전력전자학술대회 논문집 2004. 7.12 ~ 7.15

SRM 해석의 수학적 모델

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Mathematical Models for the Analysis of a SRM

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ABSTRACT

The mathematical models of the Switched Reluctance machine system integrating the state equation of the phase current with the two dimensions finite element model of the machine are advanced, no matter what the topologies of the main circuit of the power converter and the control strategies are adopted in the system. Based on the mathematical models, the comparison of the simulated and the tested results of a three-phase Switched Reluctance motor drive prototype system are given. The simulated results of the prototype tally with the tested results of the prototype. It is shown that the mathematical models have the advantage in high precision.

Ⅰ. INTRODUCTION

The Switched Reluctance machine system is a mechatronics device with the reluctance machine, the power converter and the controller. It is important to design and analyze the system based on the precise models. The mathematical models of the machine and the power converter have been set up, respectively, which are given in some literatures. The research on the optimum design method of the system, that the design of the machine, the power converter and the control strategy could be well coordinated, is one of the most important research orientations at present. The establishment of the systematical mathematical models is the major basis of doing the optimum design of the system. The paper gives the systematical mathematical models that are based on the integral whole of the machine, the power converter and the control strategy.

The reluctance machine in the system is a double salient machine. The numbers of stator poles in the machine is even number, and the numbers of rotor poles is also even number. There are some common schemes of the numbers of the stator poles and the rotor poles, such as the three-phase 6/4 structure machine, the four-phase 8/6 structure machine, and so on. There is a coil in per stator pole. There is no winding, no magnet and no brush in the rotor.

The phase windings of the machines are excited by the unipolar current with the unipolar power converter. There are some types of the power converter, such as the asymmetric bridge power converter, the bifilar winding power converter, the split supply power converter, the inductance commutation power converter, the resistance commutation power converter, the common switch power converter, and so on. There are some main switches and some flywheel diodes in the main circuit of the power converters.

There are some control parameters for the electromagnetic torque control and the rotor speed control of the machines, such as the amplitude of the phase current, the turn-on angle of the main switches, the turn-off angle of the main switches, and the average supplied voltage of the phase windings. The control strategies are as follows, such as the current chopping control, the angle position control and the pulse width modulation control.

II. MATHEMATICAL MODELS

The Switched Reluctance machine system is a nonlinear system. The iron core of the machine has the nonlinear magnetic characteristics. The machine has the nonlinear magnetic field distribution. The main circuit of the power converter is a nonlinear network. The developed mathematical models of the system integrate the state equation of the phase current with the two dimensions finite element model of the machine.

The flux linkage could be expressed as follows,

$$\psi = \frac{Nl}{3S}\sum (A_i\Delta_i - A_k\Delta_k) \tag{1}$$

Where, N is the turn numbers of each phase winding, S is the exciting source area of stator pole at one side, l is the effective length of iron core of the machine, Δ_i and Δ_k is the area of the split element at the right side of the stator poles and at the left side of the stator poles in the electromagnetic calculation of the reluctance machine with the two dimensions finite element method, respectively. A_i and A_k is the vector potential of the split element at the right side of the stator poles and at the left side of the stator poles, respectively, and,

$$\begin{cases} \frac{\partial}{\partial x}(\gamma\frac{\partial A}{\partial x}) + \frac{\partial}{\partial y}(\gamma\frac{\partial A}{\partial y}) = -J \\ A\,|_{D_2, d_2} = 0 \end{cases} \tag{2}$$

Where, γ is the permeability, J is the excited current density of the stator phase winding, D_2 is the boundary of the stator outer diameter, d_2 is the boundary of the rotor bore diameter, A is the vector potential, and the calculated domain of the reluctance machine is shown in Fig.1.

