Eccentricity Compensation in Switched Reluctance Machines via Controlling Winding Turns/Stator Current: Theory, Modeling, and Electromagnetic Analysis

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Abstract **─** In this paper, a new eccentricity compensation method for Switched Reluctance Machines (SRMs) is presented. In this regard, the dependency of radial force (RF) on variation of number of turns for stator coils and fault level is demonstrated analytically and principle of the new compensation strategy is introduced as well. This strategy is implemented on an SRM utilizing Finite Element Method (FEM) under different fault conditions. This approach is accomplished through switching among the various arrangements in the number of turns for the coils on the stator poles; hence, unbalanced magnetic force (UMF) is controlled without additional auxiliary coils. Simultaneously, regulating the stator currents guarantees the motor torque is not diminished. This comprehensive approach is suitable for different types and structures of SRMs and will compensate or control eccentricities in a wide range of eccentricity faults namely 10%-70% while motor performance is not impaired.

Index Terms - Electromagnetics characteristics, eccentricity compensation, finite element analysis, fault control, and switched reluctance machines.

I. INTRODUCTION

SRM has been a charming choice for industrial and household applications due to its advantageous characteristics such as simplicity in winding and manufacturing, durability, and rotor permissible temperature [1, 2].

SRM air gap is considered to be uniform for ideal operation, which is smaller compared to other types of machines [3]. When there are uneven air gaps between stator and rotor poles eccentricity fault will happen [4]. Eccentricity fault results in excessive vibration, noise, bearing wear, and UMF. They change flux pattern and flux density distribution and accordingly causes some errors in motor control, rotor position estimation, and also considerable effects on produced torque [5, 6].

In the fabrication process a relative eccentricity between the stator and rotor axes up to 10% is common [7] and therefore the faulty conditions are assigned to those of more than this value, which must be controlled or compensated to prevent motor from irreparable damages. In this regard, in [8] artificial intelligence like Neuro-Fuzzy controller is suggested to compensate manufacturing inaccuracies namely eccentricity. This strategy is simulated for a 6/4 SRM and minimizes the torque ripple; however, a reduction in average torque is expected.

A remedial strategy for eccentricity via controlling current in each coil proposed in [9]. It puts forward that, to control eccentricity the current magnitude of each coil should be controlled separately. And through augmenting and mitigating current intensity in the facing poles reduces the UMF. In [10], eccentricity effects in a 12/8 SRM has been reduced by some modifications in stator windings. It shows that if in every phase, the four poles be connected such that

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they create two parallel paths with neighboring coils in series with an equalizer, the UMF will be lessened significantly. This strategy seems useful in 33 % eccentricity but it is not analyzed that for higher degrees of eccentricity this scheme will be such helpful too or not. Also this winding configuration is just suitable for those other SRMs, which have four stator poles per phase but no other configurations. The possibility of different winding methods and their features under various type of faults in a 6/4 SRM has been reported in [11]. It proposes six winding configurations and discusses their main characteristics under open circuit and short circuit conditions and then different detection possibilities are suggested but obviously the focus is not on mechanical faults like off-center rotor. The substantial effect of parallel stator winding on reduction of UMF in eccentric rotor in induction and synchronous machines has been discussed and evaluated in [12, 13].

As it can be seen in available papers in the literature, little portion is dedicated to eccentricity compensation in SRMs. Considering that each of these mentioned methods are intended for a particular SRM design, a more comprehensive strategy is needed to satisfy different motor structures.

In the previous works, authors have assessed SE (static eccentricity) [14], DE (dynamic eccentricity) [15], ME (mixed eccentricity) [16], and AE (axial eccentricity) [17] in the SRM. In this paper, a novel approach is proposed to compensate eccentricity in SRM. In this method by changing the arrangement of stator winding turns, not only UMF will be mitigated significantly, but also the motor torque will be kept around its nominal value, which is accomplished by controlling the stator current.

II. PROBLEM STATEMENT

One of the common faults in SRM is eccentricity. Eccentricity faults change SRM characteristics through making the produced magnetic field and flux distribution non-uniform. This asymmetry leads to an unbalanced flux density in front of two opposite poles of one excited phase, which results in a huge UMF acting on the rotor. This phenomenon brings about excessive vibration, noise, bearing wear, and irreparable damages.

UMF is the difference between two large RFs produced by two facing coils. These RFs are exerted on the opposite rotor poles, so through counterbalancing the ampere-turns in every two facing coils, UMF could be mitigated. This idea is accomplished by modifying arrangements of number of turns in each coil and regulating the stator current.

It is needed first that the relation among the RFs and motor torque with number of turns and stator current be investigated. Thus, in section III a linear model for RFs is presented and then the analytical model of the new method is demonstrated.

