Investigation of a Multiphase Winding Arrangement for Mitigating Short-Circuit Fault Currents

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Abstract –**Electric machines can experience various types of short-circuit faults when the insulation fails. Inter-turn short-circuit (ITSC) faults can be particularly hazardous for surface-mounted permanent magnet (SPM) machines. This paper proposes a multiphase winding configuration to mitigate ITSC fault currents. With the proposed winding arrangement, ITSC faults become phase-phase faults and can be blocked by the drive. Alternatively, control actions can reduce the fault current and allow the machine to continue normal operation. Short-circuit faults between turns are evaluated using finite element analysis for an example 12-slot, 10-pole SPM machine. The case study demonstrates that the proposed winding arrangement reduces the short-circuit fault from 5400% of the nominal current to 46%, in some cases, even without any adjustment of the control. Additionally, adjusting the voltages supplied to the affected phases can further reduce the short-circuit current to 10.5% of the nominal current with a negligible impact on the torque.**

Index Terms--**Fault current mitigation, fault tolerance, inter-turn short-circuit (ITSC) faults, multiphase electric machines, permanent magnet machines, phase-to-phase faults, reliability, short-circuit currents, winding configurations.**

I. INTRODUCTION

INCREASINGLY high torque densities and efficiencies are being demanded of electric machines to meet modern applications from electric aviation and electric vehicles to renewable energy generation. Thus, permanent magnet synchronous machines (PMSMs) are achieving increasingly widespread adoption, especially in electric traction applications [1]. While PMSMs can achieve very high torque densities and efficiencies, the uncontrolled permanent magnet (PM) excitation presents a challenge for achieving high reliability designs [2]. In order to meet the demands for higher power density, the electric machine is subjected to higher electrical, mechanical, and thermal stresses. For example, due to the very fast switching capabilities of wide-band-gap (WBG) devices, an increased voltage gradient is applied to the electric machines winding, which puts more electrical stress on winding insulation [3]. Similarly, allowing the windings to operate at higher temperatures reduces the insulation lifespan. As the insulation of the winding degrades over time, the probability of a short circuit fault occurring increases. A short circuit fault can produce large currents, which cause temperatures to rise rapidly. This can cause the fault to cascade and quickly cause complete failure and shut down of the machine. Electric machine windings are prone to different kinds of short circuit faults, including phase-ground, phase-phase, and inter-turn short circuit (ITSC). ITSC faults are particularly dangerous in surface mounted permanent magnet (SPM) machines because SPM machine windings tend to have low inductances, so the ITSC fault currents can be very large [4]-[5]. Furthermore, even if the stator excitation is removed, the PMs continue to excite a large circulating fault current, which rapidly converts the kinetic energy of the system into heat. This rapid heating can cause cascading faults, demagnetization of the PMs, or even fires. As a result, SPM machines could be disqualified for high reliability applications even though they achieve among the highest torque densities. On the other hand, for induction or wound-field synchronous machines, the rotor excitation can be removed or reduced to prevent or diminish the circulating current, although this prevents the machine from continuing its normal operation [6].

The need for fault tolerant traction drives and machines has inspired researchers to propose a variety of analysis approaches and solutions. Some researchers have found equivalent circuit models useful for exploring system dynamics during operation with faults. Such models use machine parameters determined either analytically or with finite element analysis (FEA) [7]-[10]. Many authors have investigated multiphase drives and electric motors for fault tolerant applications. In case of an open-circuit fault, the motor can continue normal operation at reduced power using the remaining healthy phases [11]-[15]. However, multiphase systems do not solve the problem of large ITSC fault currents. Various diagnostic methods for detecting ITSC faults in PMSMs have been introduced [16]-[21]. Once the fault is diagnosed, the ITSC fault current can be reduced by injecting d-axis current to oppose the flux from the PMs [22]-[23]. However, this increases the copper losses and derates the machine. Additionally, while this strategy may have some benefit for interior permanent magnet (IPM) machines, a much larger d-axis current would be required for SPM machines, which tend to have smaller inductances.

