

The Simulation of Switched Reluctance Motor with the Rapid Nonlinear Method

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Abstract

Considering the significant magnetic saturation and the double salient poles of Switched Reluctance Motor (SRM), this paper presents a new method combining the Rapid Nonlinear Simulation Method with the Equivalent Magnet Circuit Analysis Model, which can make the accuracy and rapidity of the calculation of the performance of SRM achieved. This paper also presents a model of SRM, implements the rapid nonlinear simulation method to the model and lay the necessary foundation for SRM optimization.

Keywords: SRM, Equivalent Magnet Circuit Analysis, Rapid Nonlinear Simulation

1. Instruction

The switched reluctance motor (SRM) is simple, low cost, fault tolerant, and has simple converter and control requirements. The motor is suitable for many variable-speed and servo-type applications and is gaining increasing attention in the motor drive industry. However, the nonlinear magnetization characteristics of the SRM is one of the main disadvantages, which produced by piecewise first- or second-order function of flux linkage against rotor position. There are many ways to analyze the nonlinear magnetization characteristics, such as nonlinear magnet parameter analysis, rapid nonlinear theory analysis, equivalent magnet circuit analysis model, inductance parameter analysis and so on. The method of Nonlinear magnet parameter analysis is very accurate, but with great computation load and it only can be used to analyze the situation when one phase is in work; the algorithms of the rapid nonlinear theory analysis are extremely fast, but not enough accurate; performance characteristic can be analyzed by the inductance parameter method, however, increment inductance or average inductance is the function of winding current and rotor position, it is very difficult to calculate the inductance accurately; the precision of the equivalent magnet circuit analysis model is high and it can be applied to analyzed the situation when many phases are performed, but the disadvantage of this way is that it inquired greater computation. If more accurate mathematical model is established, it will result in greater computation and will slow the calculation speed due to significant nonlinear magnetization characteristics of SRM. So a better method should be found to establish mathematical model which not only own more precision character but also greater calculation speed. This paper presents a new method combining the rapid nonlinear simulation method with the equivalent magnet circuit analysis model. It can make the accuracy and the rapidity of the calculation of the performance of switched reluctance motor achieved and laid the necessary foundation for SRM optimization.

2. The Foundation of Equivalent Magnet Circuit Analysis Model of SRM

Phase linkage is concerned when establishing the equivalent magnet circuit analysis model and variable structure model and it is proposed in article (Miller T J E, McGilp M. 1990). With the introduction of "overlapping unit and equivalent magnet circuit" (F. Filicori et al. 1993), equivalent magnet circuit analysis model four-phase motor is found. The parameters of the model are defined in Figure 1.

$G_1 \sim G_4$ are the equivalent permeances of the overlapping unit, we can obtain them as follows:

$$G_i = \Phi(F, \theta) / F \quad (i=1,2,3,4)$$

$\Phi(F, \theta)$ is equivalent magnetic flux of the overlapping unit and F is the magnetic potential drop between different equivalent surface of the overlap unit. $G_5 \sim G_8$ are the equivalent permeances of the stator-pole root segment,

$$G_i = \mu_{Fe} B_p L_s / (0.5 H_p) \quad (i = 5, 6, 7, 8)$$

μ_{Fe} is the magnetic permeability of core, B_p, H_p are stator-pole width and stator-pole height respectively.

L_s is the length of the core. G_{sl} is the equivalent linkage permeance of the adjacent poles,

$$G_{sl} = 0.5 \mu_0 H_p L_s / B_0$$

μ_0 is the magnetic permeability of air, B_0 is average width of stator slot. $G_9 \sim G_{12}$ are the equivalent permeances of the stator yoke end respectively,

$$G_i = \mu_{Fe} A_c / L_c \quad (i = 9, 10, 11, 12)$$

A_c is equivalent sectional area of stator yoke end, L_c is the length of stator yoke end. $F_1 \sim F_4$ are magnetic potentials of stator concentrated winding,

$$F_k = NI_k \quad (k = 1, 2, 3, 4)$$

N is the number of turns of concentrated winding, I_k is phase current of the number k .

We can get the values of phase currents, torque and power through calculation after obtaining the equivalent permeance.

3. The Application of the Rapid Nonlinear Simulation Method to Equivalent Magnet Circuit Analysis Model of SRM

The structure of the model is shown in Fig2 for a single curve corresponding to a fixed value of current i . The key points along this curve are denoted by ξ , with appropriate subscripts, and the corresponding rotor positions are represented by the small diagrams below (Figure 2).

