Development of Switched Reluctance Machines Model in MATLAB/Simulink

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Abstract: It is profitable to carry out the research of dynamic electromechanical processes in Switched Reluctance Machines (SRM) by using mathematic modeling. The development of switched reluctance machine's computer modeling is performed by MATLAB/Simulink software tool. The initial data for SRM modeling is the calculation results of magnetic system run by finite elements method. The implementation of the model designed along with Toolbox MATLAB-SimPowerSystems allows us to develop and research the models of different motor drive systems equipped with SRM as well as models of vehicle electrical power transmission.

Key words: Switched reluctance machines, mutual inductance, analytical model, electromechanical, MATLAB

INTRODUCTION

In recent decades designers have been drawing their attention to inductor motor drives equipped with Switched Reluctance Machines (SRM). Energy efficiency improvement of traction systems with SRM is mostly defined by high value of efficiency factor of electrical machine-about 96% (Miller, 1993). Designing new electromechanical systems it is necessary to take into account dynamic processes flowing in electrical circuits and mechanical part of the system. The research of given processes should be performed by applying Mathematical Modeling. The given study describes the implementation of SRM mathematical model in MATLAB/Simulink Software package.

Switched reluctance machine operating principle: Figure 1 shows SRM consisting of salient-pole stator and rotor. At the stator's pole, there are concentrated phase windings while rotor does not have any windings. The SRM phase as a rule consists of two coils located at the opposite poles. Depending on rotor position, phase flux linkages vary several-fold. The scheme of phase substitutionn is given at Fig. 2. Differential equation describing the electrical processes in SRM phase is the following:

$$u = R \times i + \frac{d\psi(\theta, i)}{dt} \quad (1)$$

Where:
u = Voltage across the phase (applied to phase)
I = SRM phase current
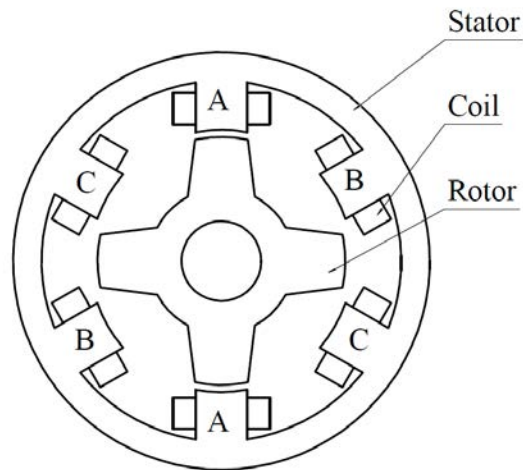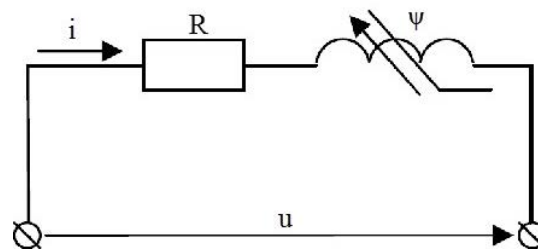Ψ = Phase flux linkage

Fig. 1: SRM arrangement

Fig. 2: Substitution scheme of SRM phase

SRM is a mechanical power converter, so in the model it is also required to link the mechanical processes

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and processes flowing in electrical circuits. Movement equations describing the rotational motion are given below:

$$J\frac{d\omega}{dt} = T_e(\theta,i) - T_1 - T_e \tag{2}$$

$$\frac{d\theta}{dt} = \omega \times N_R \times 180 / \pi \tag{3}$$

Where:

ω = Rotor rotational frequency
T_e = SRM electromagnetic torque
T_1 = Resistance torque of steel loss
T_e = External torque (it is positive in motor mode and negative in generator mode)
J = Equivalent moment of rotor inertia
θ = Angular rotor position against stator, electric degree
N_R = Number of rotor's tooth

