A Novel Method of Phase Current Compensation for Switched Reluctance Motor System Based on Finite Element

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Abstract—**Torque ripple is a major problem of switched reluctance motor drive system, which causes undesirable vibration and acoustic noise. In this paper, a novel method of torque closed-loop and fuzzy compensation control for the switched reluctance motor drive system based on finite element model is described. In terms of the simulation results and the special characteristics of static torque-current-angle which are calculated by finite element method, the phase current can be treated just as the nonlinear function of phase torque. With the proposed control concept, a compensating signal is added to the phase current, the current shape can vary with the fuzzy control ruler to minimize the torque ripple. In the end, an example of 8/6 poles switched reluctance motor is simulated. Simulation results show that the torque ripple coefficient T*i* can be reduced about fifty percent and the total torque also can be advanced, which verifies the effects of the proposed fuzzy compensation control technique.**

Index Terms—**switched reluctance motor, torque ripple, phase current compensation, finite element**

I. Introduction

Switched Reluctance Motors(SRM) have advantages such as rotor simplicity, high speed operation, ease of repairing, high degree of independence between phases, short end-turn, and low inertia. SRM drives have been used for aerospace systems, marine propulsion systems, linear drives, mining drives, hand held tools and home utilities applications. The SRM is also suitable for variable speed as well as servo type applications [1]-[3]. However, a major disadvantage of SRM is the large torque ripple during lower speeds which produces intensive and undesirable vibration and acoustic noise and limits the application areas of SRM. Nowadays, torque ripple reduction in SRM has become an important and difficult research theme. Especially, at low speed, the torque ripple is very serious, which will cause undesirable vibration and acoustic noise. To avoid and reduce these disadvantages, many authors have reported methods to minimize the torque ripple which include motor structure design and control strategy. Paper [4] and paper [5] study the new motor shapes to minimize torque ripple. In paper [4], the author gives an approach to determine optimum magnetic circuit parameters and train a neural net by which the data are extracted to predict the torque performance produced by a given geometry and excitation at any position of teeth. In paper [5], the author proposes a motor with notched teeth. The disadvantage of these two studies is that the new motor shapes will affect the total torque value or average torque value. Paper [6] describes a new stator pole face having a nonuniform air-gap and a pole shoe attached to the lateral face of the rotor pole, which can minimize the undesired torque ripple and get higher average torque. But the improved structure of motor is difficult to manufacture. Paper [7] uses the fuzzy logic controller for turn off angle compensation to reduce torque ripple. But the turn off angle is a very important and pivotal modulation parameter in SRM system, so, once the turn off angle is changed, many other operation performances may be affected badly, like the speed and efficiency of machine. Paper [8] gives an offline current modulation method using a neuro-fuzzy compensation scheme to reduce torque ripple, in this paper, a neural network is trained to learn the non-linear relationship between phase current, rotor position and electromagnetic torque of a SRM. After the training process is accomplished and the neural network has successfully learned the relationship, the neural network can be used as a model of the SRM in order to produce the optimum phase current that can minimize the torque ripple. In Paper [9]-[11], authors optimize the phase current waveform to study the torque ripple. Paper [12] uses continuous sliding mode control technique to minimum the torque ripple of SRM based on the control of the phase currents by using only two current sensor and analog multipliers. In paper [13], the direct torque control is used to reduce the torque ripple in line with the nonlinear relation between torque and current. The author of paper [14] uses B-spline neural networks to study the problem of torque ripple.

In this paper, we combine the direct torque control, phase current waveform optimizing control and fuzzy control strategy into a whole system of SRM to study the torque ripple. A new method of torque closed-loop and fuzzy compensation control for the switched reluctance motor drive system based on finite element model is described which can be implemented simply and can reduce and restrain the torque ripple effectively. Furthermore, the total torque of SRM can be advanced to a higher value. First, we use ANSYS to build and analyze the electromagnetic field for obtaining the static flux linkage and torque characteristic which can clearly describe the nonlinear relation between torque and current. Second, based on finite element calculation, build the whole model of SRM system to study the dynamic performance of machine. Third, design and insert the fuzzy controller into the system to optimize the phase current profile for obtaining a steady torque waveform. Here, in terms of the simulation results and the special characteristics of static torque-current-angle which are calculated by Finite Element Method (FEM), the phase current can be treated just as nonlinear function of torque. However, the nonlinear relationship between the current and torque is very complex and can not be described easily. So, we employ a fuzzy logic control strategy to implement the compensation technique.

