Chapter 13
Research on Low Frequency Torque Ripple of In-wheel Motor of Four Wheel Independent Drive

Zhe Li, Zheng Ling, Yue Ren, Yinong Li, Ke Wang and Zhenfei Zhan

Abstract In-wheel motor is a key power element for four wheel independent drive electric vehicle. It can supply accurate driving force control and achieve energy saving in electric power vehicle. Switched Reluctance (SR) motor has become an ideal candidate due to high output torque and reliable performance. However, huge output torque ripple in operation, which affects the comfort and handling stability of electric vehicle, limits its application in vehicle. In this paper, some factors behind low frequency noise and torque ripple of SR motor are investigated from a view of energy consumption including magnetic flux path pattern in SR motor and current imbalance. Furthermore, phase current balance control strategies to improve output torque ripple in operation are proposed. Results show that low frequency noise and torque ripple can be eliminated by applying the proposed current balance control strategy. It provides a good design method for SR motor to achieve excellent comfort and handling performance in four wheel independent drive vehicle.

Keywords Four wheel drive · Switched reluctance motor · Torque ripple · Control

13.1 Introduction

Four-wheel independent drive electric vehicle with in-wheel motors has cancelled the traditional mechanical transmission system. It has integrated wheel motor as power source, reduce the quality of the chassis, makes convenient arrangement possible. Additional, Acceleration Slip Regulation (ASR), Anti-Lock Braking system (ABS) and Electronic Stability Program (ESP) can be integrated easily and controlled due to an accurate driving/braking force control. It has become one of the future development direction of electric vehicle [1].

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Switched Reluctance Drive (SRD), as one of the optimal schemes of motor drive system for electric vehicle, has a series of competitive advantages. SRD system is composed of switched reluctance motor, power converter, motor controller and position detector. SR motor is the actuator of the SRD system. SR motor has doubly salient structure of rotor, composed of silicon steel laminations and without any form of winding, permanent magnet, slip ring. The stator of motor has simple concentrated winding, and end of the winding is short, So SR motor has the advantages of high reliability, simple structure and low maintenance. The operation principle of the SR motor is followed the magnetic flux along the minimum path closure, the output reluctance torque is irrelevant to current direction. Because only unidirectional current excitation is needed in operation, in theory, each phase winding of a power converter can be connected in series with a main switching device. This makes the power converter has the advantages of simple circuit, high reliability, prohibit the shoot-through state of the inverter bridge. SRD system has similar series characteristic of direct current contact motor. By controlling phase current amplitude, opening angle and the conduction angle, the controller can obtain the mechanical characteristics and is easy to implement the four quadrant operation. The power, torque-speed and efficiency characteristics of SRD system are very suitable for the motor drive system of electric vehicles. In addition, phases of SR motor are independent each other, can still run reliably under the condition of lack of phase, which makes the driving system has strong fault tolerance ability, above mentioned characteristics is not only crucial for driving system of four-wheel independent electric vehicle but also is an important advantage of SRD system relative to other drive systems.

Due to the impact of power supply current harmonic component, stator and rotor doubly salient characteristics, eccentric rotor, stator and rotor magnetic circuit saturation and error factors on motor control system measurement, driving motor of four-wheel drive electric vehicle is in operation of a certain range of torque ripple. The vibration and torque ripple will directly effect on tires and suspension, caused impact and fluctuation of longitudinal and vertical force between tire and ground, which can affect longitudinal driving performance of the vehicle, cause vertical vibration problem. If the wheel motor's torque ripple is too large, it may also lead to vehicle suspension resonance, located in its front and rear direction. Therefore, it is an important task for SR in-wheel motor drive system to study mechanism of torque ripple of driving motor and to use effective measures to eliminate the torque ripple.

