Design Optimization on Conductor Placement in the Slot of Permanent Magnet Machines to Restrict Turn-turn Short-Circuit Fault Current

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In Permanent Magnet (PM) machines, a turn-turn Short-Circuit (SC) fault is the most critical fault to eradicate. The fault introduces high SC current in the shorted turn which may consequently lead to secondary faults unless the fault is appropriately controlled. This paper proposes feasible conductors' placement in a slot of PM machine to minimize such turn-turn fault current. In order to minimize the fault current, the conductor arrangement in a slot is optimized using multi-objective Genetic Algorithm (GA) incorporating with both analytical and Finite Element (FE) numerical tool. The possible combinations of conductors' placement are set as variables and optimized for a given machine which is designed for safety critical applications. It is shown that the fault current associated to a single turn fault can be significant for the random winding placement even though the remedial strategies are put in place. It is also shown that the fault current can be limited significantly by rearranging the winding placement in a way to share slot-leakage fluxes. This is confirmed via experiment on E-core. Influences of the winding arrangement on both frequency dependent resistances and windings capacitances are experimented. It is demonstrated that adopting the winding arrangement that shares the slot-leakage flux effectively benefits to minimize the AC losses in addition to improved fault tolerance. But it increases the turn-turn capacitances whose effect however can be neglected as the resonance frequency occurs beyond the operational frequency range of the machines of interest.

***Index Terms*—Electric, Fault Tolerance, Genetic Algorithm, Mitigation, Optimization, Permanent magnet, Reliability, Short-Circuit**

I. Introduction

FAULT TOLERANT (FT) CONCEPT is more important for safety critical applications as they prevent causing catastrophic damages due to failure in the system. One of the areas FT is often considered is electrical drives assisted systems, for example actuators, fuel pumps and starter-generators in more-electric aircraft system and power steering, motor and generator in electric automobiles. The key challenge involved in implementation of FT concept within the electric drive systems is to achieve the required level of reliability whilst satisfying both fail safe and availability requirement at event of a fault [1-4]. To overcome this, complete redundant system is often adopted whilst the system is designed to meet the reliability level. On the contrary redundancy can also be implemented within the same system to minimize the component count, size and weight. Such system is likely to be oversized in order to provide the availability required by system.

In electrical machines in which magnetic field is produced due the electric excitation, for example, DC machines, Induction Machines (IM), Switch Reluctance (SR) machines, fail-safe can easily be achieved as the field can be fully controlled. But this is not the case in the Permanent Magnet (PM) machines where the field is generated by the permanent magnet which cannot be controlled. In the event of a fault, this may lead to catastrophic damages, unless the fault is effectively accommodated within the drive system. Although this is a key drawback, consumer requirements which are driving the electrical machines to be smaller, compact and efficient, place the PM machines or PM assisted machines to be dominant amongst other machine types.

In early 90s, general FT concepts for PM machine to improve the fail safe and reliability have been proposed in [5-7]. It has been demonstrated that in order to cope with the faults associated to the PM machines, physical, electrical, thermal and magnetic isolation between the phase windings are necessary. These isolations can be achieved by adopting fractional slot concentrated winding arrangements in which each phase windings are fed by separated H-bridge inverter unit. In addition, the winding inductances should be designed with certain value in a way to limit the Short-Circuit (SC) current in the turn equivalent to safest value or rated value that the machine is designed for. Also the machine should be overrated to handle the additional current loading in case of fault and thus, the system can be able to perform continuously while the fault is managed. Also it has been suggested that relatively better magnetic isolation can be achieved using surface mounted PM rotor than other PM rotors [5], for example interior PM rotor, due to presence of both retaining sleeve and the magnets which greatly reduces the air-gap component of the armature reaction field, so that in effect the mutual coupling becomes insignificant.

In [8, 9], instead of having separated H-bridge for each phase, three-level inverter which control a three phase winding unit, has been proposed. It has been demonstrated that having three phase unit controlled by an inverter unit simplifies the control strategy and provide balance operation under a fault. Furthermore feasible machine segmentations to improve FT have been investigated in [10] in which trade-off between axial and circumferential segmentations are detailed. In [11, 12], it has been demonstrated that the fault current associated

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with a single turn-turn fault became significant if the fault is located very close to the slot-opening region as in that region the faulted turns have less inductances than other fault locations. As a solution to this high fault current, a vertical winding arrangement which eliminate the position dependent fault current by sharing slot-leakage flux almost equally, has been proposed in [11]. Wherein, it was demonstrated that implementation of the vertical winding increases the AC losses.