Neglecting the mutual inductance, and no matter what the topologies of the main circuit of the power converter and the control strategies and adopted in the system, the state equation of the phase current in the Switched Reluctance machine system is as follows,

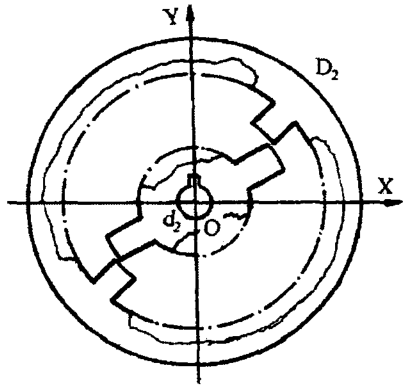


Fig. 1. The calculated domain of the switched reluctance machine

$$\begin{bmatrix} \frac{di_1}{dt} \\ \frac{di_2}{dt} \\ \frac{di_3}{dt} \end{bmatrix} = \begin{bmatrix} \frac{R}{\frac{\partial\psi}{\partial i_1}} & 0 & 0 \\ 0 & \frac{R}{\frac{\partial\psi}{\partial i_2}} & 0 \\ 0 & 0 & \frac{R}{\frac{\partial\psi}{\partial i_3}} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} + \begin{bmatrix} \frac{1}{\frac{\partial\psi}{\partial i_1}} & -\frac{a}{\frac{\partial\psi}{\partial i_1}} & 0 \\ 0 & -\frac{c}{\frac{\partial\psi}{\partial i_2}} & -\frac{d}{\frac{\partial\psi}{\partial i_2}} \\ -\frac{g}{\frac{\partial\psi}{\partial i_3}} & 0 & -\frac{b}{\frac{\partial\psi}{\partial i_3}} \end{bmatrix} \begin{bmatrix} U_S \\ U_T \\ U_D \end{bmatrix} - \frac{\pi n}{30} \begin{bmatrix} \frac{\partial\psi}{\partial\theta}\cdot\frac{1}{\frac{\partial\psi}{\partial i_1}} \\ \frac{\partial\psi}{\partial\theta}\cdot\frac{1}{\frac{\partial\psi}{\partial i_2}} \\ \frac{\partial\psi}{\partial\theta}\cdot\frac{1}{\frac{\partial\psi}{\partial i_3}} \end{bmatrix} \tag{3}$$

Where, i_1 is the phase current during the period of supply, i_2 is the phase current while the power supply could not be continued naturally, i_3 is the phase current during the period of commutation. R is the phase resistance, U_s is the supply voltage of one phase circuit, U_T is the on-state voltage drop of the main switch, and U_D is the on-state voltage drop of the flywheel diode. θ is the rotor position, n is the rotor speed, and t is the time. a is the numbers of the main switches in one phase circuit during the period of supply, b is the numbers of the flywheel diodes in the per phase flywheel circuit during the period of commutation, c is the numbers of the main switches in per phase natural flywheel circuit, d is the numbers of the flywheel diodes in per phase natural flywheel circuit and,

$$g = \frac{U_C}{U_S} \tag{4}$$

Where, U_C is the commutation voltage.

Neglecting the stray loss and the mechanical power loss of the machine, the output torque of the system as a motor drive could expressed as follows,

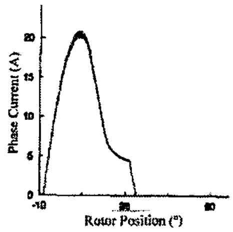
$$T_2 = m\frac{\partial W'}{\partial \theta}\bigg|_{i=const} \quad (5)$$

Where, m is the numbers of phase, W' is the co-energy in the magnetic field of the machine.

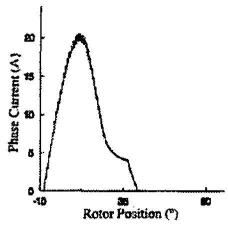
III. SIMULATION AND EXPERIMENTS

Based on the mathematical models, the comparison of the simulated and the tested results of a Switched Reluctance motor drive prototype system are given. The prototype is a kind of three-phase system, which consists of the three-phase 6/4 structure reluctance machine with 6 stator poles and 4 rotor poles, the three-phase asymmetric bridge power converter with 6 main switches and 6 flywheel diodes. The pulsewidth modulation control strategy is adopted in the prototype.