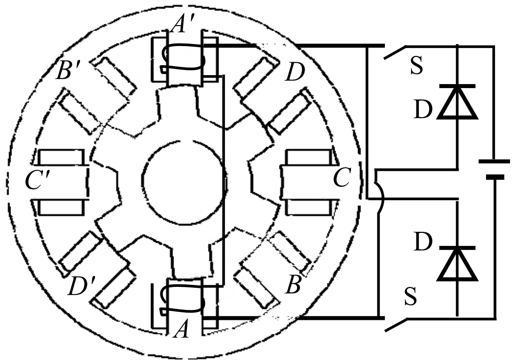


Figure 1. Classical structure and circuit of SRM

II. BASIC PRINCIPLE OF SRM

In SRM, only the stator presents windings, the rotor is just made of steel laminations without conductors or permanent magnets. The very simple structure reduces and avoids greatly its cost and losses heat effectively. Motivated by this mechanical simplicity together with the recent advances in the power electronics components, many studies have been developed recently [15]-[17]. Fig.1 shows the classical structure and simple circuit of an 8/6 poles SRM. The motion of SRM is produced by the variable reluctance in the air gap between the rotor and the stator. When a stator winding is energized, producing a single magnetic field, reluctance torque is produced by the tendency of the rotor to move to its minimum reluctance position. A sequence of anti-clockwise excitations of the stator phases results in a clockwise rotation of the rotor due to a positive torque generation. For example, as Fig. 1 shows, the sequence of excitations: A-B-C-D will produce a clockwise rotation. The SRM is characterized by a flux linkage and inductance, varying with position and current. The position-dependent behavior is due to the geometry of the overlapping stator and rotor teeth. In most SRM applications, saturation occurs, resulting in a nonlinear inductance and flux linkage. This nonlinear behavior explains the difficulty in modeling and controlling SRM drives.