III. ANALYTICAL MODEL OF THE NEW METHOD

A precise model is needed for the physical motor simulation to incorporate the essential dynamics of the motor [18-21]. In literatures such as [22] a very detailed analytical model for RF is presented. However, here a simplified and linear analytical model is employed to predict the RFs on individual stator poles and the UMF on the rotor. These expressions will be derived just for those rotor positions where the rotor and stator overlap. In this model it is assumed that all of the magnetic energy is stored in the air gap where the B-H curve is given by,

$$\vec{B} = \mu_o \vec{H} \tag{1}$$

where μ_0 is the permeability of air, B is flux density, and H is magnetic field intensity, which can be calculated using the following equation,

$$\vec{H} = \frac{Ni}{g} \tag{2}$$

where N is the number of turns, i is the magnitude of current in each stator coil and g is the radial air gap length in the case of uniform air gap in healthy motor. Also, the flux equation can be given by,

$$\varphi = B.A \quad . \tag{3}$$

The symbol A is the surface of overlapping region of rotor and stator poles (Fig. 1), which can be evaluated using the following equation,

$$A = l_r r_r \theta \tag{4}$$

where r_r is the radius of rotor so $r_l\theta$ is the arc for overlapping region and l_r is the length of the rotor. By considering equations (1) to (4), the flux linkage can be defined as follow,

$$\lambda = N\varphi = \frac{\mu_o N^2 A}{g} i = \frac{\mu_o N^2 (l_r r_r \theta)}{g} i \ . \tag{5}$$

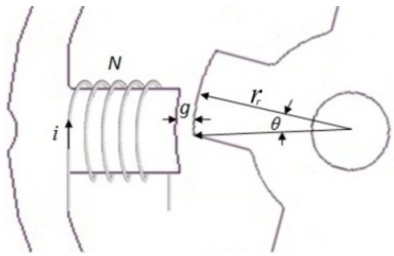


Fig. 1. Configuration of SRM for one pole.

The co-energy (W_f') for each pole due to λ is given by

$$W_f' = \oint \lambda \, di = \oint \frac{\mu_o N^2 A}{g} i \, di = \frac{\mu_o N^2 (l_r r_r \theta)}{2g} i^2 \ . \tag{6}$$

The RF produced by every pole can be obtained from the rate of change in co-energy with respect to the air gap. So the RF (F_r) will be easily derived by

$$F_r = \frac{\partial W_f'}{\partial g} = -\frac{\mu_o N^2 (l_r r_r \theta)}{2g^2} i^2 \ . \tag{7}$$

Torque will be achieved by the rate of change in co-energy with respect to the rotor position, as follows,

$$T = \frac{\partial W_f'}{\partial \theta} = \frac{\mu_o N^2 l_r r_r}{2g} i^2 \ . \tag{8}$$

The unbalanced RFs acting on the rotor are calculated assuming that stator poles on opposite side of the machine are independent and this is the reason that electromagnetic energy has been computed per pole instead of per phase. Supposing an SE fault which means, rotor is off-center from stator symmetrical axes (Fig. 2) the degree of eccentricity will be given by,

$$\varepsilon = \left(\frac{\Delta}{g}\right) \times 100\% \tag{9}$$

where Δ is the displacement of the rotor. Thus, the RF produced by poles 1 and 2 can be derived respectively by,

$$F_{r1} = \left.\frac{\partial W_f'}{\partial g}\right|_{g+\Delta}, \ F_{r2} = \left.\frac{\partial W_f'}{\partial g}\right|_{g-\Delta} \ . \tag{10}$$

Furthermore, the UMF on the rotor is the sum of these forces

$$UMF = F_{r1} + F_{r2} \ . \tag{11}$$

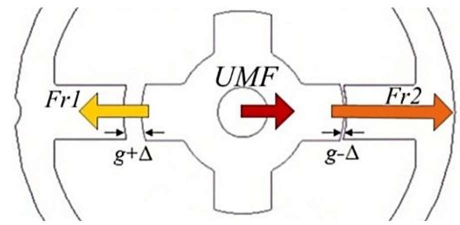


Fig. 2. Rotor is displaced from its symmetrical axes.

Due to the opposite direction of fluxes in two poles in one phase (i.e., λ is leaving one pole and entering into the other one) F_{r1} is exerted in the reverse direction with respect to F_{r2} on the rotor (Fig. 2). In the healthy condition, the magnitudes of these forces are equal so the overall force on the rotor is nearly zero, in other words, there is no UMF. But as it was shown up to here eccentricity causes that these RFs have different magnitudes and therefore the UMF will arise. It seems reasonable if it was possible to somehow balance the RFs on the opposite side of rotor the UMF will be diminished significantly. To nullify UMF there are two choices: a) augmenting the MMF on the pole where air gap has been increased (pole 1 in Fig. 2) or b) mitigating MMF on the opposite pole where air gap has been decreased (pole 2 in Fig. 2). Even a combination of both approaches is also possible.

