Modeling, Simulation and Experimental Verification of Four-Phase 8/6 Switched Reluctance Motor Considering Interactive Excitation

YUEYING ZHU\(^1\), (Member, IEEE), YITAO JIA\(^1\), AND HAO WU\(^{1,2}\)

\(^1\)College of Mechanical Engineering, Tianjin University of Science and Technology, Tianjin 300222, China
\(^2\)Tianjin Key Laboratory of Integrated Design and On-Line Monitoring for Light Industry and Food Machinery and Equipment, Tianjin 300222, China

Corresponding author: Yueying Zhu (zhuyueying@tust.edu.cn)

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ABSTRACT In the single-phase excitation mode of a four-phase 8/6 switched reluctance motor (SRM), the switch angle for each phase is usually high enough to improve the performance of the SRM, which can directly result in overlapping in excitation periods of each adjacent phase. Ignoring the torque variation caused by magnetic coupling between adjacent charged phases during excitation overlap period, which is a general method to establish the model of SRM currently, would greatly influence the accuracy of the simulation model. Aiming at the problem of the general modeling method, a new SRM ontology modeling method is proposed by considering overlapping excitation, based on nonlinear mathematical model established by means of mutual inductance which could influence the electromagnetic characteristics of SRM. Firstly, the reason of interactive excitation and the distribution of the magnetic field are analyzed by (FEM), and the mathematical model is also developed. Then, the detailed static characteristics including mutual inductance and torque are analyzed based on the results of FEM, which are compared with those of the model without considering the effects of interactive excitation. Furthermore, the dynamic simulation model of SRM drive system (SRD) is built, and the simulation results are analyzed and compared with those of the traditional model. Finally, a static experiment is designed and performed to verify the mutual inductance and static torque under long magnetic circuit (LMC) and short magnetic circuit (SMC) in interactive excitation. The comparison results show that the data from experiment are greatly consistent with those from FEM, and the characteristics of mutual inductance and torque under interactive excitation should be considered when establishing the model of SRM.

INDEX TERMS Switched reluctance motor, modeling method, interactive excitation, electromagnetic characteristics.

I. INTRODUCTION

The driving system of switched reluctance motor (SRM) has the advantages of simple structure, low cost, and inherent fault tolerance performance, making it becomes one of the best options for driving system of electric vehicle, renewable energy harvesting, aircraft generators, and other industrial applications [1], [2].

The SRM is a doubly salient machine with a rotor without permanent magnets and a stator with independent phase windings. The adjacent rotor poles are attracted to the exciting stator poles for minimizing the reluctance of the magnetic path when one phase of the SRM is excited [3]. Therefore, torques are produced by the excitation regardless of the direction of the current in the phase winding. Moreover, a constant torque is developed when the windings are energized phase by phase [4]. However, there are still some performance deserving further improvement, many scholars have made highly effective research, including SRM ontology [5], [5], [7], [8], excitation and winding modes [9]–[11], and controlling strategy [12]–[15]. In order to improve the electromagnetic energy conversion capability of SRM, the magnetic
The excitation mode of SRM directly affects the magnetic characteristics of the motor, which makes SRM difficult to obtain its accurate non-linear electromagnetic mathematical model to predict the performance of the system [4]. Hence, the accurate modeling of SRM is very important for studying its electromagnetic characteristics, improving output efficiency, and obtaining good performance characteristics in those applications.

