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The Switched Reluctance Electric Machine with Constructive Asymetry

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ABSTRACT

Results of researches of forces of a unilateral attraction of a rotor to a stator of switched reluctance electric machines taking into account unevenness of an air gap are given. It is offered for configurations of magnetic systems with weak magnetic communication between the coils making a phase to carry out a supply of coils in parallel or independently from each other for reduction of not compensated forces of a unilateral attraction of a rotor to a stator.

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1. INTRODUCTION

Theory of switched reluctance machines (SRM) was in good progress. As a result SRM technical and economic indexes are on a level of the best traditional electric machines with circular air gap magnetic field. However there are unsolved problems. One of the most difficult to solve is vibroacoustic indexes development.

Taking into account the lost in value of high quality power electronic it is possible now to set and to solve new problems of SRM electromechanical characteristics development. The improvement of vibroacoustic indexes is among of them.

Analytical review of SRM noise and vibration reduction implies that problem is intricate and do not have simple solutions. Umbrella approach is necessary to find out the factors acting on the SRM vibration and noise. One of those factors is force of unilateral attraction rotor to stator. It is variable and takes place practically always. The main cause of unilateral attraction is margin tolerance on parts of SRM. The force of unilateral attraction is more in small air gap SRMs because of greater dissymmetry of magnetic system [1].

2. RESEARCH METHOD

SRM magnetic systems are distinct in number of phases, tooths and coils. The most of SRM has weak magnetic coupling between phases and the magnetic flux is common for all tooths of one phase (Figure 1).

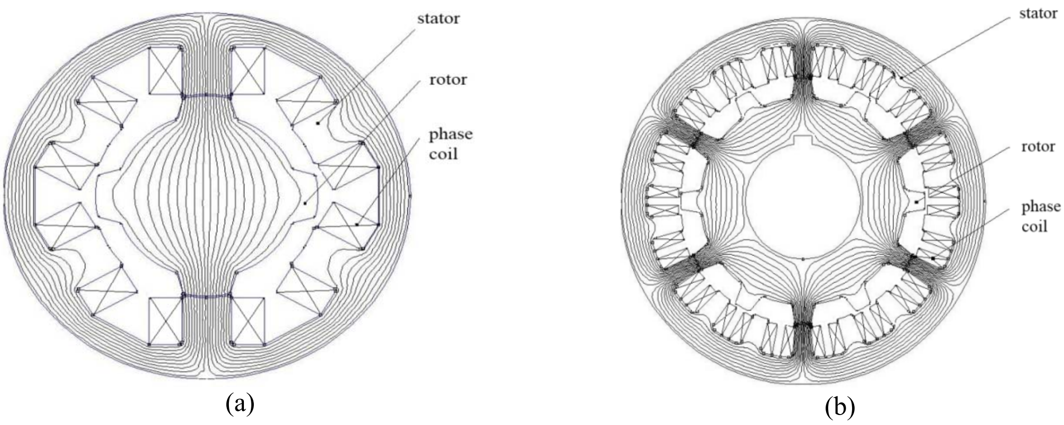


Figure 1. Distribution of magnetic field lines of SRM; a) 6/4, b) 18/12

SRM rotor is always shifted in no matter which side within tolerance. When the air gap is rather small even small shift of the rotor is the cause of occurrence of the forces of unilateral attraction stator to rotor. It is difficult to cancel out those forces by current regulation in separate coils because of common flux in traditional SRM configurations. However, it is possible to do in "short-flux" SRM where separate phase coils have separate flux [2], [3]. It will reduce the bearing assembly load and will increase the margin of safety.

Let us consider magnetic system on Figure 2 [2]. Phase coils are set at an 120 degrees angle and produce oncoming fluxes.