This paper proposes a multiphase winding arrangement that can inherently reduce or block fault currents resulting from insulation failure between adjacent turns. In the following sections, the proposed configuration will be presented and a case study evaluated using FEA to investigate the effectiveness of the winding arrangement.

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II. PROPOSED SOLUTION

In this section, a new winding arrangement is proposed to address ITSC faults in motors with form-wound windings, which often involve rectangular conductors. Form-wound windings with rectangular conductors can achieve high slot fill factor, which improves torque density and efficiency [24]-[25]. Additionally, rectangular conductors achieve better thermal contact than round conductors, improving heat dissipation from the conductors [24]. Thus, rectangular conductors are common in traction motors and large machines [24]-[25].

For the proposed winding arrangement, the conductors are arranged in such a way that no conductor is adjacent in the slots or end windings to another conductor of the same phase or of a phase that shares a connection within the motor. Thus, any short-circuit fault between adjacent conductors is a phase-phase fault rather than an ITSC fault. Additionally, any short-circuit fault current must flow through the drive and cannot circulate only inside the motor. Thus, if a current source inverter (CSI) is used to drive the motor, the fault current will be zero as long as the CSI continues to supply the nominal currents to each phase, and the system can continue normal operation. Alternatively, if a voltage source inverter (VSI) is used to drive the motor, the VSI can block the fault current by opening the switches of the affected phases; then, the system can continue operating with reduced power. However, in some cases, the VSI may be able to adjust the voltage supplied to one or both of the affected phases to reduce the fault current to an acceptable level while still maintaining close to the nominal currents in the affected phases, allowing the system to continue operating near its nominal conditions.

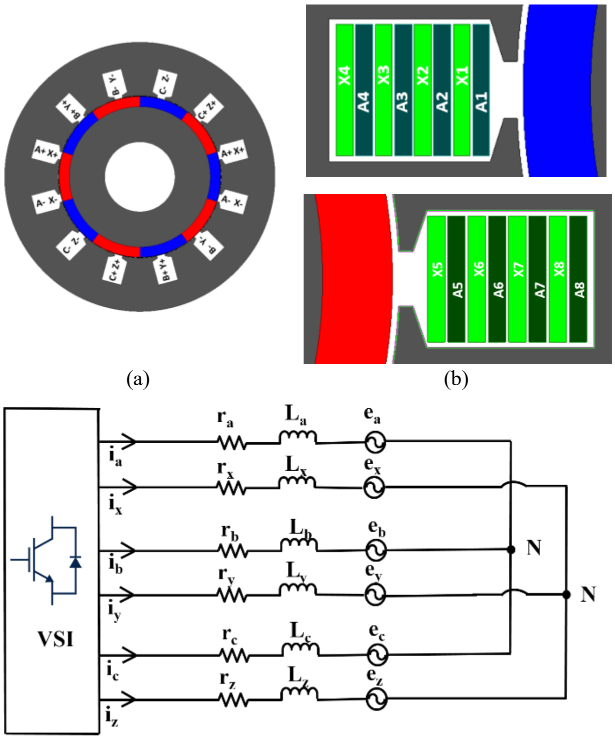
Fig. 1 shows an example of the proposed winding arrangement with two sets of three-phase windings in a 12-slot, 10-pole motor. The two sets are not phase shifted from each other, and they do not share a common neutral point. A VSI is used to drive all six phases. As can be seen from Fig. 1, with this arrangement, any ITSC fault becomes a phase-phase fault, and the fault current can be blocked by the VSI.

However, the proposed winding arrangement does have some disadvantages. As with all multiphase machines, the complexity is increased as more current sensors, gate drivers, and switches are required, although each switch can be rated for a lower voltage. Additionally, the motor may be more difficult to wind because turns from two phases must alternate in each slot. While the proposed configuration allows the drive to block the short-circuit fault current produced by a single short-circuit fault, in the event of multiple short-circuit faults, there may be a fault current loop completely inside the machine. In this case, the fault current can freely flow in that loop without the drive being able to block the fault current.

