Journal of Engineering and Applied Sciences 10 (2): 28-32, 2015
ISSN: 1816-949X

Analytic Model of Electromagnetic Processes in Switched Reluctance Machines 18/15 Configuration

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Abstract: This study presents developing an analytical model for switched reluctance machines. The analytic model for the six-phase SRM of 18/15 configuration has been developed with account of the mutual inductance between the phases.

Key words: Switched reluctance machines, mutual inductance, analytical model, account, machines

INTRODUCTION

Switched Reluctance Machines (SRM) are designed as a high-quality type of electromechanical energy converter and can be applied to the industrial transport. The main distinguishing feature of SRM is the lack of winding at the toothed rotor. In comparison with electrical machines of another types, SRM is structurally simpler and technologically effective, it has less copper and insulating materials consumption when almost identical masses of electrical steel. As a result, it makes possible to achieve higher energy and weight-size parameters to reduce the cost of electrical machines and expenses for their operation.

During SRM modelling and designing it is usually assumed that all machine's phases are independent both in electrical and magnetic relation. It is accepted that mutual inductance is low in these machines and it can be ignored. However, at the present time researchers are having tendency to take into account the mutual influence of phases for classical SRM (Fleury *et al*., 2010; Feyzi *et al*., 2009; Alrifai *et al*., 2008; Bae, 2000; Liu and Pillay, 2004; Grebennikov, 2011). This mutual interaction gives the positive effect as a rule the power of the machine is increased by 5-15%.

This study is focused on "non-classical" SRM of 18/15 configuration. It is a six phase machine which contains 18 teeth at the stator and 15 teeth at the rotor. There are 18 concentrated coils at the stator (three coils per one phase located at the stator poles, the angle between them is 120°). The passive rotor has no winding and commutator and brush assembly. This configuration provides a strong magnetic coupling between phases of the machine that must be considered when modelling.

ANALYTIC MODEL

For magnetic characteristics calculation of SRM 18/15 configuration (Grebennikov, 2011; Grebennikov and Petrushin, 2012), Finite Element Method Magnetics (FEMM) package was used. The distribution pattern of the magnetic field lines to the SRM 18/15 configuration is shown in Fig. 1.

It is obvious that all coils within one phase are connected in opposite direction. Magnetic flow generated by phase A is completely run through adjacent phases (B, C, D, E, F). As the result of SRM 18/15 calculation it was received the relation of self and mutual flux linkages with other phases presented in Fig. 2. It is obvious that intensity of mutual flux linkages reaches 50% of its own.

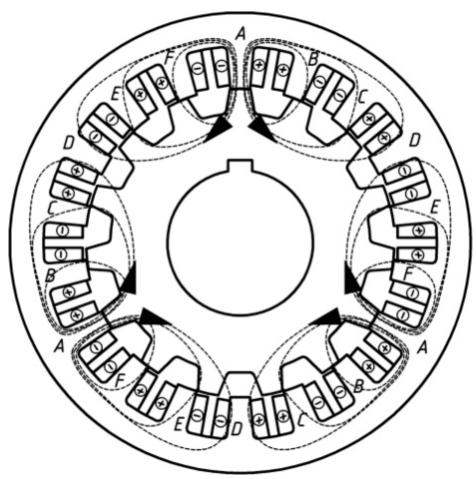

Fig. 1: Layout of coils and distribution of magnetic field lines in SRM 18/15 configuration under operation of phase A