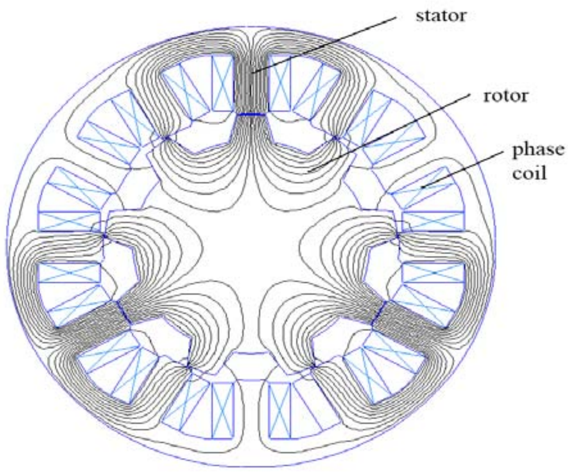


Figure 2. Distribution of magnetic field lines of SRM 12/9

It is rational to connect phase coils in parallel with power supply in SRM configurations like shown at Figure 2. In that case constructive dissymmetry will be compensated by currents in the phase coils. Smaller air gap means less coil inductance. As a result coil current will grow faster in the coil with the smaller air gap. Different current in phase coils will produce the radial force counterbalancing the rotor.

The calculations were carried out for magnetic system with connection phase coils in parallel and with connection in series. To create the constructive unbalance the rotor was vertically moved. For example moving the rotor in 0.05 mm (25% of nominal air gap) in align position the inductance of coil A is 2.332 mH and the inductance of coils B and C is 1.921 mH. The difference in inductance is 17%. Numeric values of coil inductance were computer calculated by finite elementary method.

Mathematical model of SRM phase with coils connected in series is as follows [4]-[6]:

$$\begin{cases} \dfrac{di}{dt} = \dfrac{1}{L(i,\theta)}\left(v - i \cdot R - \omega \cdot \dfrac{\partial\psi(i,\theta)}{\partial\theta}\right), \\ \dfrac{d\omega}{dt} = \dfrac{1}{J}\left(T - B\cdot\omega - T_L\right), \\ \dfrac{d\theta}{dt} = \omega, \end{cases} \quad (1)$$

Where: i – phase current, A;
L(i,θ) – phase inductance, H;
θ – rotor position, rad;
v – voltage, V;
R – phase resistance, Ohm;
ω – rotation frequency, rad/s;
ψ(i,θ) – flux linkage, Wb;
J – equivalent moment of inertia, kg·m2;
B – friction ratio;
T – electromagnetic torque, Nm;
T_L – load torque, Nm;

When the phase coils are connected in parallel there is no magnetic coupling between phase coils. It is possible to calculate phase coil currents independently. Phase voltage is applied to all phase coils at the same time. Consequently for coil currents it can be written:

$$\begin{cases} \dfrac{di_a}{dt} = \dfrac{1}{L_a(i,\theta)}\left(u - i_a \cdot R_{pc} - \omega \cdot \dfrac{\partial\psi_a(i,\theta)}{d\theta}\right), \\ \dfrac{di_b}{dt} = \dfrac{1}{L_b(i,\theta)}\left(u - i_b \cdot R_{pc} - \omega \cdot \dfrac{\partial\psi_b(i,\theta)}{d\theta}\right), \\ \dfrac{di_c}{dt} = \dfrac{1}{L_c(i,\theta)}\left(u - i_c \cdot R_{pc} - \omega \cdot \dfrac{\partial\psi_c(i,\theta)}{d\theta}\right), \\ \dfrac{d\omega}{dt} = \dfrac{1}{J}\left(T_a + T_b + T_c - B\cdot\omega - T_L\right), \\ \dfrac{d\theta}{dt} = \omega, \end{cases} \quad (2)$$

Where: Rpc – phase coil resistance, Ohm.

3. RESULTS AND ANALYSIS

To compute SRM parameters by Equation (1) and (2) the accepted assumption is to neglect the mutual phase coupling. For magnetic system under discussion (Figure 2) magnetic phase coupling is usually taken into account. However to receive qualitative result of comparison of series and parallel phase coils connection that assumption can be accepted because only the difference of coil currents is estimated.

Calculations were carried out in SIMULINK/MATLAB [7]. SRM phase modes for series and parallel connection of phase coils are shown in Figure 3 and 4 as follows.