As for the non-linear modeling problem, a model was presented in [16] which presumed that the mutual flux did not depend on currents of all exciting phases, which was not suitable in the case of magnetic saturation. A dynamic two-phase excitation model accounting for mutual coupling was presented by [17]. However, the model was not compatible when the number of phase and winding mode change because the symmetry would no longer exist. Comparative studies of dynamic performance and magnetic characteristics of the dual-channel switched reluctance machines (DCSRMs) were proposed in [18]. Modeling and simulation of DCSRMs with the coupling effects under single and double excitation modes were also carried out. However, it was only suitable for DCSRMs, rather than general four phase 8/6 SRM. The coupling effects were discussed in [19] and incorporated into the dynamic model, which greatly reduced the harmonic content in the torque ripple. This method needed a lot many look-up tables (LUT) calculated by FEM, whose accuracy is impaired if the interval between successive values of current in LUT was large, because computation relied on linear interpolation between two flux-linkage values in a highly nonlinear system like SRM. A new model with multi-phase excitation based on single-phase nonlinear model was proposed in [20], and the effectiveness of the model was verified by FEM. However, the equivalent magnetic resistance of the magnetic saturation will be varied with the change of magnetic saturation, which will influence the accuracy of the mathematical model. Besides, their models were simplified as only considering simultaneous excitation, which was no longer applicable if freewheeling currents existed and were not equal to the exciting current. These studies have greatly developed the non-linear modeling theory of SRM considering the coupling effects between each exciting phase. However, when the SRM worked under the period of simultaneous excitation, the total torque generated by the two charged phases with coupling effects was approximately computed by summing the torques of both phases, which could influence the accuracy of the dynamic model. In order to solve that problem, a novel modeling method for SRM is proposed in this paper, where the excitation overlap is considered to improve the model accuracy. A new nonlinear mathematical model is also established by means of mutual inductance. The coupling effects between two charged phases on electromagnetic characteristics are analyzed and compared to traditional methods. Modeling, simulation, and experiment are applied to verify the correctness of the proposed modeling method, and the results show the proposed method can improve the accuracy of the SRM dynamic model.

This paper is organized as follows: firstly, the interactive excitation is introduced by analyzing the power circuit and distribution of magnetic density in Section II. Then, the mathematical model is developed in Section III. Electromagnetic characteristics including mutual inductance and torque are analyzed in Section IV to explore the coupling effects during interactive excitation in LMC and SMC modes by FEM. In Section V, dynamic simulation of the SRD is operated in various conditions and the results are compared with those of traditional model. In addition, an experiment is designed to verify the correctness of the modeling method in Section VI. Finally, the conclusions are summarized in Section VII.

II. INTERACTIVE EXCITATION

Considering the four-phase 8/6 SRM under the single-phase excitation mode, the excitation angle of each phase is usually high enough in the actual operation process in order to improve the performance of the motor and reduce the torque ripple. The exciting phase can also maintain continuous current because of freewheeling after cutting off the phase circuit. As a result, even under single-phase excitation mode, there will be some time when two phases of the SRM flow currents simultaneously, which is similar to two-phase simultaneous excitation, but both phase currents are not always the same. In this case, the active total torque should be different from the summation of torques of both phases and couldn’t be neglected due to the coupling effects between these phases. Fig. 1 is a typical diagram of phase currents of the four-phase 8/6 SRM running when \( \theta_{on} \) and \( \theta_{off} \) are fixed to 3 and 22 degrees under single-phase excitation mode. When one phase is in excitation, the previous phase still has freewheeling currents. This condition of excitation overlap with coupling effects is called interactive excitation. Therefore, the magnetic field between the two charged phases cannot be a simple superposition of both single-phase magnetic fields, and the interaction of them should not be neglected. Hence, the establishment of SRM dynamic model considering interactive excitation is of great significance for accurate analysis of electromagnetic characteristics and prediction of motor performance.

The excitation mode of SRM directly affects the magnetic polarity of each phase and the order of exciting phase.
which could change the magnetic field distribution in the stator and rotor. For the four-phase 8/6 SRM, the winding mode is NSNSSNSN, which is commonly used in single-phase excitation mode. Fig. 2 is the typical power converter circuit of this excitation mode, where each phase, A, B, C, or D, is connected with power source $U_s$ by two switches and two diodes. There could be two paths of current in the power circuit of phase A, which corresponds to excitation current $i_{A1}$ and freewheeling current $i_{A2}$. When phase B begins to be excited, there could be $i_{A1}$ or $i_{A2}$ in phase A, such that the magnetic field generated by excitation current $i_B$ can interact with that generated by current of phase A.

Furthermore, due to the variation of magnetic fields caused by different current distributions, there are two different magnetic circuits for four-phase 8/6 SRM shown in Fig. 3, which are long-magnetic circuit (LMC) and short-magnetic circuit (SMC). Correspondingly, the magnetic density distributions for LMC and SMC are analyzed by FEM as shown in Fig. 4, based on the four phase 8/6 SRM whose parameters are listed in Table 1. According to the magnetic density nephogram, when the exciting phases interact, the magnetic field distributions of LMC and SMC are completely different, which should be considered independently in modeling the SRM.