In order to solve the equation system it is required initially to get the following relationships of flux linkage and electromagnetic torque depending on angular position and phase current:

$$\psi = f_1(\theta,i) \tag{4}$$

$$T = f_2(\theta,i) \tag{5}$$

Relationships Eq. 4 and 5 are highly non-leaner which is defined by SRM operating principle and its geometric features. The equation for instantaneous electromagnetic torque (Eq. 6) can be calculated by using the flux linkage derivative with respect to rotor's turning angle:

$$T_e(\theta,i) = i\frac{\partial\psi(\theta,i)}{\partial\theta} \tag{6}$$

Therefore, the initial data for modeling is the main design characteristics of SRM as well as the relationship of flux linkage against angular position and phase current $\psi = f_1(\theta,i)$. The last one should be calculated by finite elements method.

MATERIALS AND METHODS

Computer model: Simulink package of Matlab software has all necessary capabilities to develop SRM computer model (Grebennikov and Kireev, 2014, 2015; Petrushin *et al.*, 2015). SRM phase is simulated as a controlled current source (Fig. 3) connected to active resistance of big nominal value.
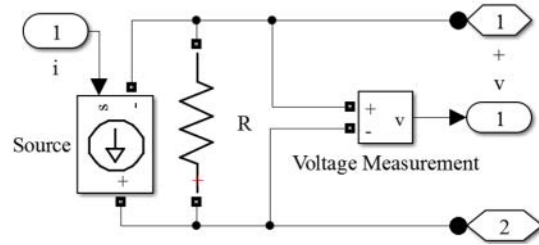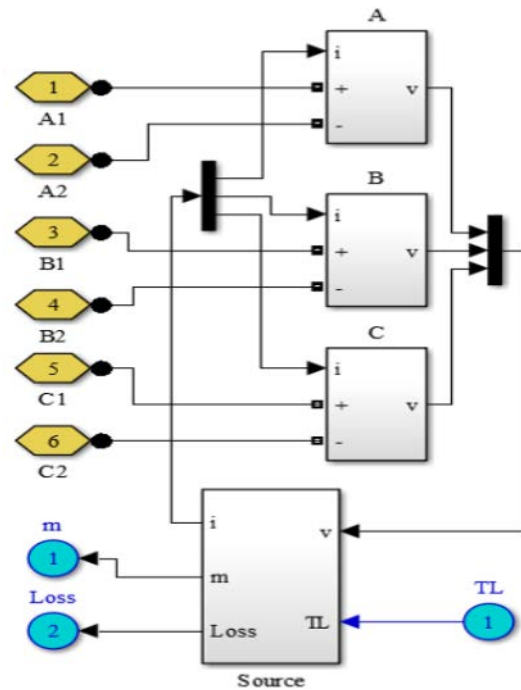

Fig. 3: SRM phase model

Fig. 4: SRM model

Where input i is supplied with the current value obtained by solving of SRM differential Eq. 1 output u-voltage value applied to phase is transmitted to the block of differential equation solution. Terminals "+" and "-" are used for connection of SRM phase to power converter. Figure 4 presents the model of three-phase SRM. Blocks of (A-C) phases contain the model of SRM phase presented at Fig. 3. The solving of SRM differential equation is performed in Source block (Fig. 5).