III. SIMULATION STUDY

A. *Description of evaluated motor*

The proposed configuration is implemented in the SPM tooth-wound fractional slot concentrated winding (FSCW) motor with 12 slot and 10 poles illustrated in Fig. 1. The geometric parameters of the case study motor are given in Table I. The motor is driven with a six-phase VSI to operate in the maximum torque per ampere (MTPA) condition. The nominal operating conditions for the case study motor are given in Table II. Fig. 2 compares the conventional machine, which shares the same geometric parameters, and the machine with the proposed winding arrangement. All turns in each phase are connected in series for each motor. Because the proposed machine has six phases, rather than the three phases in the conventional machine, the proposed machine has half as many turns per phase as the conventional machine. Thus, the conventional machine has twice the operating voltage of the proposed machine. Fig. 3 shows the back-emf and self-



(a) (b)

(c)

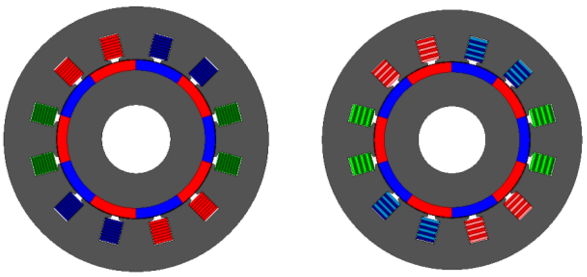
Fig. 1. a) A 10-slot, 12-pole motor with two sets of three-phase windings, b) placement of the conductors in two of the slots according to the proposed arrangement, c) the equivalent circuit for the machine during healthy operation.

TABLE I
GEOMETRIC PARAMETERS OF THE CASE STUDY MOTOR

Parameter	Value	Unit
Outer/inner diameter of stator	134/81	mm
Outer/inner diameter of rotor	80/35	mm
PM thickness	5	mm
Core stack length	100	mm
Air gap length	0.5	mm
Stator slot opening depth/width	1/4	mm
Stator slot depth/width	12/10	mm
Number of stator slots	12	-
Conductor cross sectional area	11.5	mm^2

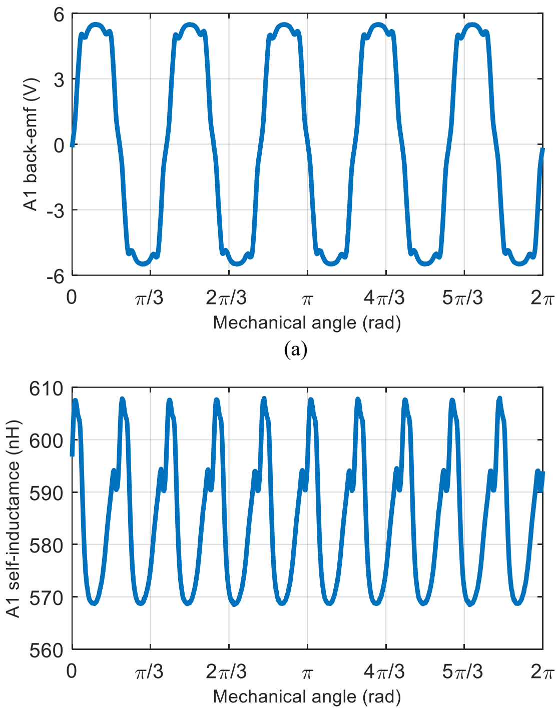
TABLE II
NOMINAL OPERATING CONDITIONS FOR THE PROPOSED MOTOR

Parameter	Value	Unit
Average output torque	18.8	Nm
Rotational speed	6000	rpm
RMS phase voltage	36.1	V
RMS phase current	59.8	A



(a) (b)

Fig. 2. Motors with the (a) conventional and (b) proposed winding configurations.



(a)

(b)

Fig. 3. (a) Back-EMF and (b) apparent self-inductance of the A1 coil for both the conventional and proposed machine.

inductance of one turn in the position closest to the slot opening.