Considering Fig. 2, let us develop equation (11) to see how analytically is possible to reduce this force

$$\begin{aligned} UMF &= F_{r1} + F_{r2} \\ &= \frac{\mu_o N_1^2 (l_r r_r \theta)}{2(g+\Delta)^2} i^2 - \frac{\mu_o N_2^2 (l_r r_r \theta)}{2(g-\Delta)^2} i^2 \\ &\begin{cases} g-\Delta & in\ front\ of\ Coil\ 1 \\ g+\Delta & in\ front\ of\ Coil\ 2 \end{cases} \ . \end{aligned} \tag{12}$$

By rearrangement, UMF will be given by,

$$\begin{aligned} UMF &= \frac{1}{2} \frac{\mu_o (l_r r_r \theta_o) i^2}{(g-\Delta)^2 (g+\Delta)^2} \\ &\times \left((N_1^2 - N_2^2)(g^2 + \Delta^2) - 2g\Delta (N_1^2 + N_2^2) \right) \ . \end{aligned} \tag{13}$$

Equation (13) shows that displacement (Δ) directly affects UMF. There is no straight method to reach the degree of eccentricity but the occurrence of eccentricity and where it was happened is completely diagnosable. Thus, due to the dependence of RF on number of turns and current intensity in each coil, it is possible to diminish faults effects. Controlling currents means that two opposite coils of one phase must be energized separately, in other words, there must be either an electrical source for each one or having an independent set of power switches for each pole, which however, increases the total cost.

Assuming like most of typical SRMs, two opposite coils of one phase are connected in series, and considering i constant, equation (13) will be rewritten as,

$$UMF = K\left(\left(N_1^2 - N_2^2\right)\left(g^2 + \Delta^2\right) - 2g\Delta\left(N_1^2 + N_2^2\right)\right) \tag{14}$$

where K is given by,

$$K = \frac{1}{2}\frac{\mu_o\left(l_r r\theta_o\right)i^2}{\left(g-\Delta\right)^2\left(g+\Delta\right)^2} \quad . \tag{15}$$

The symbol K depends on motor dimensions and cannot be zero. Noting equation (14) for an SRM in healthy condition where,

$$\begin{cases}\Delta = 0\\ N_1 = N_2\end{cases} \quad . \tag{16}$$

UMF will be equal to zero. But in eccentric conditions for a typical SRM where,

$$\begin{cases}\Delta \neq 0\\ N_1 = N_2\end{cases} \quad . \tag{17}$$

It is not possible for UMF to be zero. Supposing the possibility of changing the number of turns and developing equation (14) UMF will be zero on condition that

$$UMF = K\left(\left(N_1^2 - N_2^2\right)\left(g^2 + \Delta^2\right) - 2g\Delta\left(N_1^2 + N_2^2\right)\right) = 0$$
$$\left(N_1^2 - N_2^2\right)\left(g^2 + \Delta^2\right) - 2g\Delta\left(N_1^2 + N_2^2\right) = 0$$
$$\frac{N_2}{N_1} = \left(\frac{g-\Delta}{g+\Delta}\right) = 1 - \left(\frac{2\Delta}{g+\Delta}\right) \quad . \tag{18}$$

Assuming an SE fault (Fig. 2), equation (18) implies that if the turn's ratio between coils 2 and 1 be modified like this, UMF will be about zero. The advantage of this method here is that in the case of eccentricities faults there is no need to get the SRM removed from the production line to fix it anymore. There is the feasibility of remedial actions during SRM operation.

To modify turns ratio, it is possible to increase the number of turns in coil 1 (N_1), or decrease the number of turns in coil 2 (N_2). Increasing the number of turns means the existence of some additional windings that are idle in the healthy operation of motor, which requires some changes in its design structure and consequently all of these demand extravagant money. Thus, here the focus is just on decreasing the number of turns.

Considering equation (18), assuming coil 1 has 120 turns and is constant, the relationship between number of turns in coil 2 (N_2) and degree of eccentricity (ε) in order to cancel UMF is obtained and plotted in Fig. 3. As it can be seen in this figure there is a nonlinear relation between N_2 and ε.

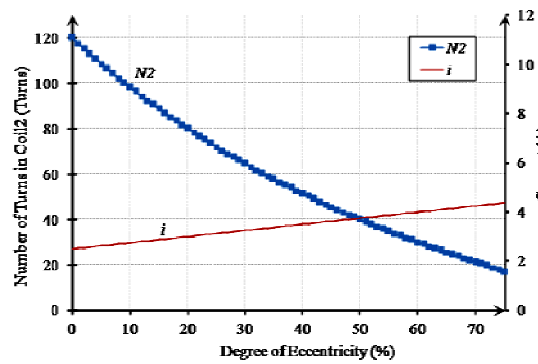


Fig. 3. The number of turns and stator current to nullify UMF and keeping the toque at its rated value, respectively for different degrees of eccentricity.