Source block contains the blocks with tabular data of ITBL current depending on angular position and flux linkage as well as data of TTBL electromagnetic torque depending on angular position and current. Solving of SRM differential equation is performed in the following way. The voltage value v serves as an input signal which is a composed signal and it contains data about voltage
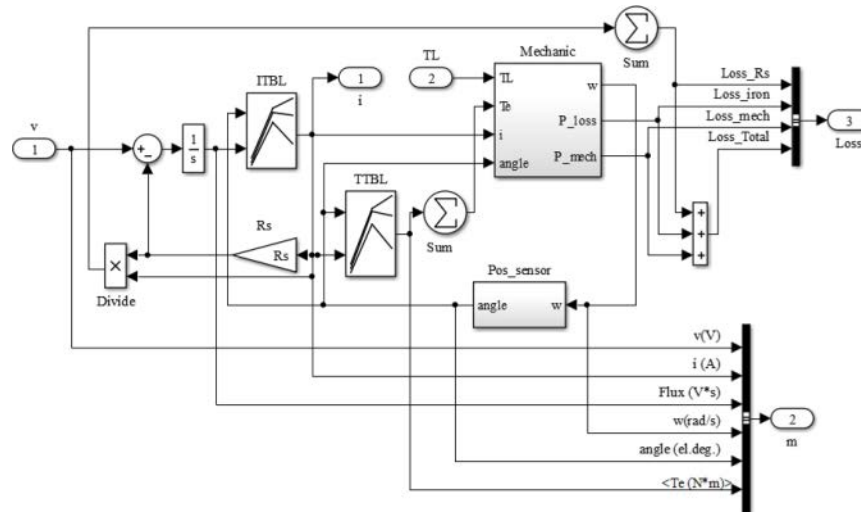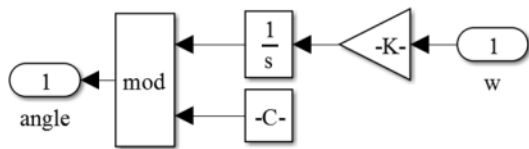
Fig. 5: Source block structure

Fig. 6: Pos_sensor block structure

of all SRM phases. The solution processing is performed by cycle searching through all signal components. The received signal goes to summation block where the voltage loss value at the active resistance of Rs phase is subtracted from the current voltage value. As the result the rest voltage value goes for incrementation of flux linkage (voltage integral). As a consequence of voltage value integration we receive the instantaneous value of flux linkage. Having the values of flux linkage, current rotor position relative to stator and the tabular data of magnetization curves we define the value of phase current and transfer it to output i of Source block. This is the way how the current source is controlled in the model of SRM phase (Fig. 4).

The flux linkage and electromagnetic torque depend on rotor angular position which is defined by Pos_sensor while solving the Eq. 3. Pos_sensor block (Fig. 6) executes the integration of angular speed and as a result we receive the turning angle value of rotor relative to stator. Using the conversion coefficient K, depending on the number of rotor tooth, we get the rotor angular position in electrical degrees. Mod block is used to design the developed view of angular position (in the range from 0-360 el.deg) depending on time (Fig. 7).

TTBL block defines the instantaneous electromagnetic torque of each phase by tabular data. The
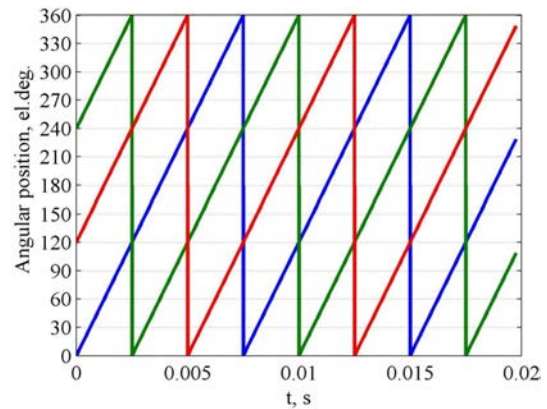

