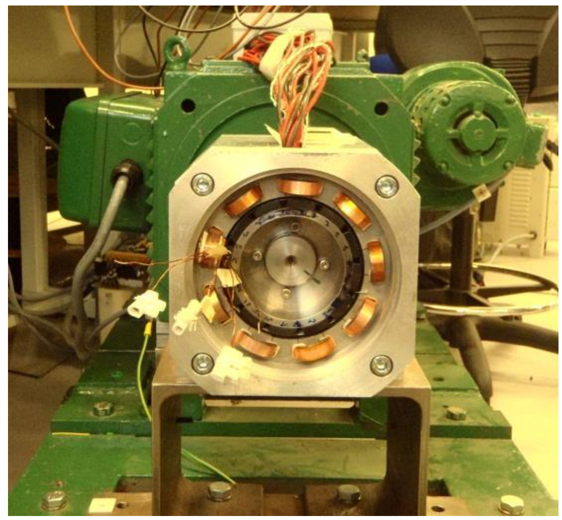

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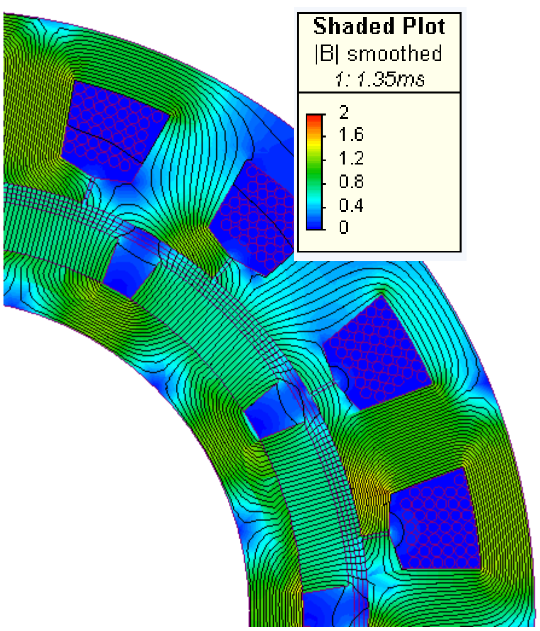

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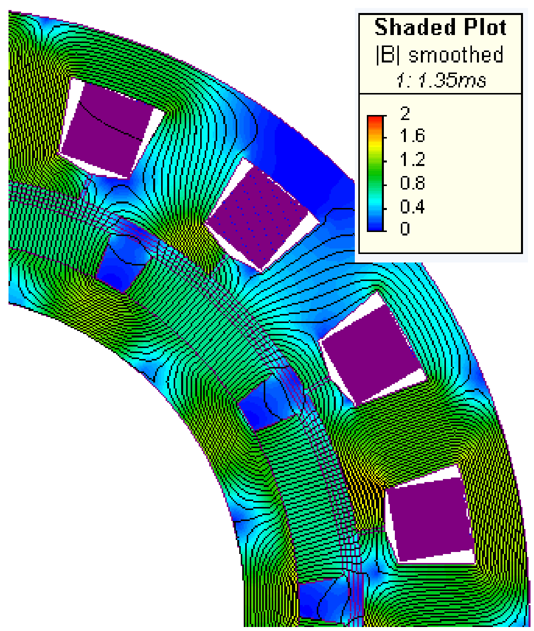


(d)

Fig. 9. (a) Conventional round conductor wound and (b) vertical conductor wound FT-PM machine, and associated FE flux density plot of (c) conventional round conductor wound machine and (d) vertical conductor wound machine under a healthy operation

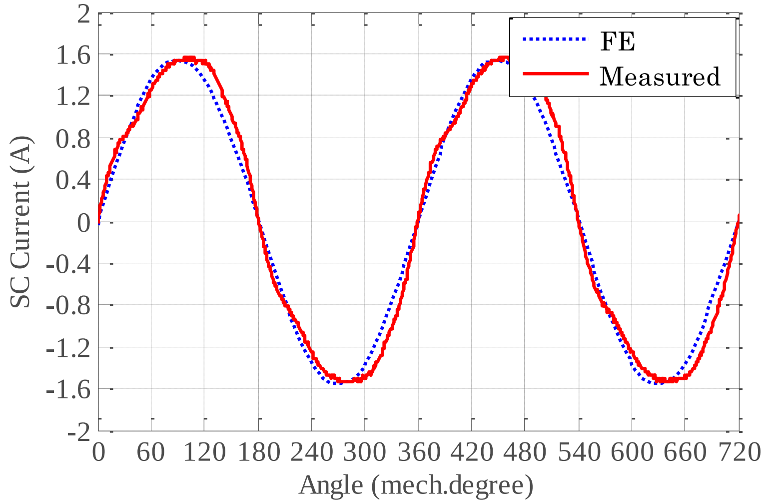
TABLE III

Specification of the 18-slot 12-pole PMSM

Number of phase (*m*)	3
Number of slot (*S*)	18
Number of pole (*p*)	12
Number of turns per coil (N_C)	40
Rated current (*rms*)	7.77 A
Rated speed (ω)	2000 rpm
Rated torque	6 Nm
Output Power	1.25 kW

It is worth highlighting that both machines have similar DC resistance and number of turns and thus, same copper fill factor (of K_f = 0.52) is kept in both cases. However, if the slot is completely filled, the fill factor of the vertical conductor wound machine is expected to be less than the conventional round conductor wound machine. This is due to shape of the vertical conductor which does not facilitate the winding to be placed at trapezoidal slot edges as shown in Fig.9d. But, still higher fill factor can be achieved using the vertical conductor due to the placement and its compactness. Also the fill factor can be further improved if parallel slot is adopted. This allows the machine to be loaded slightly higher. On the contrary an additional weight will be added to the machine. These trade-offs should be considered at the design stage; however this is not the scope of this paper and therefore not considered in detail.