Recently in [13, 14] a 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 so performing safe operation at an event of fault can be possible, the monitoring shield of the winding introduces the eddy current losses whilst the armature windings increases DC losses due to reduced fill factor. Adopting the methods proposed in [8, 13, 14], the SC can be limited and thus, FT can be improved but, the efficiency of the machine needs to be compromised. A trade-off is therefore required to find a fine balance between FT and efficiency.

In this paper, feasible conductors' placement in a slot of PM machine has been proposed to minimize the turn-turn fault current. In order to minimize the fault current the conductor arrangement in a slot is optimized using multi-objective Genetic Algorithm (GA) incorporating with both analytical and Finite Element (FE) numerical tool. The possible combinations of conductors' placement are set as variables and optimized for a given machine which is designed for rotorcraft actuator. The considered machine has 12-slot, 10-pole arrangement with integrated redundancy within the stator. Thus, one machine (set of three phase stator winding) can be controlled with remedial strategies to minimize the high current if fault occurs while other machine is used to produce the torque required by actuator system. It is shown that the fault current associated to a single turn fault can be significant for the random winding placement even though the remedial strategies are put in a place. It is also shown that the fault current can be limited significantly by rearranging the winding placement. This is confirmed via experiment on E-core arrangement. Influences of the winding arrangements on both frequency dependent resistances and turn to turn capacitances are investigated. It is demonstrated that adopting the winding arrangement which shares the slot-leakage flux effectively benefits to minimize the AC losses in addition to improved fault tolerance. But, this arrangement influences the turn-turn capacitances; however the effect can be neglected as the resonance frequency beyond the operational frequency range.

II. BACKGROUND: A TURN-TURN SC FAULT AND AN EFFECTIVE REMEDIAL STRATEGY

A turn-turn SC fault causes a change in winding resistance, inductance, and also the electrical circuit of the winding. This can be demonstrated via circuit representation (Fig.1). The most common adopted winding arrangement for the safety critical applications is alternate tooth wound concentrated winding arrangement. This is mainly due to they provide the better magnetic isolation between the phases and thus, mutual couplings between the phases are almost zero.

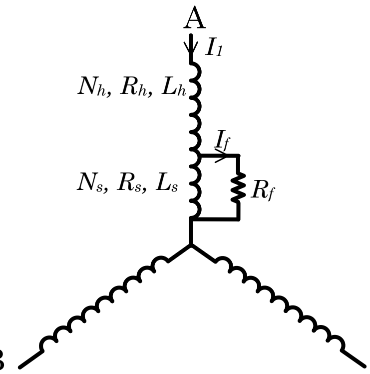


Fig. 1. Representation of a turn-turn SC fault

By assuming that the mutual between the phases are negligibly small, the equations governing faulty phase circuit can be represented as follow.

$$V_1(t) = I_1(t)R_h + \left(I_1(t) - I_f(t)\right)R_s + L_h\frac{dI_1}{dt} + L_s\frac{d\left(I_1 - I_f\right)}{dt} + L_m\frac{dI_1}{dt} + L_m\frac{d\left(I_1 - I_f\right)}{dt} + e_1(t) + e_2(t) \quad (1)$$

$$0 = I_f(t)R_f + \left(I_1 - I_f\right)R_s + L_s\frac{d\left(I_1 - I_f\right)}{dt} + L_m\frac{dI_1}{dt} + e_2(t) \quad (2)$$

where,

V_1: voltage across the phase winding
e_1: electromotive force (emf) in the healthy (N_h) turns
e_2: emf in the shorted (N_s) turns
I_1: phase current
I_f: SC fault current
R_f: Conductive resistance between N_h turns and N_s turns
R_h: resistance of healthy (N_h) turns
R_s: resistance of shorted (N_s) turns
L_h: self-inductances of healthy (N_h) turns
L_s: self-inductances of shorted (N_s) turns
L_m: mutual inductance between N_h and N_s turns

The equation (2) can be re-arranged as:

$$-I_f(t)R_f = \left(I_1 - I_f\right)R_s + L_s\frac{d\left(I_1 - I_f\right)}{dt} + L_m\frac{dI_1}{dt} + e_2(t) \quad (3)$$

Thus, replacing (3) in (1) yields,

$$V_1(t) = I_1(t)R_h + L_h\frac{dI_1}{dt} + L_m\frac{d\left(I_1 - I_f\right)}{dt} + e_1(t) - I_f(t)R_f \quad (4)$$

From (3) and (4), it is clear that the magnitude of the fault current is influenced by the winding's impedances and both the source and the emf voltages. Since there are no control over the windings impedances and the emf, a way to minimize the fault current is through controlling the source voltage.