From Fig. 3, two noteworthy points can be deduced: a) to compensate high degrees of eccentricities, N_2 must be decreased very much; this is not possible because it will ruin the symmetrical structure of the motor. If the difference between the number of turns in adjacent poles becomes very much so the resultant MMF of these poles will vary greatly and consequently causes extra vibration indeed. Therefore, 40 % of the total number of turns is supposed to be the maximum number of turns to be decreased, which is 50 turns here. b) Another point is that according equation to (8) the torque produced by each stator pole has direct relation with square of the number of turns and current intensity,

$$T \propto N^2 \times i^2 \quad . \tag{19}$$

Thus, regarding the reduction in the number of turns and assuming i constant, the overall torque will be lessened, which means the performance of motor will be deteriorated and that is not acceptable. Thus, to keep the torque at its nominal value i must be intensified. To develop an analytical model, let's start with equation (8),

$$T_1 = \frac{\mu_o N^2 l_r r_r}{2g} i^2 \quad . \qquad (20)$$

This is the torque produced by one stator pole. The overall torque as a result of two facing poles in one phase in healthy condition will be given by

$$T_h = T_1 + T_2 = \frac{\mu_o N^2 l_r r_r}{g} i^2 \quad . \qquad (21)$$

The above equation is for healthy operation of motor but in eccentric condition the torque will be given by

$$T_e = T_1 + T_2 = \frac{\mu_o {N_1}^2 l_r r_r}{2(g+\Delta)} i^2 + \frac{\mu_o {N_2}^2 l_r r_r}{2(g-\Delta)} i^2 \qquad (22)$$

As it was mentioned earlier, the objective is that while N_2 is decreased to compensate eccentricity, the torque remains unchanged ($T_e \approx T_h$) or in acceptable range. So it can be accomplished through increasing i, equalizing equations (21) and (22)

$$T_e = T_h$$
$$\frac{\mu_o {N_1}^2 l_r r_r}{2(g+\Delta)} i_e^2 + \frac{\mu_o {N_2}^2 l_r r_r}{2(g-\Delta)} i_e^2 = \frac{\mu_o N^2 l_r r_r}{g} {i_h}^2 \qquad (23)$$

Where i_h is the stator current in healthy condition and i_e is the stator current in eccentric condition. Let us suppose during a fault the number of turns in coil 1 is kept constant at its design number ($N_1 = N$) and number of turns in coil 2 is modified according to equation (18). So considering these assumptions, equation (23) will be simplified to,

$$\frac{i_e}{i_h} = 1 + \frac{\Delta}{g} \quad . \qquad (24)$$

This equation emphasizes in order to maintain torque at a constant level while number of turns is decreased in eccentric condition the current must be increased, which is also demonstrated by Fig. 3. At this point this question may be raised that intensifying current to increase torque might augment UMF as well, and of course considering the assumption that in developing equation (18), i was supposed to be constant. It is essential to mention that this will not happen. As it is shown in section V when N_2 is decreased to 70 turns at its maximum reduction level, current must be increased from 2.5A to 3A, it is demonstrated by simulation that the effects of this addition will be negligible. In this section the theory of the new method was proved. The following section is dedicated to the analysis of the proposed compensation strategy.

IV. THE NEW COMPENSATION STRATEGY

To create the possibility of modifying the number of turns for each coil, a switching box is designed which has three power switches. These switches must be able to operate at the rated motor current, which is only 2.5A and the high frequency switching is not needed, so they can be any ordinary and cheap switch. Different combinations of these switches will produce different arrangement of number of turns. The configuration of the switching box for one phase is shown in Fig. 4. It must be mentioned that only one switching box is required for the proposed method. When a fault is diagnosed in one phase afterwards the pole, which its MMF should be reduced will be specified, and finally the terminal of the switching box will be connected to the windings of this coil of the faulty phase.

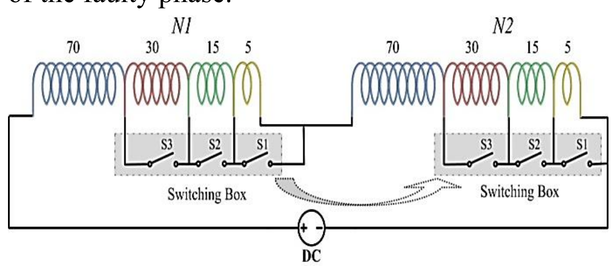


Fig. 4. Configuration of the switching box in phase.