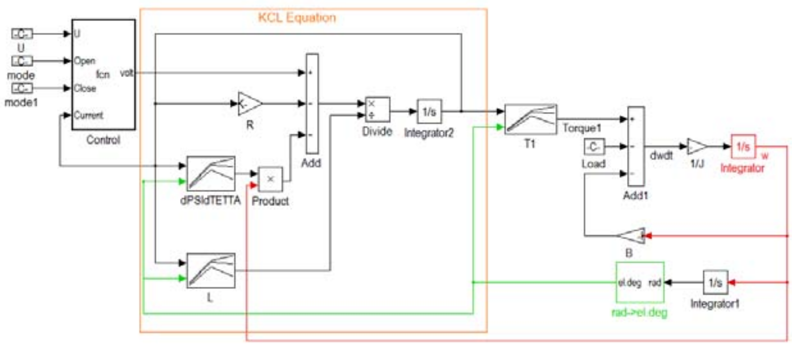


Figure 3. SIMULINK model of SRM phase with series-connected coils

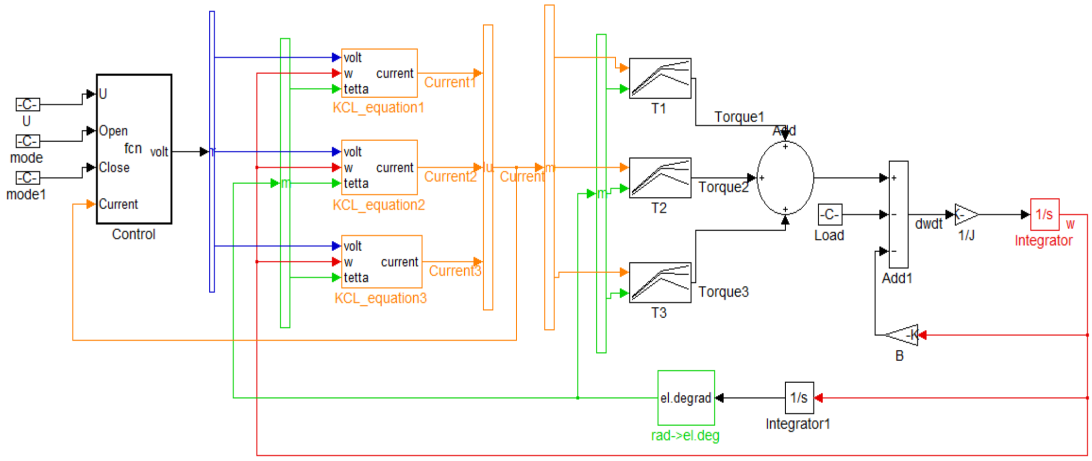
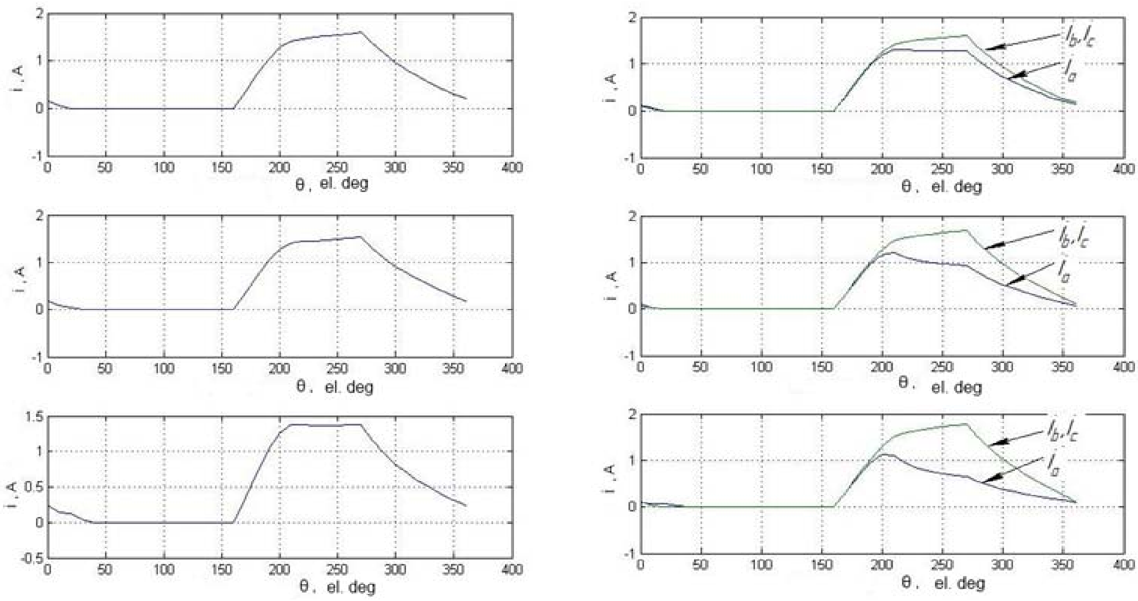