Unless, the existence of continuous voltage V_1 across the phase will result high SC fault current.

The common approach to control this high current is shorting the phase windings through the power converter switches [5] as a remedial strategy. This nullifies the voltage V_1 across the phase winding and allows sharing of the magneto motive force (*mmf*) generated by the PMs equally by all turns. The SC current associated with the shorted turn is therefore diminished, but not completely nullified. Also it is worth noting that severity of the fault is dominated by the conductive resistances (R_f) and the number of faulty turns (N_s). Thus, a fault condition that has a single turn-turn fault (N_s = 1 and N_h = total turns - 1) and negligible conductive resistance ($R_f \sim 0$) is considered to be a worst case fault scenario amongst the whole turn-turn faults cases. If the R_f is assumed to be zero and the remedial strategy is applied (V_1=0), the equation (3) and (4) can be re-written as

$$0 = I_1(t)R_h + L_h\frac{dI_1}{dt} + L_m\frac{dI_s}{dt} + e_1(t) \tag{5}$$

$$0 = I_s(t)R_s + L_s\frac{dI_s}{dt} + L_m\frac{dI_1}{dt} + e_2(t) \tag{6}$$

where I_s replaces the term (I_1 - I_f) which represents the resultant SC current flowing through the shorted turn (N_s). This condition of fault represents a circuit which is magnetically coupled, but electrically isolated [11]. Thus, the SC fault current can be estimated if the mutual interactions between the circuits are known.

Since the worst-case condition of a single turn-turn fault is investigated in the study, the SC fault current induced in the shorted turn closer slot-opening region is marginally higher than the other fault locations [11]. This is mainly due to both the inductances and the resistances which are position-dependent as they are subject to slot-leakage fluxes. Re-arranging the winding arrangement and thus, conductors' locations allow changing the inductances and resistances associated with a single turn. This will minimize the fault current if the turns are located appropriately. This is the subject of this paper.

III. PM MACHINE AND REQUIREMENTS FOR A FT APPLICATION

This section describes a FT-PM machine (Fig. 2) considered for the study. The PM machine is designed for a rotorcraft swashplate actuator which is a primary flight control actuator where high reliability is essential. Failing to move the swashplate to a desired position or holding it in a particular position can be catastrophic for the rotorcraft. Thus, the machine was designed to satisfy the fault tolerant criteria to avoid catastrophic damages in the system at the event of single fault. Where,

a) Dual star windings supplied through different converter units were adopted to introduce redundancy under an event of fault. This arrangement further facilitates to isolate the dual star arrangements electrically and physically.
b) Concentrated windings are used to provide physical, thermal and magnetic isolation between the phases.
c) To limit the SC current to a safe value as well as to minimize the resulting breaking torque at operation under the fault, the phase winding is designed to have an appropriate inductance. The complete SC fault current can therefore be limited to a safe value, in this case rated current value that the machine designed for.
d) The machine is oversized to handle the increased current loading and thus provide required torque during faulted operation.

The specifications of the machine that satisfy the abovementioned FT criteria are presented in Table I. The machine is capable of operation after any type of winding failure (open-circuit/SC fault) with a continuous torque of 1.25Nm and a continuous speed of 180rpm. In addition a peak torque of 8Nm and a maximum speed of 5250rpm are also needed to be delivered under fault conditions. Though the machine satisfies the performance and the FT requirements abovementioned, a turn-turn fault is still problematic as coping mechanisms [8, 13] are not considered in the design. If coping mechanisms are added, it is necessary to modify the design to handle additional heat generated due to extra losses. Design optimization on conductor placement in a slot of original machine is therefore considered to minimize the SC fault current without any design changes. This will be detailed in next section.