Fig. 7: Developed view of angular position depending on time

values of phase torques are transferred to complex output m (Fig. 5). The sum of phase torques arrives to Mechanic block (Fig. 8) where the mechanic equation and steel loss calculation are performed. Within Mechanic block the motion Eq. 2 is solved and the steel loss reduced to resistance torque is defined. Magnetic loss consists of hysteresis loss (due to the steel magnetic reversal) and eddy-current loss. Definition of magnetic loss in SRM runs into difficulties because of unsinusoidality of magnetic induction changes. At the same time for approximate evaluation of magnetic loss in SRM it can be used the formulas, applied for a calculation of loss in typical electrical machines (Kuznetsov and Kuz'michev, 2003) with specification of coefficients included in these formulas taking into account existing SRM design experience.
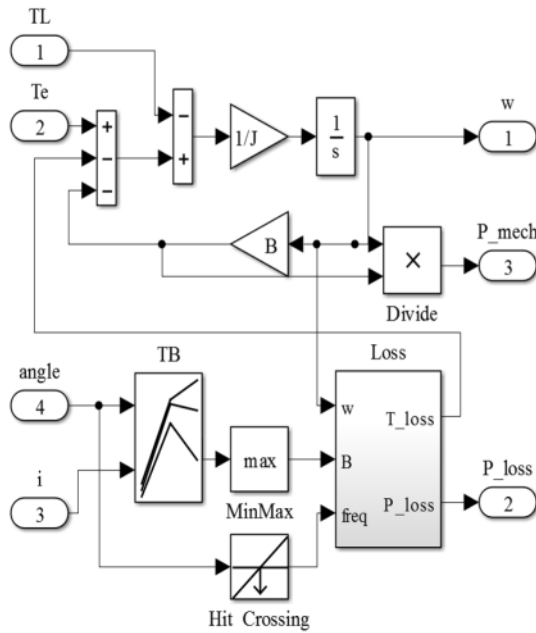
Fig. 8: Mechanic block structure

RESULTS AND DISCUSSION

Let us define the induction at the steel parts of magnetic circuit:

At the stator yoke:

$$\mathbf{B}_{aS} = \mathbf{B}_{ZS} \frac{b_{ZS}}{2h_{aS}}$$

At the rotor tooth:

$$B_{ZR} = B_{ZS} \frac{b_{ZS}}{b_{ZR}}$$

At the rotor yoke:

$$B_{aR} = B_{ZS} \frac{b_{ZS}}{2h_{aR}}$$

Where:
B_{ZS} = Induction in stator tooth
b_{ZS} = Stator tooth width
h_{aS} = Height of stator yoke
b_{ZR} = Rotor tooth width
h_{aR} = Height of rotor yoke

These formulas indicate that to define induction in the parts of magnetic circuit it is required to know the induction at stator tooth. To specify this data TB block (Fig. 8) is used, containing the tabular data of induction in the stator tooth depending on current and angular rotor position. This data can be obtained by finite elements method to determine magnetization curves. In this case the stator steel loss is:
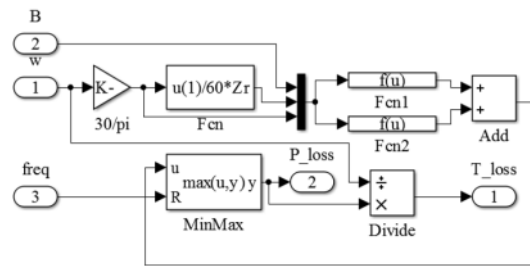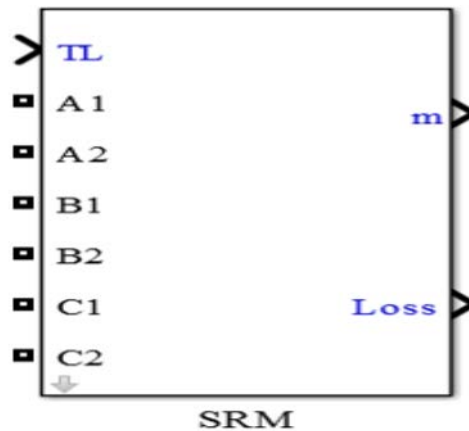

Fig. 9: Loss block structure

Fig. 10: SRM model generated by software package MATLAB/Simulink

$$P_{CS} = \frac{P_{sp}}{B_n^2} \left(\frac{f_{CS}}{f_n} \right)^{1.3} \left(k_{da} B_{aS}^2 m_{aS} + k_{dZ} B_{ZS}^2 m_{ZS} \right)$$

Where:
K_{da}, K_{dZ} = Coefficients considering the loss increasing in the steel yoke and SRM tooth due to the impact of technology factors
P_{sp} = Specific loss for chosen steel grade
B_n, f_n = Induction and frequency at which the specific loss determined P_{sp}