Region extends from the unaligned position $\xi_u (= \pi / N_r)$ to the 'corner point' ξ_1 , where the approaching corners of stator and rotor poles are aligned. Mechanical overlap begins at ξ_1 and continues until $\theta = \xi_a$ at the aligned position ($2\pi / N_r$), where the curve begins its descent along a mirror image of the curve between ξ_u and ξ_a . The overlap region is divided into regions and , with the dividing point ξ_1 and ξ_2 .

The modeling in the three regions will now be described, starting with region , which is simplest. When describing the region , ξ_1 and ξ_{hr} will be introduced from reference (B.K. Bose, T.J.E. Miller, 1986).

Region :

In region , the straight line relationship between ψ and θ is

$$\psi(\theta) = \psi_1 + k_a(\theta - \xi_1) \quad (1)$$

and the value of k_a can be obtained as follows,

$$k_a = \frac{\psi_{hr} - \psi_1}{\xi_{hr} - \xi_1} \quad (2)$$

Region :

In order to guarantee the continuity of the curve and make it more precise, the curve is modeled by a modificatory Frohlich-like relationship:

$$\psi(\theta) = \psi_1 - \frac{A(\xi_1 - \theta)}{B + (\xi_1 - \theta)^C} \quad (3)$$

Due to $\psi(\xi_u) = \psi_u$, $\psi'(\xi_u) = 0$, $\psi'(\xi_1) = k_a$, so the answer is

$$C = \frac{k_a \xi_{1u}}{k_a \xi_{1u} - \psi_{1u}}$$

$$B = -(1 - C)\xi_{1u}^C$$

$$A = k_a B$$

Region :

The ψ / θ curve is modeled by a second Frohlich-like equation:

$$\psi(\theta) = \psi_{hr} + \frac{A'(\theta - \xi_{hr})}{B' + (\theta - \xi_{hr})^{C'}} \quad (4)$$

Due to $\psi(\xi_a) = \psi_a$, $\psi'(\xi_a) = 0$, $\psi'(\xi_{hr}) = k_a$, then the answer is

$$C' = \frac{k_a \xi_{ahr}}{k_a \xi_{ahr} - \psi_{ahr}}$$

$$B' = -(1 - C') \xi_{ahr}^{C'}$$

$$A' = k_a B'$$

We can calculate the magnetization curve using the equations mentioned above after modeling different regions of the magnetization curve. The rapid nonlinear simulation method is more rapid in algorithm comparing with the finite-element techniques. We can obtain the accurate result as same as that by using the 3D finite-element techniques as long as four significant rotor positions are input correctly. Then the calculation of the equivalent magnet circuit of the overlapping unit and characteristic analysis will be accomplished.

4. The nonlinear simulation result of the system and its analysis

We have done the steady-state operation performance simulation using the method of combination between the rapid nonlinear simulation and the equivalent magnet circuit analysis. Chopped Current Control and Angular Position Control are two control methods of SRM. When using the Chopped Current Control, winding current is set by drive circuit, so the simulation procedure provided by this paper is applied to analyze the steady-state operation performance and we have done the calculation of the phase current, torque, power and so on. Different parameters are show as following: number of rotor poles is 6, number of stator poles is 8, stator outer diameter is 175mm, stator inner diameter is 98mm, air gap is 0.3mm, stator core length is 100mm, firing-angle is -10° , angle of flow is 18° , winding resistance is 0.08Ω , number of turns per phase is 90, based on the parameters mentioned above, we get the simulation Fig 3 as follows and Fig4 are experimental results.

From the Fig 3 and Fig 4, we know that simulation datum are close to experimental datum and calculation speed is more rapid than finite element method and accuracy is perfect, so we can say the method of combination between the rapid nonlinear simulation and the equivalent magnet circuit analysis is effective.

5. Conclusion

Nonlinear simulation method of steady-state operation performance is an important way to study the characters and the control methods of SRM. How to accomplish the nonlinear simulation calculation of a new project rapidly is significant to the design and optimization of SRM. This paper presents a new method that is the combining the rapid nonlinear simulation method with the equivalent magnet circuit analysis model which can make the accuracy and rapidity of the calculation of the performance of motor achieve and lay the necessary foundation for SRM optimization.