For the moment, there are two methods to reduce the torque ripple of switched reluctance motor. One is in motor operation stage. By means of control methods such as Direct Torque Control (DTC), Current Chopper Control (CCC) and Angle Position Control (APC) to optimize output torque curve [2, 3]. The second is in motor design stage, by improving the structure of stator and rotor pole, to obtain the desired output torque curve. Finite element method (FEA) was used by Li [4] and Emmanuel [5] to analyze influence of the design parameters of SR motor, such as rotor and stator yoke height, air gap and pole arc on torque ripple. Mohammad [6], Zhang [7] used Search Optimization Approach (SOA), Genetic Algorithm (GA) and Ordinary Kriging (OK), to optimize the key parameter design of SR motor through design parameters of the switched reluctance motor as the optimization variables, output torque as the boundary condition, output torque ripple as optimization objectives. Lee [8] researched on SR motor flux distribution and effect of edge flux on torque ripple. The influence of different rotor pole shape on torque ripple of SR motor is studied by Dadpour [9], and the analysis results are verified by simulation. Hur [10] designed vacuum groove along the direction of magnetic circuit in stator pole, rotor pole and yoke of the motor respectively, achieved improvement of SR motor torque ripple by reducing radial magnetic flux density of the motor. Choi [11], Ozoglu [12], Tsuyoshi [13] change the first and second air gap of the motor, as a result, inductance/motor position curve was improved, torque ripple of the SR motor is partial eliminated.

Compared with the first method, the second focused on improving original output characteristics of the motor, which can fundamentally improve motor output characteristics and eliminate torque ripple. Most of the current researches focus on the problem of output torque ripple from control level, and the method of eliminating the torque ripple is not put forward from the design level. In this paper, the finite element model of SR motor is established, and the mechanism of low frequency noise and torque ripple of SR motor is studied from view of energy conversion, method of eliminating torque ripple is proposed and verified by two-dimensional finite element simulation. The research has laid a solid theoretical foundation for the application of SR motor drive system in electric vehicle.

13.2 Basic Operation Principles of SR Motor

Main drive system of independent drive electric vehicle is SR-motor which magnetic flux is in long flux path (LFP) pattern which phase windings are placed on opposite stator poles. Typical long magnetic path excitation 8/6 SR motor is shown in Fig. 13.1, in which, A2, A1 are stator poles.

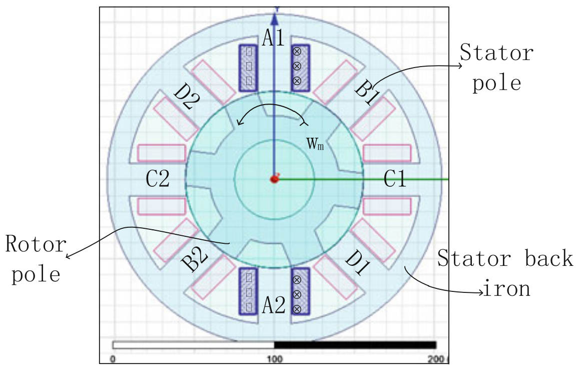

Fig. 13.1 Typical LFP structure SR motor

In an LFP-SRM, the mutual inductance effect between the windings is negligible. Thus, for a given phase, phase voltage of each is determined by the respective corresponding phase current as

$$v_a = r_a i_a + \frac{d\lambda_a(i_a,\theta)}{dt} = r_a i_a + N\frac{d\phi_a(i_a,\theta)}{dt} \text{ or } v_a = r_a i_a + l_a\frac{di_a}{dt} + e_a \quad (13.1)$$

Which, $l_a = \partial\lambda_a(i_a,\theta)/\partial i_a$ is the A phase winding inductance, $e_a = w\partial\lambda_a(i_a,\theta)/\partial\theta$ is rotational electromotive force of Phase A. Each phase of the motor is excited by independent current. For A phase winding excitation, electromagnetic co-energy is

$$W'_a(i_a,\theta) \triangleq \int_0^{i_a} \lambda_a(\varsigma,\theta)d\varsigma \quad (13.2)$$

Each phase of winding is excited and produced torque separately, is a function of the electromagnetic co-energy. A phase output torque is

$$T_a(i_a,\theta) = \frac{\partial W'_a(i_a,\theta)}{\partial\theta_m} = P_r\frac{\partial W'_a(i_a,\theta)}{\partial\theta} \quad (13.3)$$