Rotor steel loss:

$$P_{CR} = \frac{P_{sp}}{B_n^2} \left(\frac{f_{CR}}{f_n} \right)^{1.3} \left(k_{da} B_{aR}^2 m_{aR} + k_{dZ} B_{ZR}^2 m_{ZR} \right)$$

Steel loss:

$$P_C = P_{CS} + P_{CR}$$

Solving of given equation is performed in loss block (Fig. 9). The needed parameters are transferred as input values to the complex output m (Fig. 5). For further operability of developed model we can create the subsystem with a mask for input of SRM initial data. The overall view generated by software package MATLAB/Simulink presents at Fig. 10.
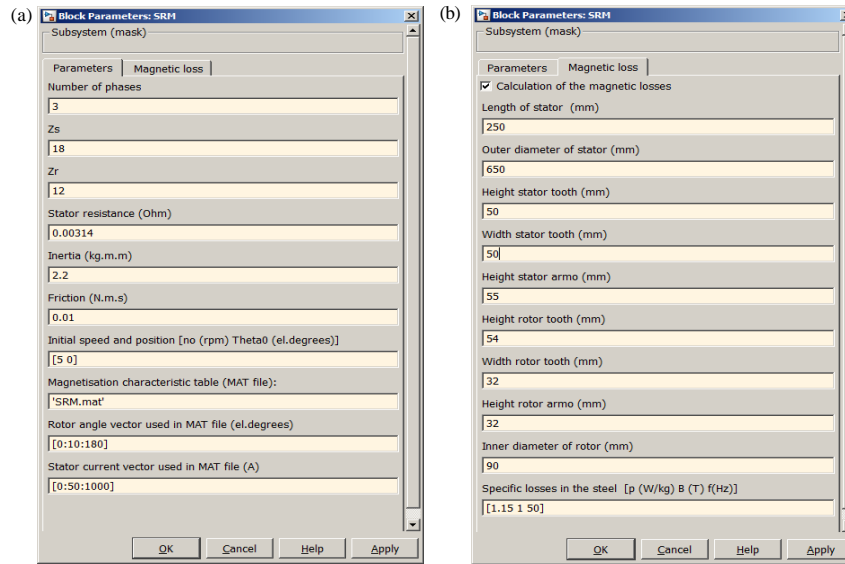
Fig. 11: Input data of SRM block

TL input is designed for external torque supply. Outputs A1, A2, B1, B2, C1, C2 are the outputs of SRM phases and used for connection the model to power converter. Output m is a complex one and it is used for transmission of the following signals: phase voltage and current, phase electromagnetic torques, flux linkage, angular position, rotation frequency. Output Loss contains data about electric and magnetic losses in SRM. The writing of input data into SRM block is conveniently to carry out through the block mask given at Fig. 11a, b.

Figure 11a, b presents the parameters given the complete description of the studied electrical machine. In the first property page parameters the following values are set: the number of phases, stator tooth and rotor tooth, stator active resistance, moment of inertial, resistance in the mechanical part, initial angular speed and angular position, a file with magnetization curves for given SRM, vector of angular position values and vector of current values for which the magnetization curves are calculated in the given file. The second property page magnetic loss gives the following parameters needed for calculation of magnetic loss appearing in stator and rotor: the stator length, the external diameter of the stator, the stator tooth height, the stator tooth width, the height of stator yoke, the rotor tooth height, the rotor tooth width, the height of rotor yoke, internal rotor diameter, properties of steel used for magnetic circuit of electric machine.

CONCLUSION

This study presents the development of SRM computer model by means of MATLAB/Simulink Software tool. The specific feature of this model is that the initial data for modeling is the result of calculation of motor magnetic system performed by finite elements method. This approach provides high accuracy in modeling of dynamic electromechanical processes. Application of this model in conjunction with Toolbox SimPowerSystems allows us to develop and research the models of different motor drive systems equipped with SRM as well as models of vehicle electrical power transmission.

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