In table 1 the complete combinations of a switching box and the resulting number of turns are listed. In healthy operation of motor the number of turns is 120 turns and all the switches are OFF (state 0). Each switch, which is turned ON means that the corresponding coil is removed (Fig. 4). So via different combination of switches, eight different number of turns are obtainable. Depending on the degree of eccentricity, the right state must be chosen. It is obvious that besides decreasing the number of turns, the current intensity must be increased to keep the torque at its nominal value. To do so, an algorithm has been used which its flowchart is shown in Fig. 5.

Table 1: Combinations of a switching box (0 : OFF and 1 : ON).

State	S3	S2	S1	Number of Turns
0	0	0	0	120
1	0	0	1	115
2	0	1	0	105
3	0	1	1	100
4	1	0	0	90
5	1	0	1	85
6	1	1	0	75
7	1	1	1	70

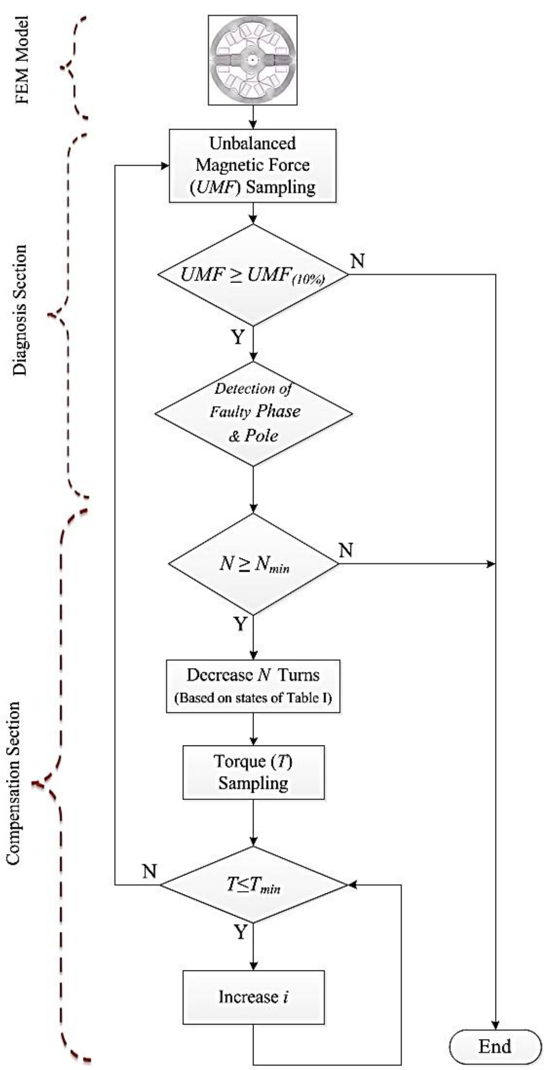


Fig. 5. Compensation strategy flowchart.

Based on the previous work of the authors, in this algorithm, UMF is sampled based on the proposed index in [23], if it is greater than UMF (10 %) it will be diagnosed as a fault. Now, the faulty phase must be determined and of course the pole, which its ampere-turn must be mitigated and should be specified too. This is viable via the procedure proposed in [24]. Because of tolerances in manufacturing and assembly process, a 10 % eccentricity is assumed to be natural and is not identified as a fault. Thus, the aim of compensation is to get back to this condition in case of eccentricities more severe than 10 %.

Now that it is clear which coil is going to be modified, in the next step it is examined that the number of turns in this coil has reached to its minimum level or not? For this motor the maximum number of turns is 120 and the minimum number is 70 turns. So at this point it is possible to go to the next step i.e., "Decrease *N* turns" because currently the number of turns is 120. In this stage, the switching box is changed to its next state (i.e., changing from state 0 to state 1) and accordingly decreases the number of turns to 115 turns. Moving to the following step, the torque must be sampled. If the torque is less than its minimum level, which is 90 % of the nominal value the current must be increased. In this stage current is augmented 0.1 A each time up until the torque reaches to the minimum level. The reason behind this minimum level is that due to the variations in manufacturing process and alterations from nominal load conditions it is not mostly possible to reach motor nominal torque, so 90 % is supposed to be the healthy performance of the motor. After restoring the torque, UMF is sampled again and if it is greater than UMF (10 %) the same procedure is followed once more. It is worth noting that in case of 40 % eccentricities and higher the number of turns reaches to its minimum (70 turns) and UMF is not less than its minimum value yet, then here the fault is compensated partially and procedure is terminated.

V. NEW METHOD IMPLEMENTATION ON SRM AND FEM RESULTS

A workbench of the test for a 6/4 SRM has been established utilizing FEM. Each phase winding consists of 120 turns with a current magnitude of 2.5A. This motor is driven for different conditions to assess the UMF in different percentages of eccentricities. Figure 6 shows UMF for different levels of eccentricities as a function of rotor position which varies from 0 to 44 degrees meaning a rotation from fully unaligned position to fully aligned position.