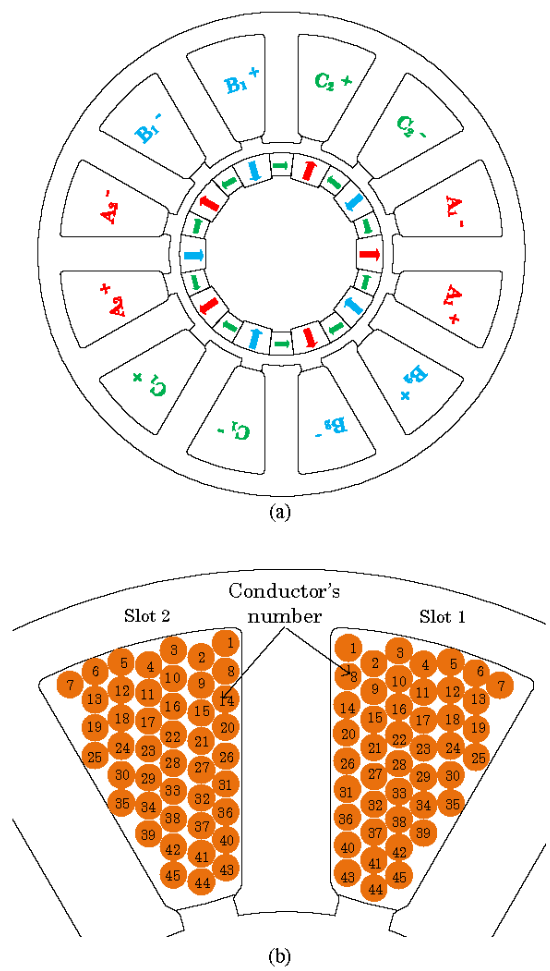


Fig. 2. (a) A cross-sectional view of 12-slot 10-pole FT-PM machine and (b) illustration of conductor placement in the slot

TABLE I
SPECIFICATION OF 12-SLOT 10-POLE PM MACHINE

Number of phase	3 (with dual channel)
Rated current, continuous (*rms*)	5.60 A
Peak current (*rms*)	24 A
Back-emf at 180rpm (*rms*)	32.50 V
Phase inductance	1.25 mH
Phase resistance	306.00 mΩ
Airgap	1.20 mm
Axial length	99.50 mm
Outer diameter	58.00 mm
Magnet height	3.20 mm

IV. DESIGN OPTIMIZATION

The method used in this study is Non-dominated Sorting Genetic Algorithm (NSGAII) which was developed in [15]. As in other evolutionary algorithms, first the NSGA-II algorithm generates a random initial population which evolves during the optimization process towards the global optimum. The objective functions are evaluated for each individual and then ranked. The offspring population is generated from the current population by selection, crossover and mutation. Finally the process is repeated until the algorithm stops or a maximum number of iterations which is the stopping condition, is satisfied. The functionality of the optimisation tool can be found in detail in [15].

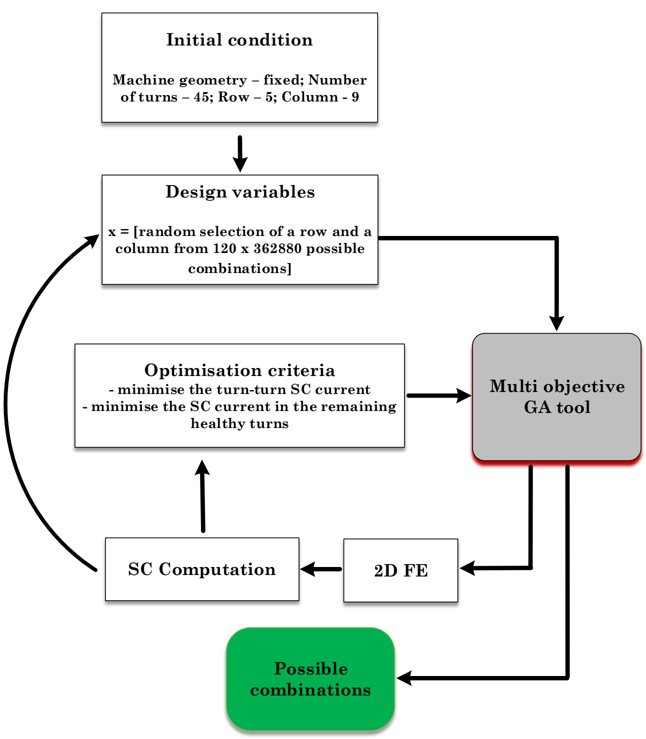


Fig. 3. Illustration of the optimization process

A flow chart illustrating the process of optimisation is shown in Fig.3. As previously mentioned NSGAII is used for the optimization process wherein a 2D FE electromagnetic model is integrated to compute the machines' parameters and then SC current is computed using differential equation (5) and (6). It is worth noting that the analytical formulation is only used here to reduce the SC computational time. The computational time further can be minimised if a complete analytical tool is adopted. But, estimating the slot-leakage inductances of round conductor (self-inductances of healthy and fault turns and mutual inductances between them) under a single turn fault condition accurately by taking into account the fault location is challenging using a complete analytical model. FE is therefore used for parameter computation. It is worth noting that both the inductances and the resistances are estimated by allowing for the high frequency effect and saturations in FE computations. However, the end effects of the windings are neglected considering that the end-winding lengths are very small compared to active length of the machines.