To validate the fault limiting capability of the winding, the fault location and the mechanism which enables to create the fault are necessary. Thus, in both winding cases the windings are accurately positioned in the slot and the short circuits are introduced via external leads connected to the end windings. Several fault locations are considered. The fault current is measured under application of shorting terminal method and compared with calculated results under same condition. The obtained results for worst-case inter-turn SC fault are presented in Fig. 10.



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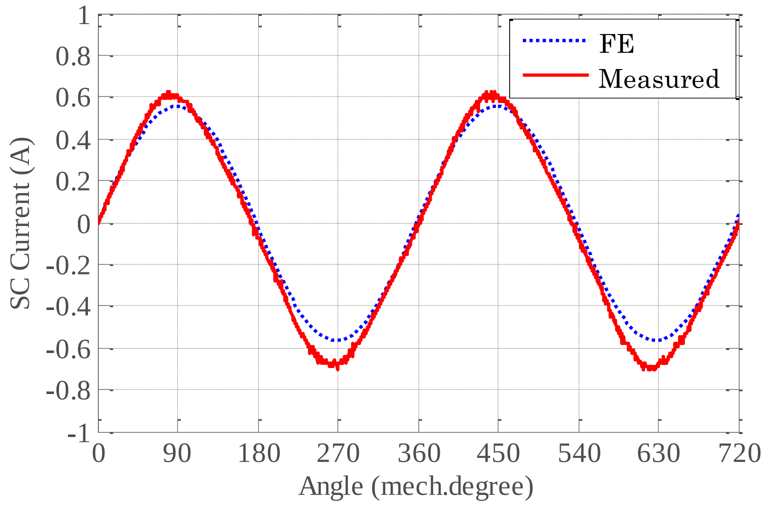

(b)

Fig. 10. Worst-case inter-turn SC current (a) round conductor winding (b) vertical conductor winding under application of shorting the terminal approach at rated operation

The results clearly show that the magnitude of the induced WSC current in the round conductor is almost twice that of the vertical winding. This confirms the fault limiting capability of the adopted vertical winding within the shorting terminal method.

TABLE IV

Comparison between the experimented machines at nominal speed and torque

	Conventional round conductor wound machine	Vertical conductor wound machine
Phase resistance (R_p)	149.56 mΩ	152.47 mΩ
Phase inductance (L_p)	2.077 mH	2.12 mH
Back-EMF at rated speed (*rms*)	47.09 V	47.14 V
Winding losses at rated operation	33.01 W (1.22 times DC losses)	38.86 W (1.41 times DC losses)
Efficiency at rated operation	93.4 %	92.7 %

From Table IV, it can be seen that there is a slight difference in both the resistance and the inductances of the vertical conductor wound machine with respect to conventional round conductor wound machine. This is mainly due to the end-winding's length of vertical conductor which increases with increasing number of turns as they are wound top of each other. Also from the Table IV, it can be seen that at the rated operation the vertical winding's losses are around 1.4 times higher than the DC static losses and these losses around 20% higher than conventional round conductor wound machines. As result the efficiency of the vertical conductor wound machine decreases by 0.7%. However, the vertical conductor wound machine does not require any design alterations to limit the WSC to a safe level and it is worth mentioning again that it has a better winding radial effective conductivity when compared to the conventional winding. Thus, considering both performance and FT the vertical winding is a better solution for fault tolerant application due to its inherent fault current limiting capability.

CONCLUSIONS

In this paper, possible fault mitigation techniques available for the turn-turn SC fault have been investigated. Amongst available options five effective methods have been adopted for a comparative study. From the analysis, it can be concluded that:

1. the terminal shorting method and the current injection scheme are easy to implement within the drive system without additional hardware. However the terminal shorting method requires the vertical winding structure in order to limit the WSC current regardless of the position in the slot of the shorted turn(s). Although the current injection scheme would be effective, accurate prediction of the required current under online operation would be challenging and a single error will put the system at risk.
2. though the mechanical shunt is effective, the additional systems in the mechanism to open and close the wedges increase the system's weight. Also it reduces the system reliability due to the mechanism which requires a longer triggering time or could jam.
3. the electrical shunt is a better mitigation technique; however it requires an additional system for control winding and reduces the performance significantly at normal operation.

Considering all these facts, amongst the investigated fault mitigation topologies it is noticeable that terminal shorting with the vertical winding is the most effective method as it is easy to implement, more reliable and doesn't engender additional weight. This has been confirmed via both FE analysis and experimental results. It is also shown that vertical winding has higher eddy current losses than conventional winding especially at high operating frequencies. To achieve the required fault tolerance a slight reduction in the machine efficiency has to be conceded.

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