It is worth noting that the possibility of increasing the number of turns was simulated too. 30 turns were added to SRM windings to use for augmenting the number of turns in case of faults, but the results showed that due to the very nonlinear characteristics of SRM, comparing decreasing and increasing the number of turns, decreasing the number of turns is much more effective in nullifying UMF. Thus here the focus is just on the control of decreasing the number of turns.

Considering Fig. 7, it is inferred that due to nonlinear features of SRM, by increasing the stator current in the range of 2.5A to 3A at the worst condition, UMF will be augmented merely 5 %, which is not any of importance. The simulation results for two degrees of eccentricities namely 30% and 70 % are analyzed.

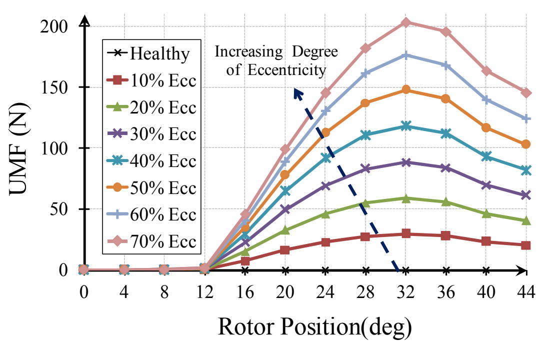


Fig. 6. UMF as a function of rotor position for different eccentricity degrees.

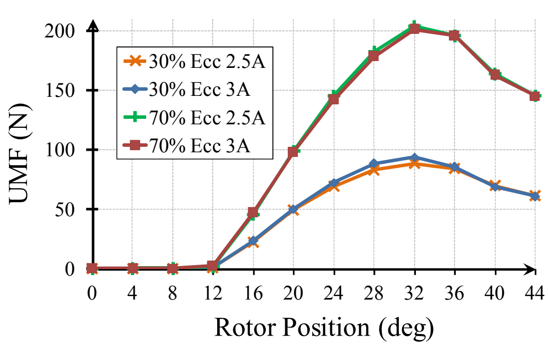


Fig. 7. Influence of increasing current on UMF.

A. 30% ECCENTRICITY

In case of 30 % eccentricity, the algorithm outcome is that the number of turns must be decreased to 75 turns (state 6) to mitigate UMF below UMF (10 %), and to keep torque at 90 % of its nominal value the current must be increased to 2.9A. UMF and torque, before and after compensation are plotted in Fig. 8 and 9. Considering Fig. 8, it is inferred that via this compensation strategy UMF at its peak value is reduced from 88 *N* to 21 *N*. It means more than 75% reduction in UMF. As it is evident the eccentricity effects are compensated completely (i.e., UMF is less than UMF (10 %)). According to Fig. 9 it is shown that via increasing the current intensity up to 2.9 A the torque is kept at 90 % of its value in healthy operation. At its peak value the torque has been decreased from 0.27 to 0.24 *Nm*. It is nearly a 10 % reduction, which is acceptable.

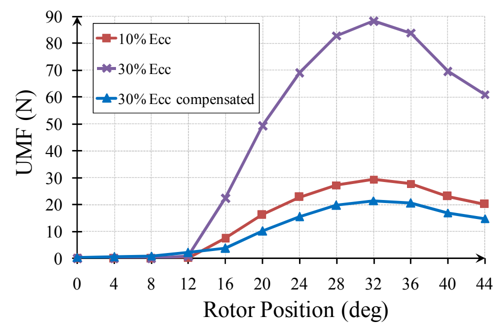


Fig. 8. UMF after implementation of the compensation strategy for 30 % fault.

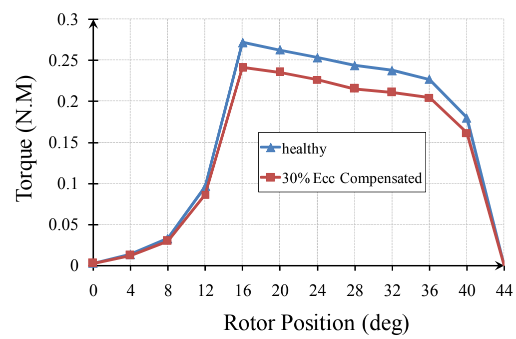
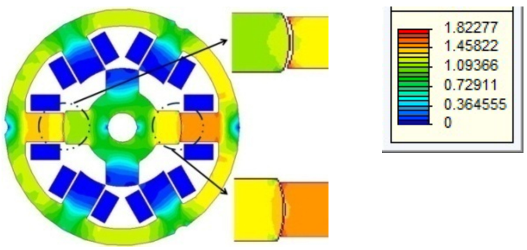
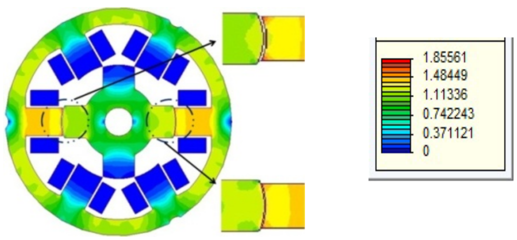


Fig. 9. Comparing torque for healthy condition and compensated 30 % eccentricity.