The optimization is carried out for 12-slot, 10-pole FT-PM machine introduced in the section III. In the process the machine geometry and its design parameters are kept same, and the maximum number of conductors' row and column are set to be 5 and 9, respectively. This would give 45 conductors per slot and 120 possible permutation for a row and 362880 permutations for a column. The reason for the maximum numbers for row and column are limited (to 5 and 9, respectively) is that the permutations of both give the possible winding combinations for the windings. This further allows limiting the computational complexity. Once a row and a column are selected, two different sets of conductors' placement are generated. These sets of conductors' arrangement are used to interconnect the coil between two different slots. Then, 2D FE is used to estimate the parameters including resistances, inductances and back-emf for a given conductors arrangement at possible set of turn-turn SC fault combinations. Finally the associated SC current is computed by replacing obtained parameters in (5) and (6).

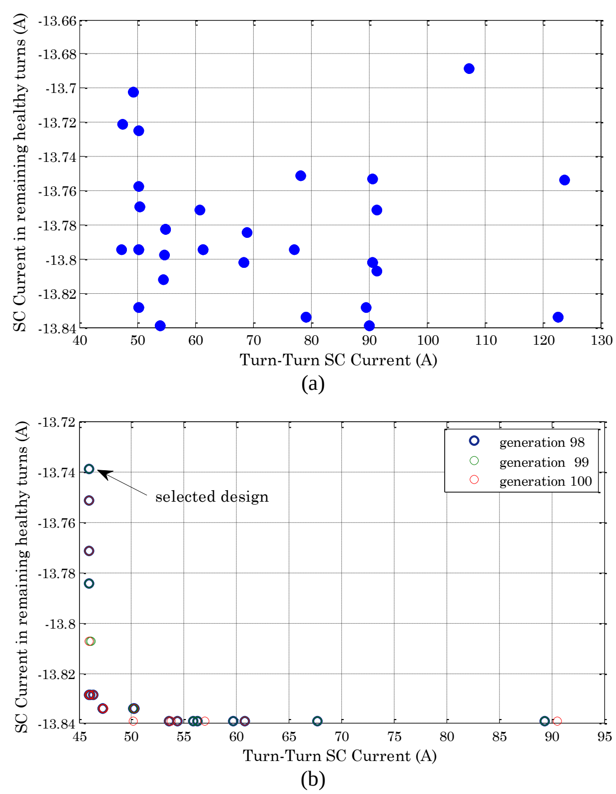


Fig. 4. Pareto-front at (a) first generation and (b) last three generation (values are in peak)

Once GA has a set of SC current from different winding placement generated in first population, it compares the optimization criteria and then generates the next population. Populations' sets of 40 and generations of 200 are initially considered and then the generations are limited to 100 since it provides the similar Pareto-front after the generation of 92. After 100 generations, the populations result are gathered and compared to obtain a feasible winding placement that satisfies the optimization criteria. The obtained results under different generations are plotted in Fig.4.

From Fig.4, it is evident that having random conductors' placement in a slot results in high SC current (~125A). However, an arrangement that has optimized conductor's placement reduces the SC current to a value as can be seen in Fig.4. This is mainly due to the slot-leakage fluxes associated with the turns which are shared effectively because of the conductor's arrangements in the slot. As a result, optimized placement of the conductors results in fault current reduction of 64% as shown in Fig.5.

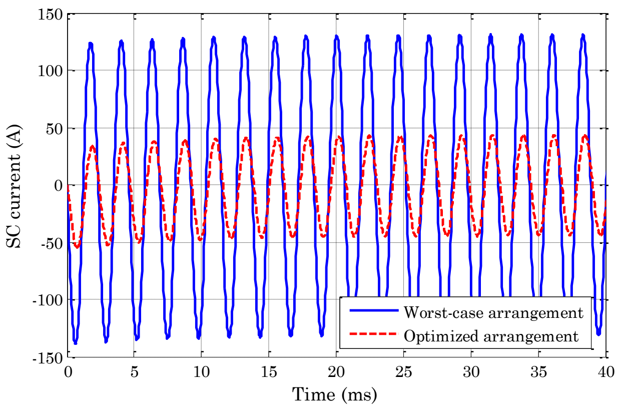


Fig. 5. SC current comparison between the different winding arrangements

To verify the influence of the slot-leakage flux sharing between the turns on SC current, three cases are further studied. The adopted cases are: conductors are arranged in an order (see Table II) considering carefully hand wound arrangement, worst-case SC current arrangement obtained in Fig.4a and arrangement optimized for minimal SC current in Fig.4b. These arrangements allowing for the conductors connecting orders are given in Table II (the conductors' numbers are referred to Fig.2b).