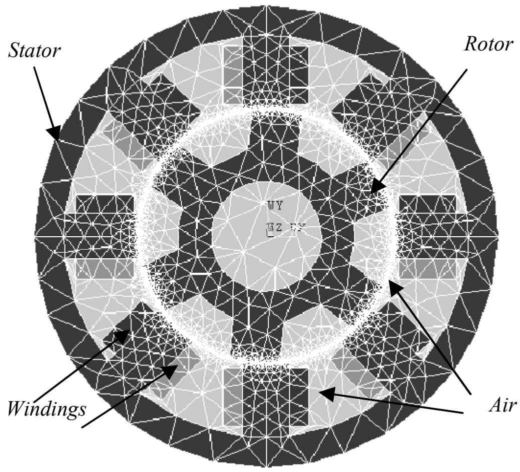


Figure 2. Meshed model and material distribution of SRM

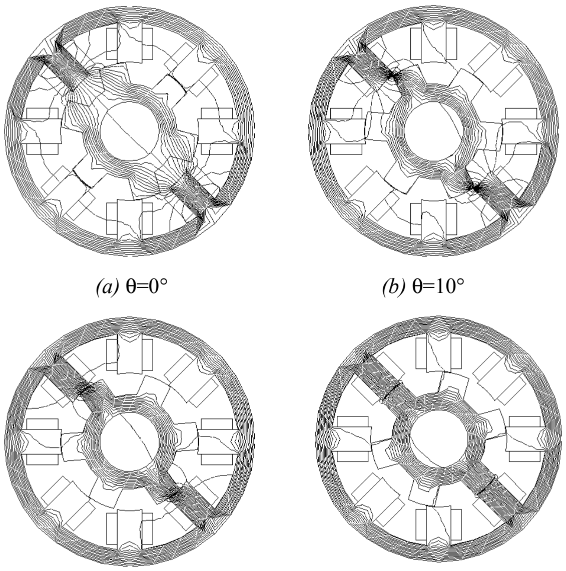
III. ELECTROMAGNETIC ANALYSIS BY FEM

Obtaining the electromagnetic characteristic is a key point to the optimizing and/or control strategy evaluation in a SRM. At present, the static characteristics of flux linkage and torque for different rotor positions and for various stator phase currents of the SRM are determined experimentally or numerically [18][19]. For the former, the real machine must be manufactured before the testing. So the influence of different geometrical structures and some electromagnetic parameters may be neglected. It is well known that FEM is the most effective and extensively applied numerical technique and it can be used to compute the magnetic vector potential on structures with a complex geometry and with nonlinear magnetic material characteristics. This ability to deal with such problems has become essential to the analysis of SRM due to its double salient structure and the intense saturation effects that occur in the partially aligned stator rotor poles. Fig. 2 shows the meshed FE model and different material of SRM in ANSYS.

The flux linkage $\psi(i,\theta)$ can be determined by computing the magnetic vector potential A over the machine crosses section. The 2-D magneto static problems with computing the vector potential A in Cartesian coordinates (x, y) are described by nonlinear Poisson's equation

$$\frac{\partial}{\partial x}\left(\nu(B)\frac{\partial A_z}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu(B)\frac{\partial A_z}{\partial y}\right)=-J_z \qquad (1)$$

Where *v(B)* is the magnetic reluctivity and J_z is the source current density. Fig. 3(*a-d*) show the flux distribution at different positions(θ=0°, 10°, 20°, 30°) respectively, when the phase current *i*=16A, the magnetic vector potential and flux distribution can be obtained by taking into consideration the saturation effects of the isotropic ferromagnetic stator and rotor material.



(a) θ=0° (b) θ=10°

(c) θ=20° (d) θ=30°

Figure 3. Flux distribution at different positions (i=16A, from unaligned position to aligned position)

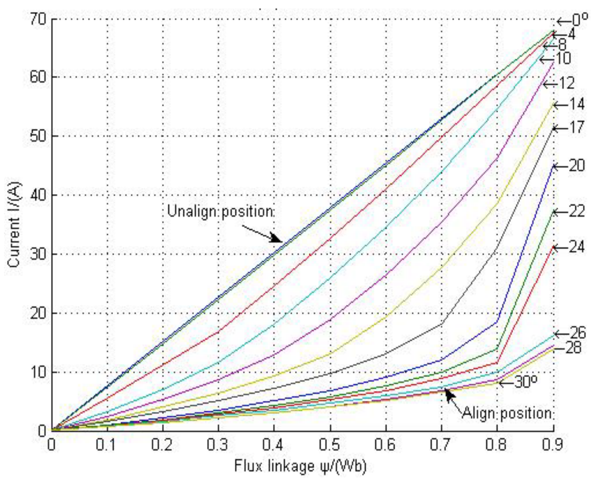


Figure 4. The inversion results of flux linkage characteristics

According to the classical electromagnetic theory, the flux linkage in each phase as

$$\psi = \frac{1}{i}\int_V \vec{J}\,\vec{A}\,dV \tag{2}$$

This, after finite element discretization or meshing, becomes

$$\psi = \frac{Nl}{S}\sum_{k=1}^{n} A_k S_k \tag{3}$$

Where *l* is the axial length of machine, *N* is the number of turns per phase, and *S* is the area of phase winding. Fig. 4 shows the inversion results of flux linkage characteristics from unalign position to align position. Seen from this figure, the magnetic saturation is produced at 30° position. Then the magnetic co-energy $W_{co}(\theta, i)$ can be calculated on the basis of flux linkage $\psi(i,\theta)$

$$W'(\theta,\ i) = \int_0^i \Psi(\theta,\ i)di\Big|_{\theta=const} \tag{4}$$

The electromagnetic torque is calculated from the co-energy derivative with respect to θ angular position as

$$T(\theta,\ i) = \frac{\partial W'(\theta,\ i)}{\partial \theta}\Big|_{i=const} \tag{5}$$

the static torque $T(i,\theta)$ characteristics can be obtained by equation (4) and (5) from $\psi(i,\theta)$ characteristics, as Fig. 7 shows.