B. *Results*

While the proposed configuration can eliminate ITSC faults, phase-phase faults can still occur. Based on the proposed winding configuration, two major types of short circuit fault that can happen. The first type of fault is An-Xn, where the fault occurs at the same position in both phases. The second type of fault is A(n+1)-Xn or An-X(n+1), where there is a one-turn difference in position for the fault location in the two phases. (Similar behavior would occur for faults involving phases B and Y or phases C and Z.)

Fig. 4 illustrates the equivalent circuit model of the conventional three-phase PMSM with an ITSC fault in phase A, and Fig. 5 shows the placement of the conductors in one of the slots according to the conventional arrangement with the resulting fault current when there is a short-circuit from turn A1 to turn A2, based on FEA. The RMS fault current for conventional arrangement can exceed 3.2 kA (5400% of the nominal phase current), which is completely unacceptable and, if not mitigated, will cause catastrophic failure. Fig. 6 shows the equivalent circuit model of the proposed winding configuration for an A1-X1 fault, which corresponds to the same position in the slot as the A1-A2 fault for the conventional motor. Fig. 7 shows the resulting fault current if the VSI continues to supply the nominal voltages. The RMS fault current has been decreased significantly to 27.7A, 46% of the motor nominal current. The reason for such a significant reduction in the fault current is that the back-emfs in turns A1 and X1 (e_{a1} and e_{x1}, respectively) almost exactly cancel each other out in the fault current path. While we expect to have close to zero fault current, there is still a nonnegligible amount of current flowing through the fault. This occurs because turns A1 and X1 have slightly different flux linkages, due to their different positions in the slot, so the back-emfs do not completely cancel each other out. Similarly, the different locations in the slot also result in a small difference between the self-inductances of A1 and X1.

The other possible type of short circuit fault in the proposed structure occurs when there is one more turn involved in the fault loop for one of the affected phases than the other affected

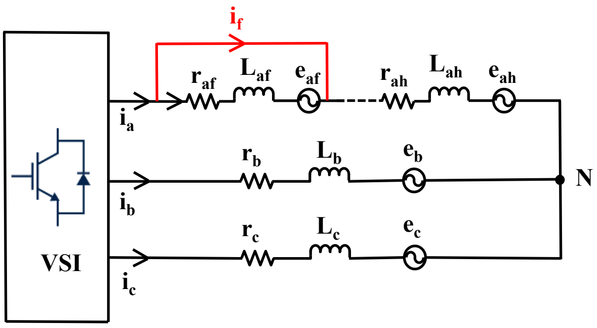
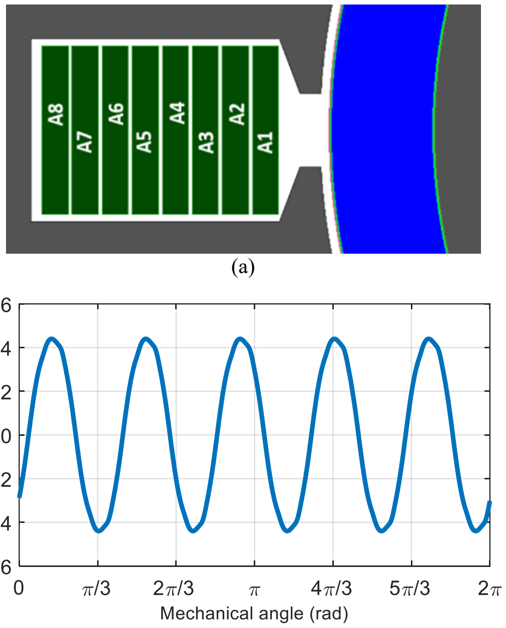


Fig. 4. Equivalent circuit model of a conventional three-phase PMSM with an ITSC fault in phase A.



(a)

(b)

Fig. 5. a) Placement of the conductors in one of the slots according to the conventional arrangement and (b) ITSC fault current for an A1 to A2 short circuit in the conventional winding arrangement.