### III. MATHEMATICAL MODEL

In order to accurately calculate the total torque of overlap period of SRM with single-phase excitation mode, a non-linear calculation method considering mutual inductance must be derived firstly because of the non-linear characteristics of SRM. Then, the torque can be calculated by numerical integration. According to the electric circuit principle of the SRM, the voltage balance equation of the $k$th phase is expressed as:

$$U_k = R_k i_k + \frac{d\psi_k}{dt}$$

(1)

where, $U_k$ is phase voltage, $R_k$ is the phase resistance, $i_k$ is the phase current, and $\psi_k$ is the flux of this phase. Among them, $\psi_k$ can be divided into two parts, self-inductance flux and mutual-inductance flux. The self-inductance flux is expressed as equation (2) by the product of self-inductance and phase current.

$$\psi_{AA} = L_A(\theta, i_A) i_A$$

(2)

where, $\psi_{AA}$ is self-inductance flux of phase A, $L_A$ is self-inductance of phase A, $i_A$ is the current of phase A. The situation of phase B is the same as phase A.

The general definition of mutual inductance $M$ is computed as equation (3), where $M_{AB}$ and $\psi_{AB}$ are mutual inductance and mutual-inductance flux of phase A impacted by phase B, while $M_{BA}$ and $\psi_{BA}$ are those of phase B impacted by phase A.

$$M = M_{AB}(\theta, i_A, i_B) = M_{BA}(\theta, i_B, i_A) = \frac{\psi_{AB}}{i_B} = \frac{\psi_{BA}}{i_A}$$

(3)

Thus, the mutual-inductance flux $\psi_{AB}$ can be expressed as the product of $M_{AB}$ and $i_B$ according to equation (4).

$$\psi_{AB} = M_{AB}(\theta, i_A, i_B) i_B$$

(4)
So, the flux of phase A can be expressed as:

$$\psi_A = \psi_{AA} + \psi_{AB}$$

(5)

where, \(\psi_A\) is the flux of phase A. Therefore, the current of phase A can be calculated by equation (1) to (5), which can be expressed as equation (6). It should be noted that the phase current of phase B is similar with phase A.

$$i_A = \int U_A - R_A i_A - i_A \frac{dL_A(i_A, \theta)}{d\theta} - \frac{1}{2} i_B \frac{dM_{AB}(i_A, i_B)}{d\theta} \, dt$$

(6)

As shown in Fig. 5, the magnetic co-energy is calculated according to the path integral method when the rotor is in position \(P\). The path is divided into three steps, OM, MN, and NP. Therefore, the total magnetic co-energy \(W_c(i_a, i_b, \theta)\), considering the mutual inductance, is calculated as

$$W_c(i_A, i_B, \theta) = \int_0^{i_A} L_A(i_A, \theta) dL_A + \int_0^{i_B} L_B(i_B, \theta) dL_B$$

$$+ \int_0^{i_A} M_{AB}(i_A, i_B, \theta) dL_A$$

(7)

The total electromagnetic torque can be calculated by the derivation of magnetic co-energy, which can be calculated as

$$T_{total} = \frac{\partial W_c(i_a, i_b, \theta)}{\partial \theta} = \frac{1}{2} \frac{\partial L_A(i_A, \theta)}{\partial \theta} + \frac{1}{2} \frac{\partial L_B(i_B, \theta)}{\partial \theta}$$

$$+ i_A \frac{\partial M_{AB}(i_A, i_B, \theta)}{\partial \theta}$$

(8)

In this paper, 0 degree of rotor position is defined to be in the unaligned position of phase A.

**A. MUTUAL INDUCTANCE**

In this part, the effects of varying current on the mutual inductance characteristics are analyzed by FEM. Mutual inductance of two charged phases are related to rotor positions and phase currents, which can characterize the effects of interaction between adjacent charged phases. The mutual inductance characteristic curves under the LMC and SMC modes are obtained as shown in Fig. 7, where the exciting currents are selected from 10 A to 60 A with a step of 10 A and the rotor positions are set to be in the range 0-60 degrees, respectively.