Fig. 10 (a) and (b) show the flux density in 30 % eccentricity before and after compensation, respectively. By examining this figure it is deduced that in the compensated motor as a result of the proposed method, flux density is balanced clearly in poles 1 and 2, which leads to a significant reduction in UMF. But it is worth noting that by increasing the source current, flux density is magnified less than 5 %, which is not concerning regarding to magnetic saturation.



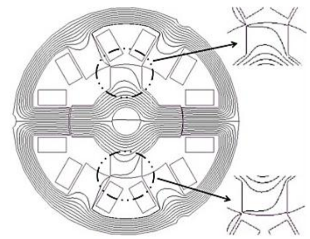
(a)



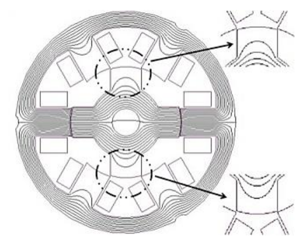
(b)

Fig. 10. Flux density in eccentric motor under 30% fault: a) before compensation and b) after compensation.

Fig. 11 (a) and (b) show the flux paths in 30% eccentricity before and after compensation in the aligned position, respectively. As it can be observed, after compensation flux leakages in adjacent poles are diminished significantly. In Fig. 12 the flux linkages for coils 1 and 2 in three conditions namely healthy motor, before and after compensation in 30 % eccentricity is shown. As it was predictable in healthy condition flux linkages for both coils are the same, of course with opposite direction. Under 30% eccentricity fault, the flux linkages are still nearly the same. It is reasonable that due to the very close flux linkages in coils 1 and 2, which have quite different air gaps the RFs will vary completely. By applying a compensation strategy the number of turns in coil 1 is not modified so its flux linkage will not alter so much but as its current is magnified it is augmented a little. But the scenario for coil 2 is totally different. As a result of 45 turns reduction in coil 2, the flux linkage must be decreased significantly, which can be seen clearly. As a result of this deduction, RF produced by coil 2 is mitigated so much, and somehow equalizes to RF produced by coil 1 and correspondingly UMF is nullified.



(a)

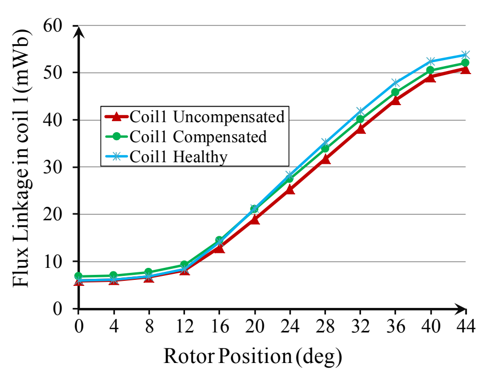


(b)

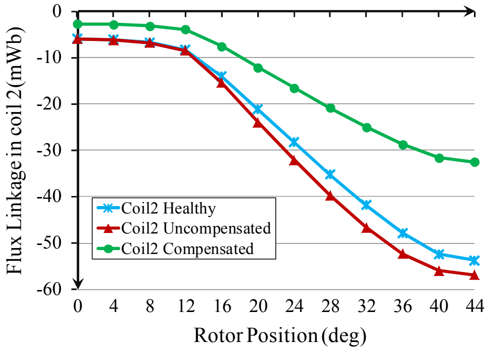
Fig. 11. Flux paths in eccentric motor under 30% fault: a) before compensation and b) after compensation.

B. 70% ECCENTRICITY

If the degree of eccentricity was more severe, suppose an extreme condition, a fault with 70% eccentricity has occurred. If the proposed strategy be applied to the given SRM, the outcome will be a reduction to 70 turns for turns number (state 7 in switching box) and an increase in current to 2.9 A. The results for UMF and torque in this compensated condition are shown in Figs. 13 and 14, respectively.



(a)



(b)

Fig. 12. Comparison between flux linkages in healthy motor, before and after compensation in case of 30 % eccentricity: a) coil 1 and b) coil 2.

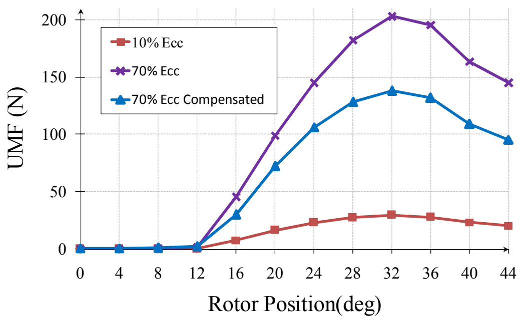


Fig. 13. UMF after implementation compensation strategy for 70 % fault.