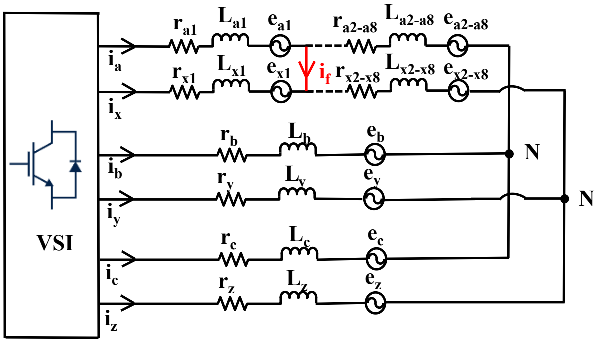


Fig. 6. The equivalent circuit model of the proposed winding configuration for an A1-X1 fault.

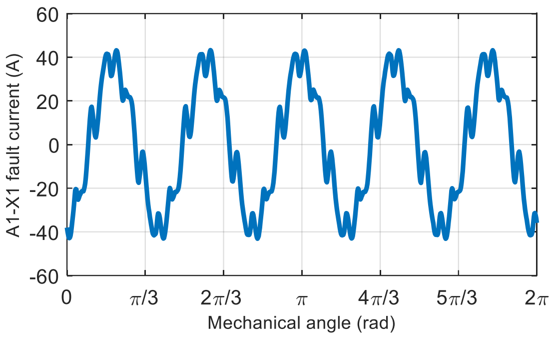


Fig. 7. A1-X1 fault current if the VSI continues supplying the same voltages.

phase. For example, A2-X1 is such a fault, as shown in the equivalent circuit of Fig. 8. Because of the extra turn in one of the affected phases, the back-emfs no longer almost cancel each other out, so the fault current is much larger, as shown in Fig. 9. Nonetheless, the fault current is smaller than the fault current in the conventional machine. While a comparison of Figs. 4 and 8 might indicate that the proposed arrangement would reduce the fault current to approximately one third of the fault current in the conventional arrangement, these figures do not show the mutual inductances between turns. When the mutual inductances are considered the overall inductance of the fault current path through the drive and turns A1, A2, and X1 is only slightly larger (due to leakage flux) than the inductance of a single turn.

Because the back-emfs will be unbalanced for all of the A(n+1)-Xn or An-X(n+1) faults, they are all expected to have unacceptably large fault currents. Even though the machine would need to stop operating in these cases, the proposed winding arrangement still eliminates the potential for a rapid, uncontrolled temperature rise in the motor, which would occur in a conventional SPM motor as the kinetic energy of the system is converted into heat through the ITSC fault current. If the machine were driven by a CSI, it could continue operating. Alternatively, if open-end windings supplied by full-bridges were used, the system could continue operating with phases B, Y, C, and Z.

Nonetheless, other An-Xn short circuit scenarios can be interesting to consider because increasing the number of turns in the fault current path increases the resistance in the short-circuit current path. Additionally, turns that are deeper in the slot have larger inductances than those near the slot opening. Figs. 10 shows the fault currents for A4-X4 and A8-X8 faults.

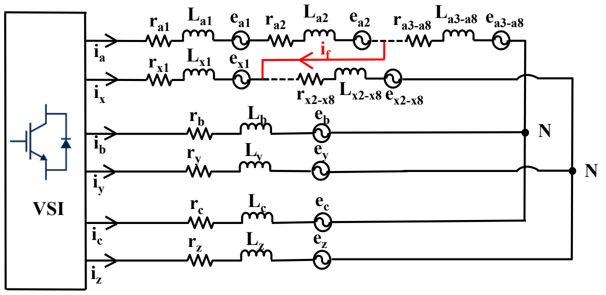


Fig. 8. The equivalent circuit for an A2-X1 fault.