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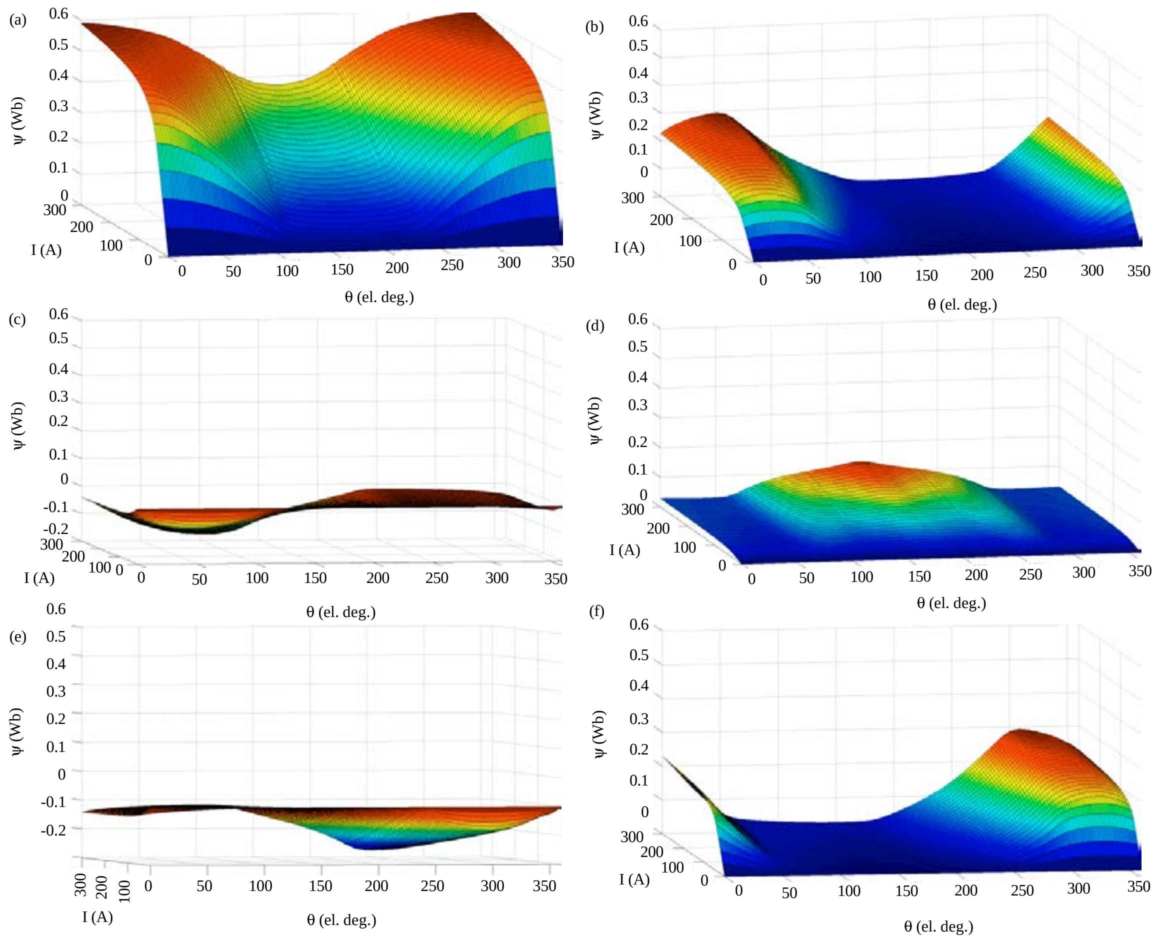

Fig. 2: The relation of self and mutual flux linkages of SRM 18/15: a) Flux linkages of phase A $\psi_{AA} = f(i_A, \theta)$; b) Flux linkages of phase A with phase B $\psi_{AB} = f(i_A, \theta)$; c) Flux linkages of phase A with phase C $\psi_{AC} = f(i_A, \theta)$ d); Flux linkages of phase A with phase D $\psi_{AD} = f(i_A, \theta)$; e) Flux linkages of phase A with phase E $\psi_{AE} = f(i_A, \theta)$ and f) Flux linkages of phase A with phase F $\psi_{AF} = f(i_A, \theta)$

Based on diagrams analysis given above, it follows that the considered SRM has intense mutual influence between phases. At the same time as can be seen there is a significant impact on the adjacent phases of the machine. SRM equation, taking into account the mutual inductance of each phase is presented as:

$$u = R \cdot i + \frac{d\psi\left(\sum_{k=1}^{m} i_k, \theta\right)}{dt} \tag{1}$$

Where:

u = Phase voltage
R = Phase resistance
i = Phase current
$\psi(\sum_{k=1}^{m} i_k, \theta)$ = Phase flux linkages (in our case it is a function of seven variables)
m = Number of phases
k = Phase number of electrical machine