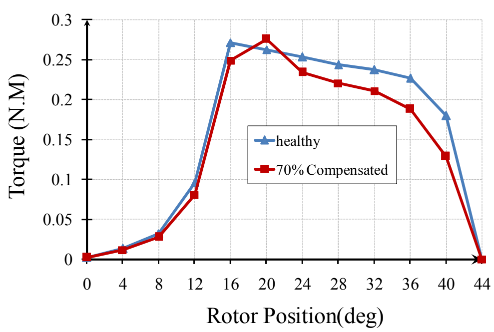
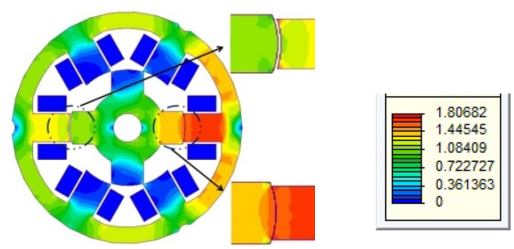


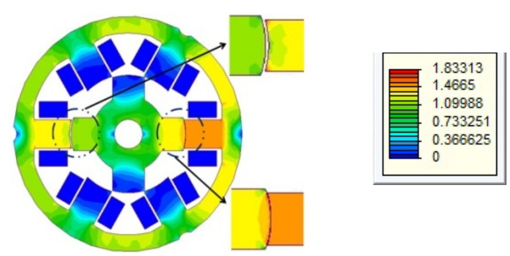
Fig. 14. Comparing torque for healthy condition and 70 % eccentricity compensated.

As it is seen in these figures despite employing the remedial strategy it is not possible to mitigate UMF below 10 % eccentricity level; however, it helps to lessen UMF at its peak value from 203 *N* to 137 *N*, which means more than 30 % reduction. In case of using the motor in critical operations this level of compensation might help the motor be able to continue its operation during the faults. Figure 14 shows the overall torque before and after compensation in case of 70 % eccentricity. One of the effects in eccentricities higher than 50 %, is the increase in overall torque which can be recognized here too. In this case the current is the same as in the case of 30 % eccentricity and also the number of turns is less than the previous case but the torque is kept around its level in healthy condition again. Figure 15 (a) and (b) shows the flux density in 70 % eccentricity before and after compensation, respectively. The explanations are similar to what was told for Fig. 16 (a) and (b) shows the flux paths in 70 % eccentricity before and after compensation, respectively. As it can be inferred, after compensation flux leakages in adjacent poles are diminished significantly, which leads to a more balanced flux distribution in the opposite poles which means reduction in UMF.

As it is inferred from the FEM results the proposed method by controlling the number of turns and stator current, has compensated the fault. In other words, applying the new strategy the RFs and motor torque are under control offering the possibility of operating even under fault condition.

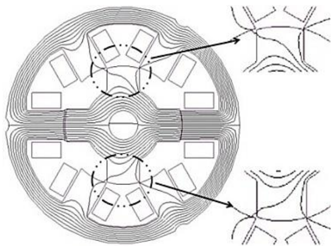


(a)

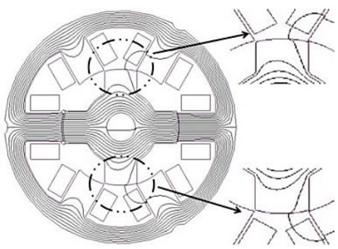


(b)

Fig. 15. Flux density in eccentric motor under 70% fault: a) before compensation and b) after compensation.



(a)



(b)

Fig. 16. Flux paths in eccentric motor under 70% fault: a) before compensation and b) after compensation.

VI. CONCLUSION

In this paper, a general method has been presented for compensating different degrees of eccentricity in SRMs. The proposed novel method is mathematically proven first and through FEM is simulated. It is found to be successful completely in compensating static eccentricities up to 40 % and mitigating the UMF up to 70 %. This strategy requires only one switching box to be able to decrease the number of turns (e.g. from 120 to 70 turns) and does not change winding structure. Thus, it is cost effective respect to changing fundamental structure of winding in motor assembly. Keeping the motor torque at its nominal value is accomplished via controlling the source current. Thereby, it can be claimed that the motor performance is not influenced at all. For instance; it is needed where the number of turns is decreased to 70 turns to nullify UMF the source current be increased from 2.5 A to 3 A to improve motor torque, which augments flux density around 5 % in 70 % eccentricity, which is not concerning. Simulations show that compensation strategy causes flux leakages in adjacent poles be diminished considerably.

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