From the Table II, it can clearly be seen that the optimized winding arrangement interconnects a turn between the slot outermost conductors and innermost conductors. Therefore the lower inductances next to the slot opening region (innermost) are compromised by outermost locations. This allows sharing the slot-leakage flux equally and thus, the location dependencies on inductances are minimized. The resultant turn-turn SC current is therefore reduced to a minimal current. But, this is not in this case in the most commonly adopted hand wound arrangements. In such placements the turn-turn SC current is significantly high if the turn is located at slot inner most where the turn consists of two inner most conductors. This confirms further that the conductors' placement in a slot influences the turn-turn SC fault current and this current can be effectively minimized if the conductor placements are optimized.

TABLE II

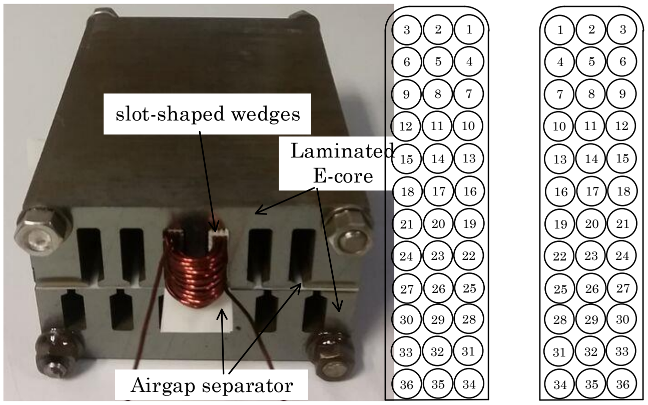
CONDUCTOR PLACEMENTS IN ALTERNATE TOOTH WOUND SLOT AT THREE DIFFERENT CASES

Turn number	Minimal SC current arrangement			Worst-case SC current arrangement			Conductors are arranged in an order		
	Conductor number for slot 1	Conductor number for slot 2	Turn-Turn SC Current (A_{peak})	Conductor number for slot 1	Conductor number for slot 2	Turn-Turn SC Current (A_{peak})	Conductor number for slot 1	Conductor number for slot 2	Turn-Turn SC Current (A_{peak})
1	20	23	24	39	8	17	1	1	37
2	25	38	29	44	43	105	8	8	36
3	5	43	27	9	3	38	14	14	31
4	35	18	14	4	13	37	20	20	23
5	10	28	25	29	23	19	26	26	15
6	45	3	45	14	38	19	31	31	17
7	30	13	18	24	28	19	36	36	32
8	15	8	34	19	18	31	40	40	54
9	40	33	32	34	33	23	43	43	85
10	19	24	28	40	10	16	44	44	125
11	24	39	22	45	45	123	41	41	90
12	4	44	46	10	5	38	37	37	30
13	34	19	14	5	15	35	32	32	16
14	9	29	25	30	25	13	27	27	15
15	44	4	46	15	40	18	21	21	24
16	29	14	23	25	30	13	15	15	31
17	14	9	34	20	20	23	9	9	37
18	39	34	45	35	35	33	2	2	38
19	18	25	22	37	6	14	3	3	39
20	23	40	21	42	41	89	10	10	37
21	3	45	45	7	1	36	16	16	32
22	33	20	15	2	11	37	22	22	24
23	8	30	18	27	21	18	28	28	16
24	43	5	27	12	36	13	33	33	15
25	28	15	23	22	26	18	38	38	58
26	13	10	36	17	16	31	42	42	89
27	38	35	46	32	31	16	45	45	123
28	17	21	28	36	7	13	39	39	56
29	22	36	14	41	42	89	34	34	34
30	2	41	30	6	2	38	29	29	16
31	32	16	17	1	12	37	23	23	24
32	7	26	24	26	22	18	17	17	32
33	42	1	30	11	37	14	11	11	37
34	27	11	25	21	27	19	4	4	39
35	12	6	37	16	17	32	5	5	39
36	37	31	23	31	32	16	12	12	37
37	16	22	28	38	9	17	18	18	32
38	21	37	14	43	44	105	24	24	25
39	1	42	30	8	4	37	30	30	17
40	31	17	17	3	14	35	35	35	34
41	6	27	25	28	24	19	25	25	14
42	41	2	30	13	39	17	19	19	31
43	26	12	24	23	29	20	13	13	36
44	11	7	37	18	19	31	6	6	38
45	36	32	23	33	34	23	7	7	37