SRM18/15 configuration is made as a “non-classical” machine. It is provided with three coils in a phase generated opposite magnetic flows closing via adjacent phases. Therefore, the modelling of this machine should take into account the interaction between adjacent phases. The interaction between phases can be classified into two categories:

- Mutual inductance influence
- Mutual saturation influence

Mutual inductance is due to the field overlap through another phase. Mutual saturation is the impact of magnetizing force of one phase on the saturation of the other one. The level of saturation impacts on flux linkages and torque at the shaft of electrical machine. We can write down the system of equations for six phase machine having 18/15 configuration. Let us assume that the adjacent phases have significant impact on the considered phases and the rest of phases do not have any strong influence:

$$\begin{aligned} u_A &= R_A \cdot i_A + \frac{d\psi_A}{dt},\ u_B = R_B \cdot i_B + \frac{d\psi_B}{dt} \\ u_C &= R_C \cdot i_C + \frac{d\psi_C}{dt},\ u_D = R_D \cdot i_D + \frac{d\psi_D}{dt} \\ u_E &= R_E \cdot i_E + \frac{d\psi_E}{dt},\ u_F = R_F \cdot i_F + \frac{d\psi_F}{dt} \end{aligned} \quad (2)$$

Where:

$$\begin{aligned} \psi_A &= \psi_{FA} + \psi_{AA} + \psi_{BA} \\ \psi_B &= \psi_{AB} + \psi_{BB} + \psi_{CB} \\ \psi_C &= \psi_{BC} + \psi_{CC} + \psi_{DC} \\ \psi_D &= \psi_{CD} + \psi_{DD} + \psi_{ED} \\ \psi_E &= \psi_{DE} + \psi_{EE} + \psi_{FE} \\ \psi_F &= \psi_{FE} + \psi_{FF} + \psi_{AF} \end{aligned} \quad (3)$$

Write Eq. 3 through inductance:

$$\begin{aligned} \psi_A &= M_{FA} \cdot i_F + L_A \cdot i_A + M_{BA} \cdot i_B \\ \psi_B &= M_{AB} \cdot i_A + L_B \cdot i_B + M_{CB} \cdot i_C \\ \psi_C &= M_{BC} \cdot i_B + L_C \cdot i_C + M_{DC} \cdot i_D \\ \psi_D &= M_{CD} \cdot i_C + L_D \cdot i_D + M_{ED} \cdot i_E \\ \psi_E &= M_{DE} \cdot i_D + L_E \cdot i_E + M_{FE} \cdot i_F \\ \psi_F &= M_{FE} \cdot i_E + L_F \cdot i_F + M_{AF} \cdot i_A \end{aligned} \quad (4)$$

where, M_{jk} mutual inductance between phases, Lk phase inductivity. Since, all phases of the machine consist of identical coils, it can be assumed that the resistance of each phase is the same:

$$R_A = R_B = R_C = R_D = R_E = R_F = R$$

Given the facts that overlap in the phase operation is 120° and the area of generator and traction modes is 180° then simultaneously not more than three phases of machine will operate in nominal mode. Thus:

$$\begin{aligned} u_Z &= R \cdot i_Z + \frac{d\psi_Z}{dt} \\ u_X &= R \cdot i_X + \frac{d\psi_X}{dt} \\ u_Y &= R \cdot i_Y + \frac{d\psi_Y}{dt} \\ u_{Y+1} &= \frac{d\psi_{Y+1}}{dt} \\ u_{Y+2} &= \frac{d\psi_{Y+2}}{dt} \\ u_{Y+3} &= \frac{d\psi_{Y+3}}{dt} \end{aligned} \quad (5)$$

where, flux linkage with analogue of Eq. 4 will be the following:

$$\begin{aligned} \psi_Z &= M_{YZ} \cdot i_Y + L_Z \cdot i_Z + M_{XZ} \cdot i_X \\ \psi_X &= M_{ZX} \cdot i_Z + L_X \cdot i_X + M_{YX} \cdot i_Y \\ \psi_Y &= M_{XY} \cdot i_X + L_Y \cdot i_Y + M_{ZY} \cdot i_Z \\ \psi_{(Y+1)} &= M_{X(Y+1)} \cdot i_X + M_{Y(Y+1)} \cdot i_Y + M_{Z(Y+1)} \cdot i_Z \\ \psi_{(Y+2)} &= M_{X(Y+2)} \cdot i_X + M_{Y(Y+2)} \cdot i_Y + M_{Z(Y+2)} \cdot i_Z \\ \psi_{(Y+3)} &= M_{X(Y+3)} \cdot i_X + M_{Y(Y+3)} \cdot i_Y + M_{Z(Y+3)} \cdot i_Z \end{aligned} \quad (6)$$