IV. Technique of Phase Current Compensation

A. Torque Ripple

Torque ripple of SRM has been the main issue in the application of this motor, especially at low speed, the torque ripple is very serious, and it will cause undesirable vibration and acoustic noise. There are many factors to affect the torque ripple, such as rotor and/or stator shape, air length, commutation strategy, control strategy and so on, but the most important factor is phase current, which can be described by the static torque characteristics, as Fig. 8 shows. The torque ripple of SRM at low speed is described in Figure 5. Because of the saliency of the stator and rotor, the torque ripple is produced when the former phase is being excited opposite voltage and the latter phase is over excited (as Fig. 12 shows). Seen from the Figure 5, the ripples produced by the four excited phases of SRM are very large, and the point of intersection between the two excited phases must be advanced to a higher value for reducing the torque ripple.

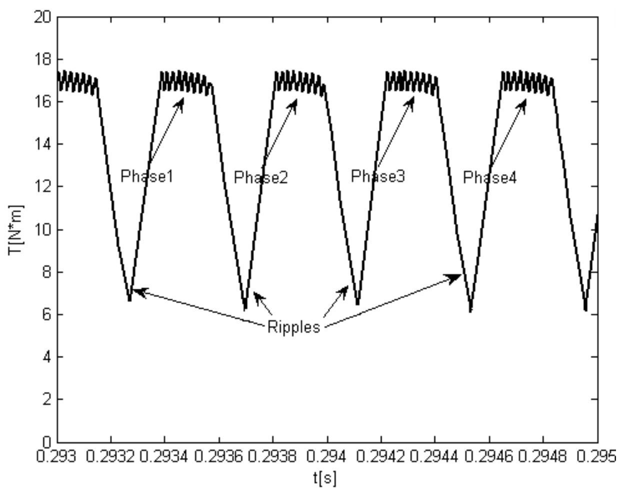


Figure 5. The torque ripple produced by the four excited phases of SRM

B. Compensation Theory

Fig. 6 shows the basic theory for the proposed ripple compensation scheme [8]. The initial phase current is constant in steady state but produce the significant ripple, as Fig. 6(a) shows. The resulted current *i* is determined by the compensated current and phase current I_{pha}, so the ideal waveforms of *i* is produced, which can get the steady torque value, as Fig. 6(b) shows. Fig. 7 shows the relationships of static torque, phase current and position angle. Seen from the Figure 7, the relationship between

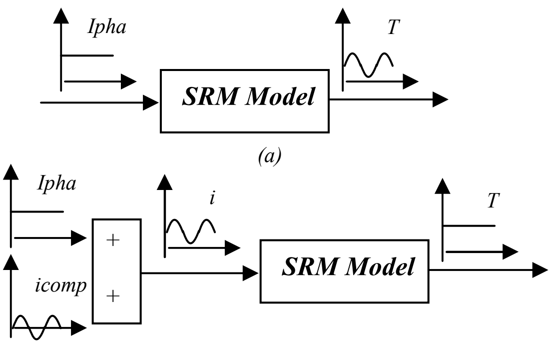


Figure 6. Basic idea of torque ripple compensation technique
(a) Torque ripple produced by constant phase current
(b) Ripple-free torque produced by compensated current

torque and current is nonlinear; it is that the phase torque can be treated as the nonlinear function of torque. In Fig. 8 the broken line shows the expectation waveforms of phase current and phase torque and the solid line shows the simulation waveforms. The technical of compensation idea comes from the simulation results and torque curve characteristic, as Fig. 7 shows that if the torque needed to be advanced, the current should be elevated at the fixed angle position. For example, in the Figure 7, at the angle 9 point, the initial current value (without compensation) is 6A and the initial torque value is 6N*m, then the torque value needed to be advanced to 12N*m, the current must be increased to 8A. So, We can make the phase current vary with the expected to get a steady torque waveform based on the relationship between static characteristic of torque and current load, which is calculated by FEM.