Figure 4. SIMULINK model of SRM phase with parallel-connected coils

Initial data for computations in the form of table ψ(i,θ) were received for SRM rotor unilateral shift to 25%, 50% and 75% of designed air gap (0,05; 0,1 и 0,15 mm). The simulation was carried out for nominal load SRM operation on a rotation frequency of 100 rad/s. DC link voltage for series phase coils connection was 60 V, for parallel connection – 20 V. As a result the dependencies i(θ) were received (Figure 5).



(a) (b)

Figure 5. Results of SRM modeling (a – series-connected phase coils, b – parallel-connected phase coils) under rotor shift 0.05, 0.1 and 0.15 mm

Subsequent to the results of SRM phase modeling forces of unilateral rotor attraction were calculated by finite elementary method (Figure 6).

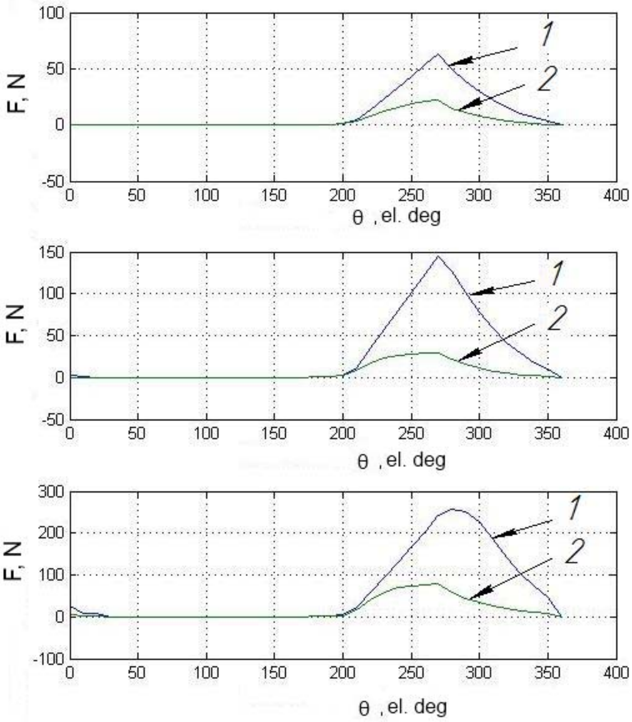


Figure 6. The force of unilateral rotor to stator attraction (1 – series-connected phase coils, 2 – parallel-connected phase coils) under rotor shift 0.05, 0.1 and 0.15 mm

As can be seen from the Figure 6 with series phase coils connection when the current is equal in all phase coils the force of unilateral rotor attraction is rather more than in case of parallel phase coils connection when coil current depend from air gap distance. Connecting phase coils in parallel it is possible to reduce the force of unilateral rotor attraction in 3 times at the average.

It is possible to reduce the force of unilateral rotor attraction in SRM with relatively low magnetic coupling between phase coils by operating in artificial magnetomoving force dissymmetry mode. In this case every phase coil is supplied by singular semiconductor switch. It is required to increase current in coil where the air gap distance is larger and to decrease current in coil with smaller air gap. It is also possible in closed-loop control system using the sensor of radial displacement to implement active magnetic levitation of the rotating rotor and to unload the bearings. Thus the vibration and noise will be reduced.

4. CONCLUSION

The specialty of the SRM magnetic systems wherein the phase coils have no magnetic coupling render possible to reduce the force of unilateral attraction rotor to stator connecting the phase coils in parallel. In this case the negative feedback between the air gap distance and unbalanced force of unilateral rotor attraction will be valid. In the case of supplying phase coil by singular semiconductor switch it is possible to compensate the forces of unilateral attraction almost completely in the same way that in active magnetic bearing. Creating conditions for bearing unload is especially relevant for high-duty electric machines operating in extreme duty cycles. Proposed solutions will make possible to reduce the SRM vibroactivity and noise as consequence.

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