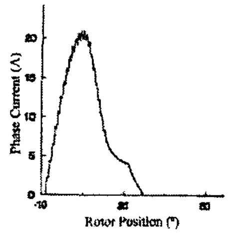
The supply voltage of one phase circuit is 513 V, and the commutation voltage is also 513 V. The on-state voltage drop of the main switch is 2.7 V, and the on-state voltage drop of the flywheel diode is 1.25 V. The turn-on angle of the main switches is fixed at $-7.5_\circ$, and the turn-off angle of the main switches is fixed at $37.5_\circ$ (While $\theta=0^0$ is the rotor position while the axis of the rotor slot is aligned with the axis of the stator pole of the conducted phase). The frequency of the pulsewidth modulation signal is 6 KHz. The simulated waveforms of the phase current, i, at the different output torque, T_2, and the different rotor speed, n, are shown in Fig.2, while, (a) n =520 r/min, T_2 = 14.37 $N\cdot m$, (b) n =1000 r/min, T_2 = 14.70 $N\cdot m$, (c) n =1500 r/min, T_2 =14.55 $N\cdot m$. The measured waveforms of the phase current at the same conditions are shown in Fig.3, while, (a) n = 520 r/min, T_2 =14.37 $N\cdot m$, (b) n = 1000 r/min, T_2 = 14.70 $N\cdot m$, (c) n = 1500 r/min, T_2 = 14.55 $N\cdot m$. It is shown that the simulated waveforms of the phase current are similar to the measured waveforms of the phase current at the same conditions.



(a)

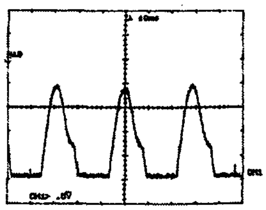


(b)

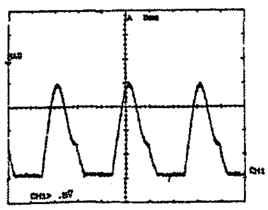


(c)

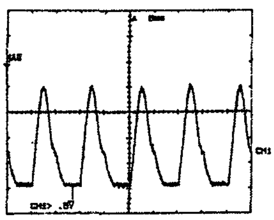
Fig.2. Simulated waveforms of the phase current



(a)



(b)



(c)

Fig.3. Measured Waveforms of the phase current
(a):Abscissa: 10.0 ms/div. Ordinate: 5.0 A/div
(b),(c):Abscissa: 5.0 ms/div. Ordinate: 5.0 A/div

Table I gives the calculated results and the tested results of the performance in the prototype. The calculated errors are within ±5%.

Table 1. Calculated Results and Tested Results of the Performance in the Prototype

Rotor Speed (r/min)	Output Torque (N.m)	Peak Value of Phase Current (A)			rms Value of Phase Current (A)			Systematical Efficiency (%)		
		Calculated	Tested	Error (%)	Calculated	Tested	Error (%)	Calculated	Tested	Error (%)
520	14.37	20.4	19.7	+3.6	9.89	9.70	+2.0	60.2	58.6	+2.7
1000	14.70	20.5	20.2	+1.5	9.49	9.20	+3.2	71.1	73.3	-3.0
1500	14.55	21.4	20.6	+3.9	9.25	9.06	+2.1	72.0	71.7	+0.4

IV. CONCLUSIONS

The Switched Reluctance machine system is a nonlinear system. The systematical mathematical models could be based on the integral whole of the reluctance machine, the power converter and the control strategy. The developed mathematical models of the system integrate the state equation of the phase current with the two dimensions finite element model of the machine. The simulated results of the prototype tally with the experimental results of the prototype. It is shown that the mathematical models have the advantage in high precision. The mathematical models are general for all types of the Switched Reluctance machine systems, no matter what the topologies of the main circuit of the power converter and the control strategies are adopted in the system.

본 연구는 과학재단 목적기초연구(No. R01-2001-0000300-0) 지원에 의해 수행되었음.

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