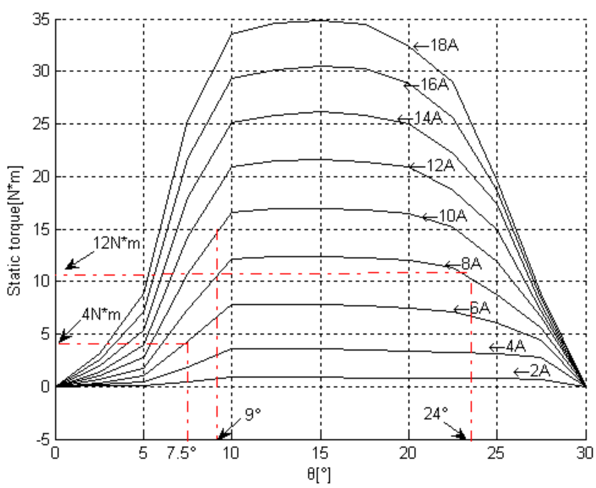


Figure 7. The static torque date for compensation condition

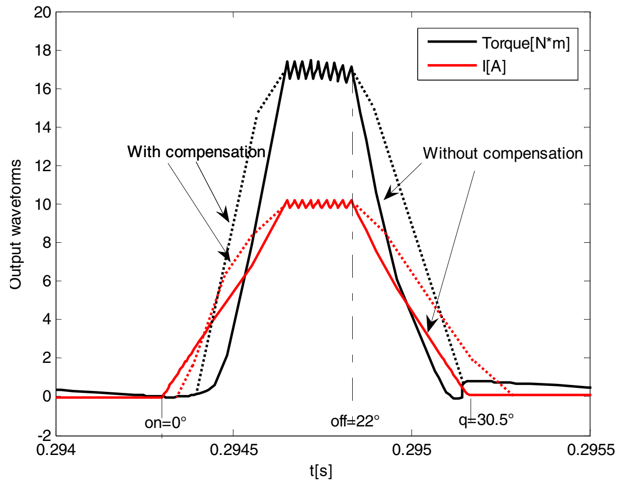


Figure 8. The waveforms of current and torque with compensation and without compensation

C. Fuzzy Control Strategy

Fuzzy control has experimentally shown excellent results, especially when faced with nonlinear control systems, like the SRM system [20]. Based on the nonlinear characteristics between phase current and the static torque which is calculated by FEM, the phase current *i* can be treated just as the nonlinear function of phase torque *T*

$$i = f(T) \tag{6}$$

To obtain the nonlinear relationship

$$\Delta i_{comp} = f(T_e, \frac{dT_e}{dt}) \tag{7}$$

Where $\triangle i_{comp}$ is the increment of compensation current, *Te* is the error of T_{ref}-T_c. The relation between static torque and current and angle position is studied. From this, the output torque T_c detected from SRM simulation system is added to the reference value T_{ref}, get the error value T_e and rate of error change dT_e/dt. So, when the output waveforms of torque are fluctuating, they can be changed in terms of the relationship which is calculated by FEM. The fuzzy controller is operation based on the ruler, such as the typical fuzzy rule is:

If T_e is A_i and dT_e/dt is B_i Then $\triangle i_{comp} = f(T_e, dT_e/dt)$ (8)

Where i=1……n

Add the $\triangle i_{comp}$ to the initial value current, i_{pha} is

$$i_{pha} = i_{pha}\big|_{initial} + \Delta i_{comp} \tag{9}$$

V. SIMULATION AND RESULTS ANALYSIS

For the purpose of verifying the idea of current fuzzy compensation, an 8KW, four phase 8/6 poles SRM is analyzed as an example for a simulation experiment. The main dimensions of a prototype motor as Table 1. shows

Table 1. Main Dimensions of SRM

Quantity	value	Quantity	value
Stator out- diameter(*Ds*)	210mm	Rotor axial diameter(D_i)	50mm
Rotor out- diameter(*Da*)	115mm	Stator yoke height (h_{cs})	13.7mm
Axial length(L_{Fe})	0.38mm	Rotor yoke height (h_{cr})	14.9mm
Air-gap (*g*)	0.4mm	Stator slot depth(d_s)	34.6mm
Stator polar arc(βs)	0.36 rad	Wings turns number(N_t)	117
Rotor polar arc(βr)	0.40 rad	rated power(P_n)	8KW

A. Mathematical Model of Motion Control

SRM is a strong nonlinear system; therefore the torque generation process can be described accurately only while using the nonlinear mathematical model. For simplification analysis, here assume that: (1) the semiconductors work at ideal operation, that is the voltage drop is zero when it turn on and the current is zero when it turn off. (2) The mutual inductance is neglected.