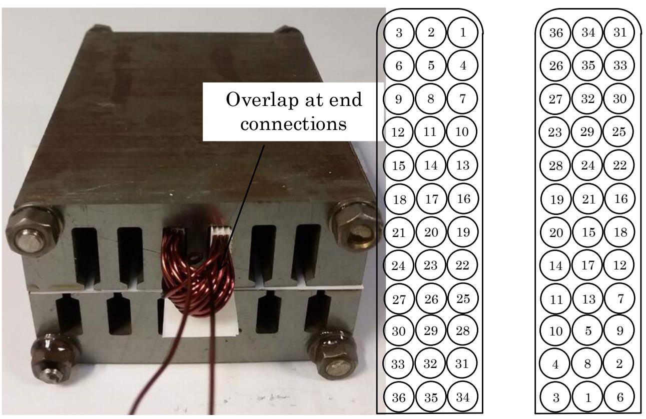
V. INVESTIGATION VIA AN EXPERIMENT

Performing the test in the PM machine is challenging task as to introduce a fault it requires additional leads for each turns and these leads increase the resistances and thus, minimize the actual SC current induced in a turn. To avoid the complexity and accurately measure the turn's inductances with its placement which dictates the SC current, an E-Core is therefore adopted. Experimented E-core is shown in Fig.6. In order to accommodate the winding at a position, a slot-shaped wedge made of peak material and has holes to insert the conductor in its place, is also manufactured. It is worth noting that having such wedge arrangement to adopt the winding in a place reduces the fill factor and thus, resultant DC losses increase. But, this is mainly related to manufacturing compatibility which is not the scope of the paper. The key focus is given into the influence of implementing the proposed concept on winding inductances. But, resistances and capacitances are also investigated since they have significant effect due to changes in the winding arrangement.

Two different winding arrangements are considered. One arrangement has the winding in an order considering carefully hand wound arrangement as shown in Fig.6a. The second one consists of turns' locations in a way to share the slot-leakage inductances effectively (Fig.6b). The conductor's location for effective flux sharing arrangement is adopted using an optimization process as explained in section IV.



(a)



(b)

Fig. 6. E-core and slot-shaped wedges to accommodate the conductors at a location and the schematic of the conductor location: (a) carefully wound arranged in an order arrangement and (b) slot-leakage flux effectively shared arrangement

High precision LCR meter [16] is used to measure the winding parameters which include inductances, resistances and capacitances. A different set of measurements is carried out at ambient temperature with an interval between each measurement since the winding parameters can be influenced by the temperature rise within the windings. The measured parameters are collected and then, the data are analyzed and compared with each set. It is observed that the differences between the measurements are less than 2%. However, the average measurement has been considered. The results obtained are presented in following sub-sections.

A. *Winding inductances*

As previously mentioned, the inductances are dictates by the SC current; therefore measuring inductances of each turns with their location provides the information of the fault. So the inductances are measured adopting condition of a turn-turn fault where different fault locations are considered. But, phase inductances and minimum and maximum inductances of faulty turn are only presented here to show the influence of the winding arrangements.

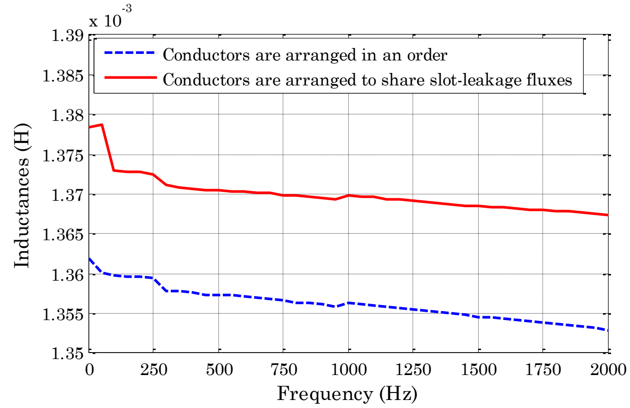


Fig. 7. Inductances comparison between the considered two arrangements

From the Fig.7, it can be seen that the inductances are slightly higher when adopting slot-leakage flux shared arrangement. This is due to increased end-windings in such case. However, this difference can be neglected as it is less than 1%. But, if inductances of a single turn are considered, the difference between the measured turns' inductance respectively to their position becomes significant in the case of conductors arranged in an order. Thus, the turn which experiences lower inductances are subject to high SC current. However, this is not the case in the effectively leakage flux shared arrangements where the conductors are arranged in a way to share the slot-leakage fluxes equally. This is evident in Table III.

TABLE III
COMPARISON BETWEEN MEASURED A TURN INDUCTANCES

	Conductors are arranged in an order	Conductors are arranged to share slot-leakage fluxes
A turn inductance - minimum	0.74uH	0.901uH
A turn inductance - maximum	1.16uH	0.922uH

B. *Winding resistances*

The winding resistances dictate the copper losses and thus, efficiency. The AC resistances can be increased or reduced due to the fact modifications in the winding placement which changes the current distribution in each conductor. Resulting current distribution is mainly due to eddy-current effects, namely skin effect and proximity effect. The effects are dependent on the physical structure of winding, winding transposition, conductor's length, slot dimensions and operating frequency. Given that altering the location influences the conductor's length and the end-winding transpositions, winding resistances are investigated.