where, indexes Z, X and Y correspond with combination of phase operation (F, A, B), (A, B, C), (B, C, D), (C, D, E), (D, E, F) и (E, F, A). As was mentioned above, the considered machine has a strong mutual phase influence, it is therefore necessary to review the mutual inductance as a function of four variables:

$$\begin{aligned} M_{XY} &= f(i_X, i_Y, i_Z, \theta) \\ M_{YX} &= f(i_X, i_Y, i_Z, \theta) \\ M_{YZ} &= f(i_X, i_Y, i_Z, \theta) \\ M_{ZY} &= f(i_X, i_Y, i_Z, \theta) \\ M_{ZX} &= f(i_X, i_Y, i_Z, \theta) \\ M_{XZ} &= f(i_X, i_Y, i_Z, \theta) \end{aligned}$$

As far as the magnetic system of the machine is symmetric and the return period is 60°, we can write the following:

$$\begin{aligned} L_X &= f(i_X, i_Y, i_Z, \theta) \\ L_Y &= L_X(i_X, i_Y, i_Z\ (300+\theta)) \\ L_Z &= L_X(i_X\ i_Y, i_Z(\theta+60)) \\ M_{XY} &= f(i_X, i_Y, i_Z, \theta) \\ M_{YX} &= M_{XY}(i_X, i_Y, i_Z\ (300+\theta)) \\ M_{YZ} &= M_{XY}(i_X, i_Y, i_Z\ (\theta+60)) \\ M_{ZY} &= M_{XY}(i_X, i_Y, i_Z\ (120\text{-}\theta)) \\ M_{ZX} &= M_{XY}(i_X, i_Y, i_Z\ (\theta+120)) \\ M_{XZ} &= M_{XY}(i_X, i_Y, i_Z\ (360\text{-}\theta)) \end{aligned}$$

Therefore, for complete computer simulation of this machine, it is necessary to get additionally by means of Finite Element Method the relation of $\psi_X = f(i_X, i_Y, i_Z, \theta)$ or $L_X = f(i_X, i_Y, i_Z, \theta)$, $\psi_{XY} = f(i_X, i_Y, i_Z, \theta)$ or $M_{XY} = f(i_X, i_Y, i_Z, \theta)$. The application of FEMM package gives the possibility to get immediately the following relations:

$$\begin{aligned} &\psi_X = f(i_X, i_Y, i_Z, \theta),\ \psi_Z = f(i_X, i_Y, i_Z, \theta) \\ &\psi_Y = f(i_X, i_Y, i_Z, \theta),\ \psi_{Y+1} = f(i_X, i_Y, i_Z, \theta) \\ &\psi_{Y+2} = f(i_X, i_Y, i_Z, \theta),\ \psi_{Y+3} = f(i_X, i_Y, i_Z, \theta) \end{aligned}$$

Let differentiate Eq. 6:

$$\frac{d\psi_Z}{dt} = M_{YZ}\frac{di_Y}{dt} + \frac{\partial M_{YZ}}{\partial\theta}\omega i_Y + L_Z\frac{di_Z}{dt} + \frac{\partial L_Z}{\partial\theta}\omega i_Z + M_{XZ}\frac{di_X}{dt} + \frac{\partial M_{XZ}}{\partial\theta}\omega i_X$$

$$\frac{d\psi_X}{dt} = M_{ZX}\frac{di_Z}{dt} + \frac{\partial M_{ZX}}{\partial\theta}\omega i_Z + L_X\frac{di_X}{dt} + \frac{\partial L_X}{\partial\theta}\omega i_X + M_{ZX}\frac{di_Z}{dt} + \frac{\partial M_{ZX}}{\partial\theta}\omega i_Z$$