Voltage equation as following

$$U = Ri + \frac{d\psi(\theta,i)}{dt} = Ri + \frac{\partial\psi(\theta,i)}{\partial i}\frac{di}{dt} + \frac{\partial\psi(\theta,i)}{\partial\theta}\frac{d\theta}{dt} \quad (10)$$

Where U is the phase windings voltage, R is the resistance. Mechanical motion equation as

$$T = J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} + T_L \quad (11)$$

Where T_L is the load torque, B is the friction damping coefficient, J is the moment of inertia of rotor.

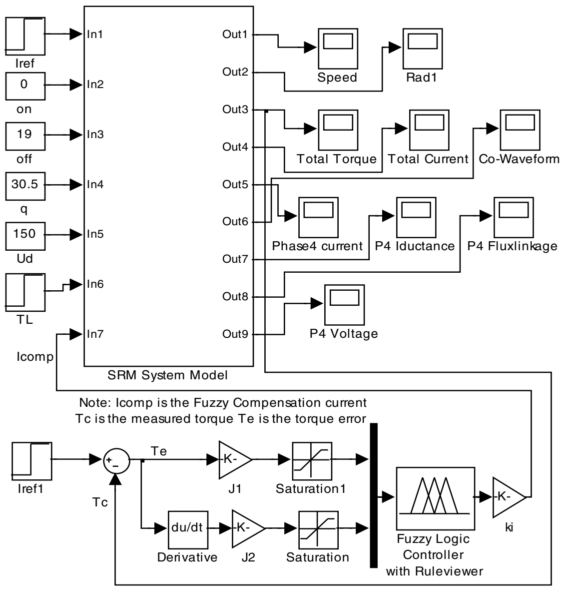


Figure 9. The simulation model of SRM system with fuzzy controller

B. Modeling and Simulating

In terms of control equation, build the simulation model of the whole SRM dynamic system in SIMULINK, as Fig. 9 shows, and Fig. 10 shows the inner model of SRM system [21]-[23]. In the Figure 9, *SRM System Model* is the encapsulation system of four phase 8/6 poles SRM. The left part of the *SRM System Model* is the input parameters of system, and the right is the output value, like speed, phase current, phase inductance, flux linkage and torque output. So, we just need to consider the input and output of SRM in this model, which is very convenient for simulation. The underside of the *SRM System Model* is the torque closed-loop and fuzzy logical controller, where the torque signal of SRM system is checked and compared with the reference torque *Iref1*. Then the torque error Te and its rate of error change are input the fuzzy logic controller, through fuzzification, they are transform into fuzzy variable. Under the compensation ruler, the output $\triangle i_{comp}$ of fuzzy logic controller is added to the phase current. Then the current shape of SRM system can vary with the fuzzy control ruler to minimize the torque ripple.