It can be seen from the Fig. 7 a) that the mutual inductance in LMC mode is negative. This is because the magnetic field in yokes of the stator and rotor is easier to be saturated and the magnetic potential drop of the stator and rotor yokes is larger relatively when the currents of phase A and B are high (30A-60A) in SMC mode. As a result, the actual total flux is also smaller than the...
total flux generated by both excited phases separately. Thus, the mutual inductance is also negative in this case as shown in Fig. 7 b). However, when the both phase currents are low (10A and 20A), the magnetic field is not yet saturated, and the magnetic path is relatively short. The magnetic potential drop is smaller, which leads the total flux larger than that calculated by two excited phases. Therefore, the mutual inductance in SMC is positive under this condition. In addition, the absolute value of the mutual inductance in LMC mode is always greater than that in the SMC mode as shown in Fig. 7 when the rotor positions and phase currents are the same. Because the lengths of the magnetic path of the stator yoke and the rotor yoke in LMC mode are three times and twice than those in SMC mode, respectively, although the saturation degrees of magnetic field for both modes are basically the same. Therefore, the magnetic potential drop in yokes in LMC is larger than that in SMC, causing the total flux smaller. It should be noted that the absolute value of mutual inductance reaches the maximum at aligned position of two-phase excitation in both modes.

For further analysis of the results, the curves of mutual inductance with different combinations of both phase currents can be obtained in Fig. 8 at aligned position of two-phase excitation. It can be seen from the Fig. 8 that the absolute value of mutual inductance in LMC mode increases according with the increase of both phase currents and reaches the maximum absolute value when the phase currents both become 60 A. The mutual inductance in SMC mode is positive when the both phase currents are low (10 A and 20 A) because of unsaturated magnetic circuit and the larger flux. However, with the increase of both phase currents, the magnetic circuit reaches saturation, then the mutual inductance becomes negative. In addition, the absolute value of mutual inductance also reaches maximum when the currents increase to 60 A.

**B. TORQUE-ANGLE CHARACTERISTICS**

In this part, the coupling effects of mutual inductance and varying current on the torque characteristics are analyzed by FEM. Torque-angle characteristics between two charged phases are also related to rotor positions and both phase currents. The torques under various conditions are obtained as shown in Fig. 9, including phase A and Phase B in single-phase excitation and two-phase excitation during overlap of LMC and SMC mode. The currents are set to be 20 A, 40 A, and 60 A.

Fig. 9 a) shows the torque-angle characteristics obtained under current of 20 A for both phases. By comparing the total torque generated by both phases in LMC or SMC mode with summing torque calculated by each excited phase in single-phase excitation mode, it can be observed that the torque curves, actual torque in LMC, actual torque in SMC, and summing torque from two phases, are very close but slightly different as shown in Fig. 9 a). Because the mutual inductance values of LMC and SMC are small enough when the current is 20A, which has little effects on torque, thus, the three curves are close. At this time, the mutual inductance is positive in SMC mode as shown in Fig. 7 b), which can promote the torque. The situation is opposite when it is in LMC. Thus, the actual torque in SMC mode is the largest, followed by the summing torque of two phases and actual torque in LMC. Fig. 9 b) and c) show the torque-angle characteristics when the currents are set to be 40 A and 60 A, respectively. The mutual inductance is negative in LMC and SMC under these conditions, thus, the actual total torques are both less than the summing torque generated by both charged phases respectively. Furthermore, the absolute value of mutual inductance in LMC is greater than that in SMC, resulting in the torque in LMC is less.

When the rotor angle is in the range of 0-8 degrees, the actual torque in LMC or SMC and the summing torque from two phases are basically coincided. Because the overlapping area of salient poles in stator and rotor is small enough, which leads the mutual inductance between both phases is very low. As a result, the total co-energy in LMC and SMC are basically equal to the summing co-energy generated by both excited
TABLE 2. Static torque difference data.