$$\frac{d\psi_Y}{dt} = M_{XY}\frac{di_X}{dt} + \frac{\partial M_{XY}}{\partial\theta}\omega i_{YX} + L_Y\frac{di_Y}{dt} + \frac{\partial L_Y}{\partial\theta}\omega i_Y + M_{ZY}\frac{di_Z}{dt} + \frac{\partial M_{ZY}}{\partial\theta}\omega i_Z$$

where, $\omega = d\theta/dt$. The torque (electromagnetic) depending on phase current and rotor position can be expressed in terms of coenergy. In our case the coenergy differential is:

$$dW_c(i_X, i_Y, i_Z, \theta) = \psi_X di_X + \psi_Y di_Y + \psi_Z di_Z + T_e d\theta \quad (7)$$

where, T_e electromagnetic torque of machine. The coenergy for the proposed machine can be found by integration (Eq. 7) along the outline by analogy with (Bae, 2000). The integration path is selected in the following way:

- Integrate by rotation angle at zero current in all phases ($i_X = 0$, $i_Y = 0$, $i_Z = 0$)
- Integrate by i_Z, keeping zero currents in the other two phases ($i_X = 0$, $i_Y = 0$) and rotation angle θ as constant
- Integrate by i_Y, keeping zero current in phase X ($i_X = 0$), rotation angle θ and i_Z as constant
- Integrate by i_X, rotation angle θ, i_Y and i_Z are constant

At the first stage of integration the torque integral is zero, since the torque is zero at zero phase currents ($i_X = 0$, $i_Y = 0$, $i_Z = 0$) at the following stages this integral is zero because the rotation angle θ is constant. After integrating we receive the expression for coenergy of the considered machine when three phases operate simultaneously:

$$\begin{aligned} W_c(i_X, i_Y, i_Z, \theta) &= \int_0^{\theta} T_e(0,0,0,\xi)d\xi + \int_0^{i_Z} \psi_Z(0,0,\xi,\theta)d\xi + \int_0^{i_Y} \psi_Y(0,\xi,i_Z,\theta)d\xi + \int_0^{i_X} \psi_X(\xi,i_Y,i_Z,\theta)d\xi \\ &= 0 + \int_0^{i_Z} L_Z\xi d\xi + \int_0^{i_Y} (L_Y\xi + M_{ZY}i_Z)d\xi + \int_0^{i_X} (L_X\xi + M_{YX}i_Y)d\xi \\ &= \frac{1}{2}L_X i_X^2 + \frac{1}{2}L_Y i_Y^2 + \frac{1}{2}L_Z i_Z^2 + M_{ZY}i_Y i_Z + M_{YX}i_X i_Y \end{aligned}$$

where, ξ, integration variable takes the following values θ, i_Z, i_Y, i_X in order for integrals. Then for electromagnetic torque calculation we get the final expression:

$$\begin{aligned} T_e &= \left.\frac{\partial W_c(i_X, i_Y, i_Z, \theta)}{\partial\theta}\right|_{i_X, i_Y, i_Z} \\ &= \frac{1}{2}\frac{\partial L_X}{\partial\theta}i_X^2 + \frac{1}{2}\frac{\partial L_Y}{\partial\theta}i_Y^2 + \frac{1}{2}\frac{\partial L_Z}{\partial\theta}i_Z^2 + \frac{\partial M_{ZY}}{\partial\theta}i_Y i_Z + \frac{\partial M_{YX}}{\partial\theta}i_X i_Y \end{aligned} \quad (8)$$

Therefore, the torque of six-phase SRM 18/15 configuration is expressed in terms of phase currents and rotor rotation angle. The effect of mutual inductance is considered in two last members of sum in the expression (Eq. 8).

CONCLUSION

Expression analysis (Eq. 8) shows the positive effect from the strong mutual inductance between the phases of SRM. In addition the positive result was confirmed by testing of two machine prototypes having 18/12 and 18/15 configurations in which it was defined that when the same stator, the power and efficiency factor is higher at SRM of 18/15 configuration. However, the strong mutual inductance has the impact on control parameters and this fact requires the application of more complicated control algorithms considering the processes occurring in all phases.

ACKNOWLEDGEMENT

The presented research has been developed with support of Russian Ministry of Education, grant RFMEFI57614X0036.

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