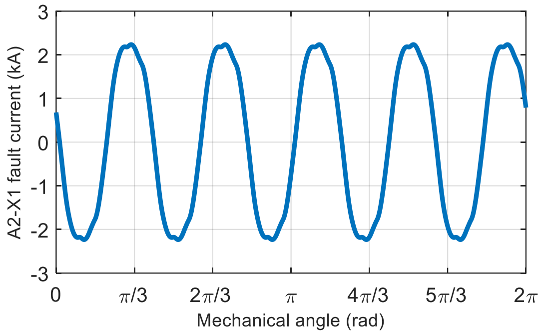


Fig. 9. A2-X1 fault current.

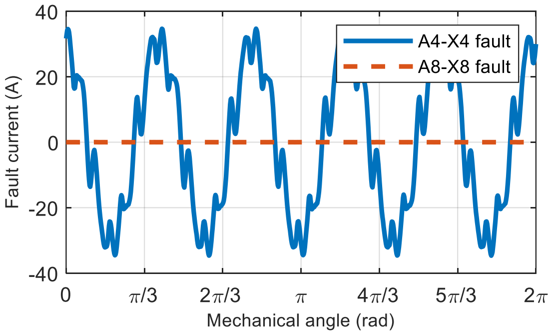


Fig. 10. A4-X4 and A8-X8 fault currents.

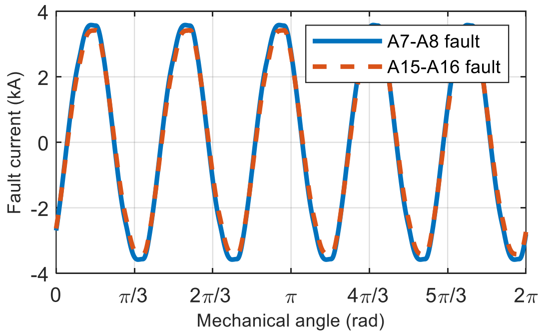


Fig. 11. A7-A8 and A15-A16 fault currents.

Fig. 11 shows the fault currents for the corresponding faults in the conventional motor, A7-A8 and A15-A16, respectively.

As can be seen from Fig. 10, in the proposed winding structure, the fault current decreases as the fault moves further away from the VSI. Thus, for A8-X8, which is essentially a fault between the neutral points, the fault current is practically zero. There are two reasons for this decrease. First, as the fault moves further from the drive the inductance of the fault current path increases, largely due to leakage inductances that are not cancelled out by the mutual inductances between the

A and X turns. Second, the positions of the second half of the turns are reversed relative to the first half of the turns. As shown in Figs. 1(b), for the first set of turns, the phase A turns are closer to the slot opening than the corresponding phase X turns, but, for the second set of turns, the phase X turns are closer to the slot opening than the corresponding phase A turns. Based on Figs. 5 and 11, the fault current for the conventional machine does reduce slightly for faults deep in the slot, due to the increased leakage inductance. (In the conventional machine, A8 and A16 are the turns deepest in the slots, so the two fault currents in Fig. 11 are very similar.) Nonetheless, no matter how far from the source, the ITSC fault current for the conventional winding arrangement is still in the range of a few kA, which could be extremely destructive.

C. *Voltage compensation for mitigating fault current*

In the conventional three-phase winding configuration, the ITSC fault cannot be directly measured. Hence, it is difficult to perform any control action to mitigate the fault. On the other hand, in the proposed configuration the fault current can be easily measured. Since the two three-phase sets do not share a common neutral point, the sum of currents in each of the three-phase sets should be zero. If there is any fault current in the system, the sum of the three-phase currents will be equal to the fault current, rather than zero. If the fault current is known, control actions can be performed to reduce the fault current to the point that motor can fully continue its normal operation. The simplest way to do this is by comparing the fault current to a zero-reference current. Then, a PI or hysteresis controller can be employed to adjust the gate signals for the faulty phases. Since phases A and X are driven by different legs of the VSI and do not share a common neutral point, the fault current can be reduced to the point that motor can operate almost normally by properly adjusting the PWM signals for the faulty phases. In the case of the A1-X1 fault, the fundamental component of the fault current can be significantly reduced by introducing a very small phase shift in the voltage supplied to phase A or X. Fig. 12 shows the resulting fault current. For the conventional winding arrangement, an ITSC fault produced an RMS short circuit current 5400% of the rated current. With the proposed winding arrangement, the fault current was reduced to 46% of the rated current, and slightly adjusting the voltages supplied to the affected phases reduced the fault current to 10.5% of the rated current. In this situation, the motor can continue operating almost normally. Fig. 13 shows the fault current of the A4-X4 after compensation. (No compensation is necessary for the A8-X8 fault.) Similar control action can be performed for other faults. Fig. 14 shows the torque waveforms for the healthy motor, the motor with the A1-X1 fault before voltage compensation, and the A1-X1 fault after voltage compensation, respectively. Because the fault current circulates through phase A and phase X, it produces a minimal impact on the magnetic fields in the motor and, thus, does not significantly affect the torque. Additionally, the slight phase shift in voltage to reduce the fault current produces a negligible impact on torque.