| θ (deg) | 0   | 3   | 6   | 9   | 12  | 15  |
|---------|-----|-----|-----|-----|-----|-----|
| T_{sum}| 14.85 | 15.73 | 19.53 | 25.46 | 22.27 | 14.85 |
| T_{short} | 14.93 | 15.88 | 19.71 | 25.45 | 20.59 | 11.94 |
| ΔT_{short} | 0.08 | 0.15 | 0.18 | -0.01 | -1.68 | -2.91 |
| ΔT_{long} | -0.06 | -0.11 | -0.41 | -1.76 | -5.41 | -6.93 |
| ΔT_{short}T_{sum} | 0.56% | 0.95% | 0.93% | -0.04% | -7.53% | -19.6% |
| ΔT_{long}T_{sum} | -0.41% | -0.69% | -2.08% | -6.90% | -24.3% | -46.6% |

FIGURE 10. Torque characteristics under SMC mode.

phases separately. On the other hand, with the increase of the rotor angle from 8-15 degrees, the differences between the three torque curves become larger as shown in Fig. 9. Because the closer the rotor position is to 15 degrees, the greater the overlap area of the salient poles is, which causes the absolute value of mutual inductance between phase A and phase B higher. As a result, the differences of three curves become greater than those below 8 degrees.

Moreover, in order to clearly evaluate the numeric differences of the three torques under various position angles, the specific values about the torques are listed in Table 2, where, $T_{sum}$, $T_{short}$, and $T_{long}$ are summing torque, torque in SMC, and torque in LMC; $ΔT_{short}$ and $ΔT_{long}$ refer to difference values subtracting $T_{sum}$ from $T_{short}$ and $T_{long}$. It can be seen from Table 2 that the differences of the three torques is much small when the position angles are low enough, but great big when the angles are high enough. The variation trend is the same with that obtained by analyzing Fig. 9.

In addition, the biggest difference ratio is up to $-46.61\%$ between $T_{sum}$ and $T_{long}$, which is too high to neglect the difference for modeling the motor.

In order to further study the influences of different currents for phase A and phase B on the torque when considering the interactive excitation, the torque characteristics as functions of the phase currents under various position angles in SMC mode are computed and shown in Fig. 10, where the rotor position are selected as 7.5, 22.5, and 37.5 degrees, respectively. It can be observed from Fig. 10 a) that the torque is none when currents of phase A and phase B are equal, because of unaligned position for single-phase excitation at 7.5 degrees. But the torque could change to be positive or negative when one of phase currents is higher than the other. Fig. 10 b) shows that the torques are positive and increase with the increase of phase currents when the angle is 22.5 degrees. Because the self-inductance of two excited phases are both in rising region, leading positive torque. When the rotor is at 37.5 degrees, aligned position of two-phase excitation, the situation is totally contrary to that at 7.5 degrees, which is shown in Fig. 10 c). It should be noted that the variation trends of torque under LMC are very similar to those under SMC. In summary, the torque values under different combinations from currents of phase A and phase B are completely different from each other. Therefore, the influences of phase currents on torques is high enough such that the interactive excitation cannot be ignored for modeling the SRM.

V. DYNAMIC SIMULATION OF SRM MODEL

Combining the SRM ontology model established in section III and electromagnetic characteristics shown in section IV, the dynamic model of SRD for the four-phase 8/6 SRM is built as shown in Fig. 11, where speed control and current control are considered.

A. SIMULATION RESULTS

As shown in Fig. 12, the partial simulation results of dynamic model, including phase current and total torque, are illustrated, where the reference speed is set as 800 r/min and 1500 r/min respectively, and the load is 1 N·m. It can be seen from Fig. 12 that the magnetic field generated jointly by phase B and C is LMC under both conditions such that the torque in LMC are slightly smaller than that in SMC.

B. COMPARISON WITH PHASE CURRENT

The current curves with and without the consideration of the interactive excitation are obtained, which is signed M1 and M2 as shown in Fig. 13. Corresponding to Fig. 13 a) and b), the simulations are carried out under condition of 800 r/min with 1 N·m, and 1500 r/min with 10 N·m, respectively. It can be seen that the dynamic currents from M1 and M2 are slightly different from each other. The largest difference of both models can reach nearly 0.5 A, which indicates the
current can be changed without considering the interactive excitation. As a result, the effects of interactive excitation cannot be neglected for modeling SRM, which is coincident with that analyzed in section IV. It should be noticed that the phase current could increase with the load torque, which leads to larger differences between the two models.