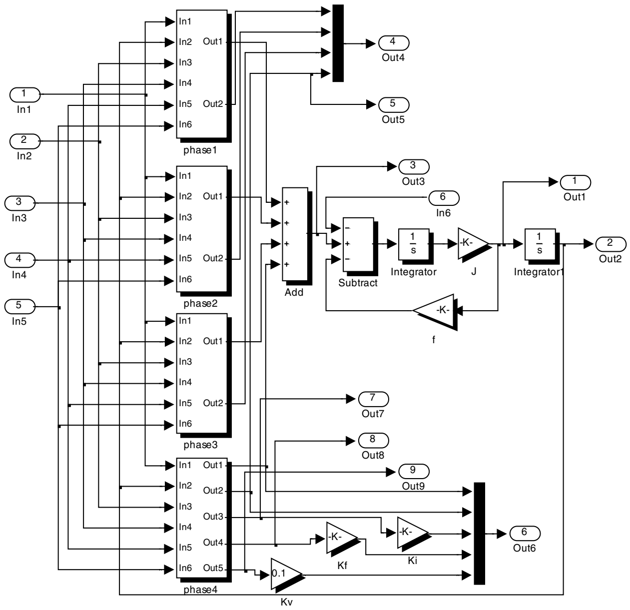


Figure 10. The model of SRM system

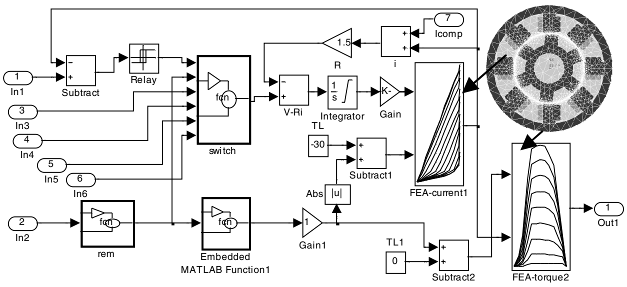


Figure 11. The power converter model of phase1

In the Figure 10, *phase1-phase4* is the four phase's structure module of SRM. In term of mechanical motion equation of SRM, the whole model of machine can be build, which includes the load torque module *TL*, the friction damping coefficient module *f* and the moment of inertia of rotor module *J*, Fig. 11 shows the inner structure of *phase1* which mainly includes the hysterics module *Relay* for limiting the current peak value, the logic phase conversion module *switch* which is implemented by programming, the angle conversion module which is used to convert the radian value into angle value, the module *FEA-current1* and module *FEA-torque2* which are the date blocks calculated by FEM. Here, the FEM modules are embedded in the system simulation model as a sub-model, which can consider the influence of the geometry structure and electromagnetic parameters.

Based on the above SRM system simulation model, the Chopped Current wave Control (CCC) strategy is employed at low speed. The main control parameters include: I_{ref} is limited at 10A, U_d=150V, θ_{on}=0°, θ_{off}=19°, θ_q=30.5°, the friction damping coefficient f=0.0183, the moment of inertia of rotor J=0.0013kg.m^2. Fix the conducting angle θ_{on} and shutoff angle θ_{off}, then control the applied voltage by hysteresis band (here, the band is 0.2A). When the motor is operating at low speed, the third item action of expression (10)-back electromotive force is very poor because the angular velocity $d\theta/dt$ is very small, then the current will increase quickly during this time. In order to limit the current peak value, control the available time of voltage U_d which is applied to the phase windings. At lower speed, the torque ripple is very significant and the fuzzy logical controller is used to compensate the current for minimizing torque ripple. During the simulation test, the torque error and error change determined by the referenced torque value and measured value are used as variables to the fuzzy logical controller.

C. Results and Analysis

For comparison purposes, the SRM drive system has been simulated without compensation and with compensation, at full-load torque(here, TL=1N*m) and a motor speed of 600 r/min. Fig. 12 shows the initial dynamic system simulation results and compensated results about the four phases torque waveforms. The black solid line is the four phases output torque waveform without compensation, the ripples from phase1 to phase2 are very serious, and the interaction point torque value between two adjacent phases is very low(about 6.5N*m). The black broken line is the four phases output torque waveform with compensation, the ripples from phase1 to phase2 are relative small, the interaction point torque value between two adjacent phases is advanced effectively (about 14N*m). It can be seen that the torque value at the interaction point of two adjacent phases increased effectively after the compensation.

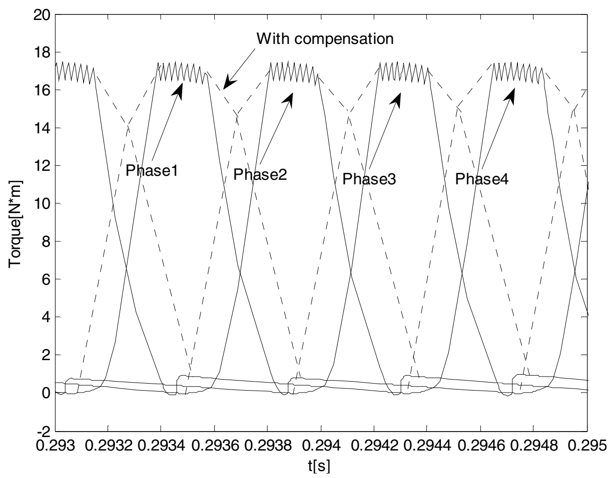


Figure 12. The torque ripple produced by four phases of SRM

To have a better general view of the torque ripple, define the torque ripple coefficient *Ti* [24]:

$$Ti = \frac{T_{\max} - T_{\min}}{T_{av}} \tag{12}$$

Where T_{max}, T_{min} are the maximal value and minimal value of total torque, T_{av} is the average value of total torque.