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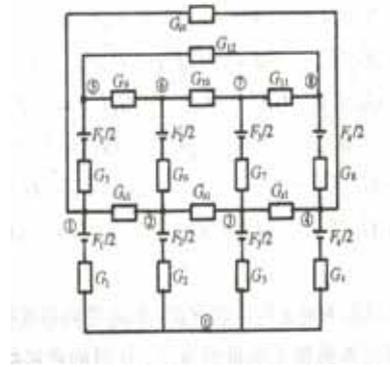


Figure 1. 8/6 SRM equivalent magnet circuit

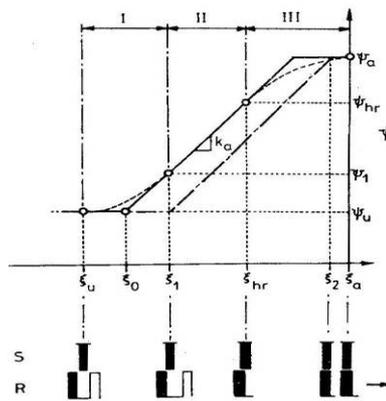
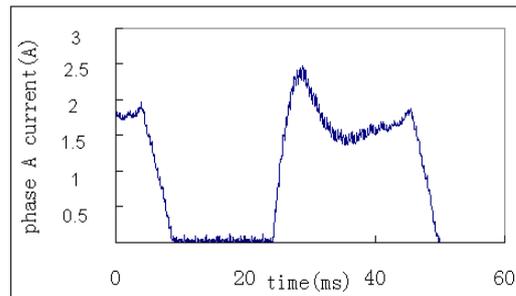
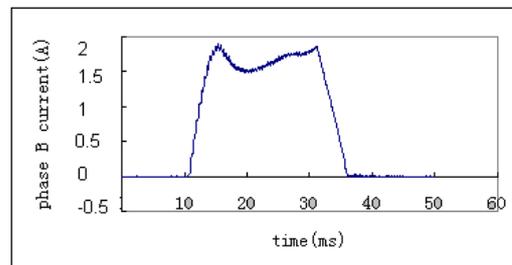


Figure 2. Modeling of a flux-linkage curve defining the domains of the three different approximation algorithms

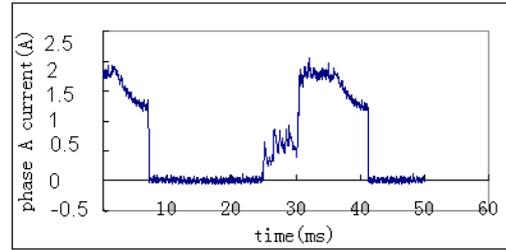


(a) Phase A current wave

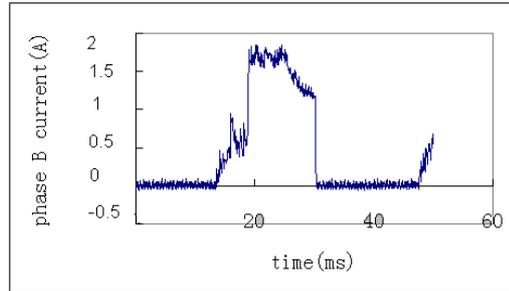


(b) Phase B current wave

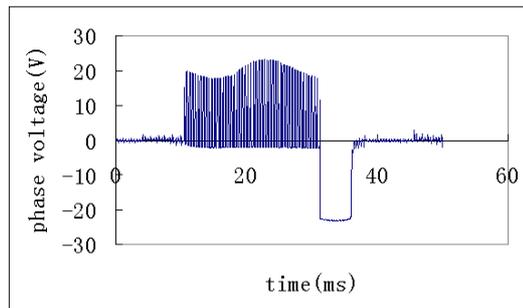
Figure 3. Simulation figures of SRM



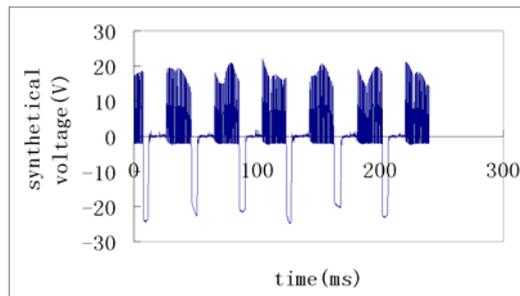
(a) Phase A current wave



(b) Phase B current wave



(c) Phase voltage



(d) Synthetic voltage

Figure 4. Experimental figures of SRM