C. COMPARISON WITH TORQUE

The dynamic torque curves under two models M1 and M2 are also obtained by model simulation at 800 r/min and 1500 r/min with load of 1 N·m and 10 N·m, which are shown in Fig. 14. Obviously, there are distinct differences in the torques generated by both models. Because the effects of interactive excitation are considered accurately in M1. Furthermore, in order to intuitively reflect the numerical differences between M1 and M2, the difference ratio between two models are calculated and illustrated in Fig. 15. The difference ratios can reach up to 15% and 8% under 800 r/min and 1500 r/min with 1 N·m respectively. When the load is 10 N·m, the difference ratios come to 3.6% and 2.9%. Therefore, the difference could influence the accuracy if the SRM model is established without considering the interactive excitation.

On the other hand, the differences between LMC and SMC should be compared and analyzed. As illustrated in Fig.12, there are three SMC and one LMC in one cycle for the SRM researched. It can be computed from Fig. 15 that, for LMC mode, the average difference ratios between M1 and M2 are 3.76% under 800 r/min and 0.77% under 1500 r/min with the load of 1 N·m. With the load of 10 N·m, the average difference ratios come to 1.7% and 1.4%, respectively. For SMC mode, however, the average difference ratios can reach 6.6% under 800 r/min and 3.9% under 1500 r/min with the load of 1 N·m. When the load reaches 10 N·m, the average difference ratios are 0.6% and 0.8%, respectively. Thus, the dynamic torques in SMC and LMC are quite different from those summed by two single-phase. Meanwhile, the torques in LMC and SMC are also different from each other. In a word, not only the effects of interactive excitation, but also the excitation modes should both be considered for modeling the SRM because of the high differences of dynamic torque.

VI. EXPERIMENT VERIFICATION

In order to verify the accuracy of modeling and FEM analysis, an experimental platform is built as shown in Fig. 16, according to the classic measurement method described in [21]. A pulse voltage is applied to both phases to be excited after the rotor is fixed to a special position during one of the trials. Then the data of the voltage and the phase current are recorded by the oscilloscope as shown in Fig. 17. Finally, the mutual inductance and torques are calculated by numerical integration and differentiation algorithms from voltage and the phase current as shown in Fig. 18 and 19. Fig. 17 shows the curves of the voltage and current collected.
by the MSO 3014 oscillograph when the rotor positions are respectively fixed at 15 and 30 degrees, in which the voltages and currents are displayed by 2.0 V/div and 200 mV/div, and the current sensor is 10A/100mv.

For further analysis of the mutual inductance, it can be observed from Fig. 18 that the results from FEM are basically consistent with those from experiment when comparing the values and trends of the curves, which are selected from rotor position of 0 to 60 degrees under phase currents of 20 and 60 A. However, the curves in the experimental results are not that smooth due to numerical integration calculation errors, measurement accuracy, and manufacturing defects of the SRM. As shown in Fig. 19, the torque curves obtained from FEM are basically consistent with those from the experimental method, except that a few values at some specific rotor positions and phase currents deviate from the experimental results. It is because that the torques are calculated through two steps of numerical integrations and differentiation algorithms, which have potential errors.

VII. CONCLUSION

In this paper, the interactive excitation condition between two adjacent charged phases and two different magnetic circuits were analyzed for a four-phase 8/6 SRM. A novel modeling method considering interactive excitation was proposed for SRM based on mathematic model of mutual inductance and torque. The electromagnetic characteristics were analyzed and compared under various conditions, which show that the effects of interactive excitation need to be considered due to the great differences of static torque. Then, the dynamic model for the four-phase SRM was established and simulated based on the proposed motor model. The simulation results showed that the phase current and dynamic torque obtained from the dynamic model with proposed modeling method are different from those without proposed method. It can also be found that the torque differences under LMC and SMC are high enough and cannot be neglected. Finally, to verify the correctness of FEM results and new modeling method, an experiment was designed, and the results were calculated and analyzed. The simulation and experiment results both showed that the proposed modeling method has higher accuracy than the traditional model. In the future, we will continue to study the effects of mutual inductance between more phases on torque, which will contribute us to further study the electromagnetic characteristics of SRM. To improve the performance of SRM, more controlling methods will be proposed based on this model.

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