Fig.8 shows the measured resistances against a frequency range. As can be seen from the results that the winding arrangement that are placed in an order has slightly less DC resistances than the winding arrangement that share slot-leakage fluxes effectively. This is mainly due to the increased end windings' length when adopting the leakage flux shared arrangement in which end connections overlap each other since the conductors' placements are irregular. Also it can be seen that as expected the AC resistances increase in both cases of winding arrangements as frequency increases. This is due to the changes in the current distribution in the winding because of the effect of both proximity effect and skin effect [17]. However, the optimized conductor's placement reduces the AC resistances at higher frequencies. This is because of the irregularity in the winding minimises the leakage fluxes linking through end connection of each turns. As a result, it reduces the current penetration in the conductor and thus, the AC resistances.

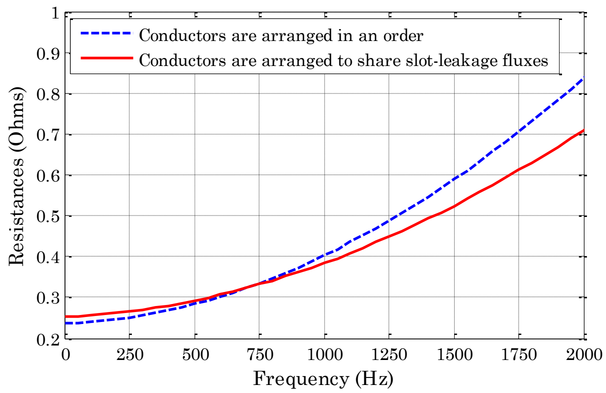


Fig. 8. Resistances comparison between the considered two arrangements

C. *Turn to turn capacitance*

The capacitances associated with the windings are capacitances between the windings and the layers, turn to turn capacitances and turn to magnetic core capacitances. Since the machine is alternate tooth wounded using single layer arrangement, both capacitances between the windings and the layers can be neglected as the coupling between the phases are insignificant. But, measuring only the turn-turn capacitance is challenging. Instead, lumped winding capacitance (C_w) for the different adopted winding configurations is therefore measured.

TABLE IV
MEASURED WINDING CAPACITANCES AND RESONANCE FREQUENCY

	Conductors are arranged in an order	Conductors are arranged to share slot-leakage flux
Winding capacitance (C_w)	6.06 pF	9.00 pF
Resonance frequency (Hz)	1.75 MHz	1.44 MHz

From Table IV, it is evident that implementing the conductors to share slot-leakage fluxes increases the lumped winding capacitances and thus, turn-turn capacitances as they wound top of each other. However these influences can be neglected as the resonance frequency is significantly high compared to switching frequencies of the drive.

VI. CONCLUSION

In this paper, feasible conductors' arrangement or placement in a slot of PM machine has been optimized to minimize the turn-turn fault current. In order to minimize the fault current the conductor arrangement in a slot is optimized using multi-objective Genetic Algorithm (GA) incorporating with both analytical and Finite Element (FE) numerical tool. FE was used to estimate the frequency dependent machine parameters such as inductances, resistances and back-emf with respect to the winding arrangements while Analytical tool was applied for SC computation. The possible combinations of conductors' placement are set as variables and optimized for the 12-slot, 10-pole machine designed for rotorcraft actuator. The obtained results confirmed that re-arranging the conductor placement in a slot allows effectively limit the SC current as the conductors effectively shares the slot-leakage fluxes, consequently eliminates the significant difference in turn inductances. This is further experimentally confirmed via E-core arrangement.

Two different conductors' arrangements are experimented. One arrangement is arranged in an order identical to carefully hand wound arrangements whole second one is slot-leakage flux shared arrangement. Turn inductances were measured as they dominate the SC current under a fault. The measured results shows that there is a significant difference between the turn inductances in the case arranged in an order as the carefully hand wound arrangements. However, the turn inductances are almost identical for the case which was arranged to share slot-leakage fluxes equally. As a result the consequential SC current will be significantly minimal than the carefully wound arrangement. Also the measurements confirmed that having slot-leakage fluxes shared arrangement significantly reduces the AC losses. But, the resonance frequency is reduced due to increase turn-turn capacitances. However the influence of the turn-turn capacitances can be neglected as the resonance beyond the frequency range.

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