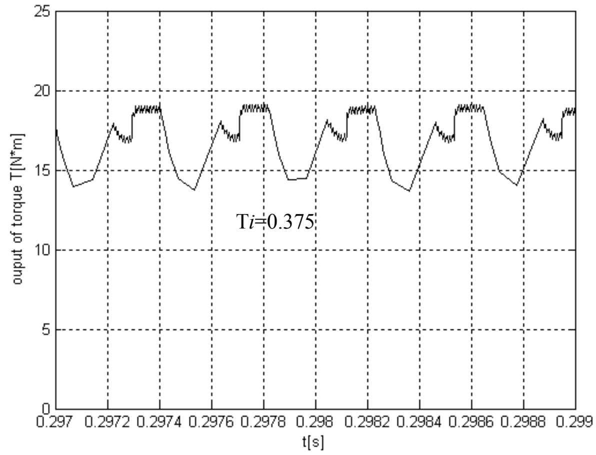


Figure 13. The co-torque produced by four phases 8/6 pole SRM without compensation

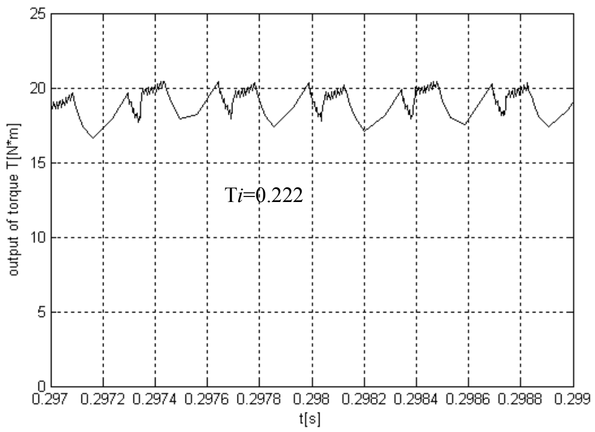


Figure 14. The co-torque produced by four phases 8/6 pole SRM with compensation

Figure. 13 and Figure. 14 describe the output total torque waveforms and torque ripple without and with compensation respectively. In the Figure 13, the torque ripple coefficient (T*i*=0.375) is very high under initial simulation, however, in the Figure 14, the compensation is done for the phase current, the torque ripple coefficient drop to T*i*=0.222 which is smaller than the former, which clearly shows the effects of the compensation technical. Seen from the comparison results, the torque ripple coefficient T*i* is reduced about fifty percent. Compare Figure. 13 with Figure. 14, it also can be seen that the average value of total torque is enhanced. In Figure 13, the average value of total torque is about 17.5N*m, after the compensation, the average value of total torque is enhanced to about 19N*m, as Fig. 14 shows, it can be clearly seen that the total torque after compensation has been advanced to a higher value.

VI. Conclusions

The study of SRM system has become a major research theme for this special electrical machine today. In servo control applications or when smooth control is required at low speeds, reduction or restraining of the torque ripple has become a main issue in an acceptable control strategy. In this paper, we give a new compensation mechanism using fuzzy logical controller with torque closed-loop control which is used to compensate the phase current to get an optimal phase current waveform for minimizing the torque ripple of SRM. In this proposed technique, the torque-current characteristics and nonlinear compensation relations between them are the very important keys to obtain the compensation idea and design the fuzzy logic controller. Under a SRM system simulation environment based on finite element model, the simulation test is implemented. Simulation results have shown the wanted phase current waveforms and the well torque ripple reduction obtained by the compensating current signal which changes the phase current shape according to the operation and special characteristic of SRM. Furthermore, the total torque of SRM can be advanced to a higher value.

The compensation control idea comes from the relation between static current and torque characteristic which is calculated by FEM. So, it also can be seen that the determination of the magnetic characteristics is a key point to the optimizing design and control strategy evaluation in SRM. Co-simulate the finite element and dynamic system to study the whole machine is a new and important research point in the future.

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