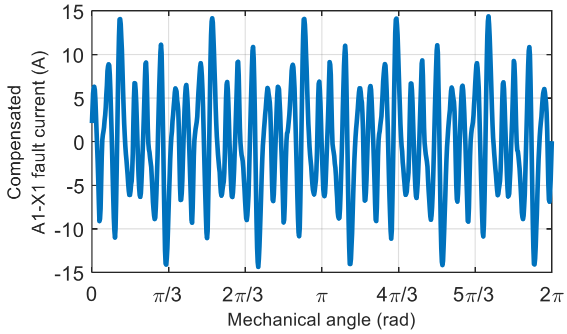


Fig. 12. Compensated fault current for A1-X1 fault.

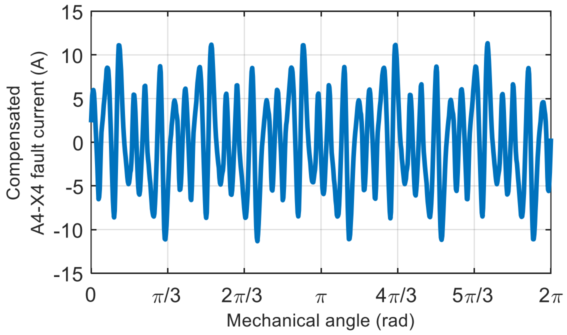


Fig. 13. Compensated fault current for A4-X4 fault.

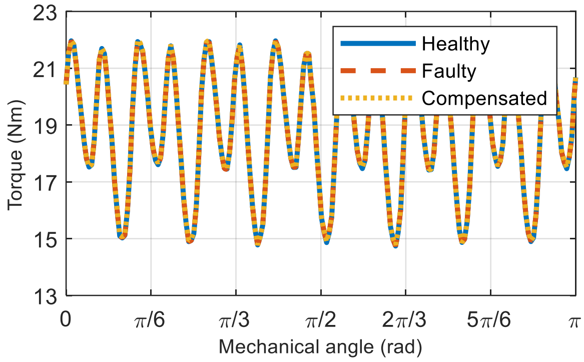


Fig. 14. Output torque in healthy conditions, with the A1-X1 short circuit fault, and with the A1-X1 short circuit fault and the voltage compensation.

IV. CONCLUSION

In this paper, a multiphase winding arrangement in which any ITSC fault becomes a phase-phase fault was introduced. This allows the drive to block the fault current. Different short-circuit fault scenarios were evaluated for a case study SPM machine. The results showed that, in some short-circuit scenarios where the back-emfs approximately cancel out each other, the fault currents are reduced from 5400% of the nominal current for the conventional winding arrangement to only 46% in the proposed winding. Additionally, the fault current can be further reduced to 10.5% of the nominal current by slightly adjusting the voltages supplied to the affected phases and the motor can continue its normal operation without even disconnecting the affected phases. In other cases, where the fault occurs between different positions in two phases, the inverter can disconnect the affected phases to prevent dangerous fault currents. Future work will include experimental validation.

V. ACKNOWLEDGMENT

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VII. BIOGRAPHIES

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