For a four-phase machine operates at a specific time periods, the output torque is produced by all separate phases. The output torque is

$$T = T_a(i_a,\theta) + T_b(i_b,\theta) + T_c(i_c,\theta) + T_d(i_d,\theta) \quad (13.4)$$

13.3 Low Frequency Torque Ripple

Figure 13.2a is typical phase current waveforms of one 8/6 SRM during unipolar excitation. As shown in that diagram, each phase currents are unidirectional. Since self-excitation is not possible, operation of the motor in this mode needs the input current and bus voltage to feed enough power to every phase in excitation. When operate at high rotation rate, motor has a short time to form sufficient magnetic flux. Thus, the excitation interval it expanded, and increases the conduction angle. In an electric cycle, phenomenon of multi-phase excitation occurred in the presence of the adjacent two-phase winding current is observed at the same time. Since electrical phase shift between consecutive phases is smaller than conduction angle, as Fig. 13.2a shows, and a significant overlap between each phase currents can be observed, what is the reason of two consecutive phases conduct current simultaneously in one subinterval of corresponding electrical cycle. During the period, the adjacent phase flux linkage and inductance are all non-zero. As shown in Fig. 13.2b, in overlap region, D phase flux linkage drops while A phase flux rises.

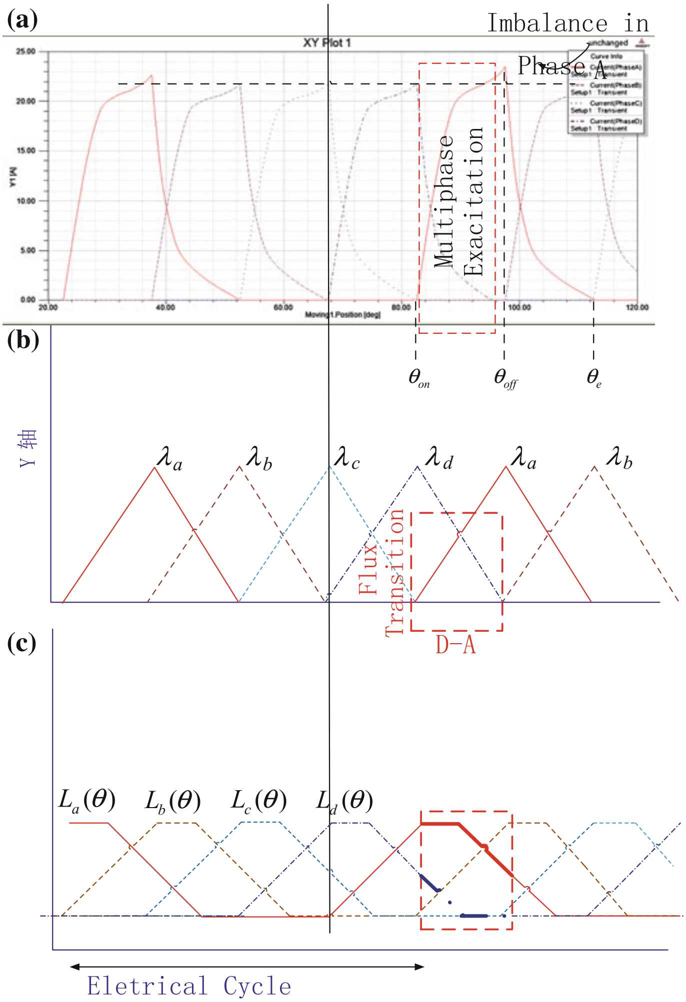

Fig. 13.2 Current/flux/inductance waveform

At the same time, each phase current appears over-lapping, the amplitude of A phase current waveform is higher than that of other phases.

13.3.1 Magnetic Flux Path Pattern of Motor

The distribution of magnetic intensity, flux density isodynamic lines of the prototype is illustrated in Fig. 13.3. Figure 13.3a shows relationship between induction flux polarity of each phase and winding mode.

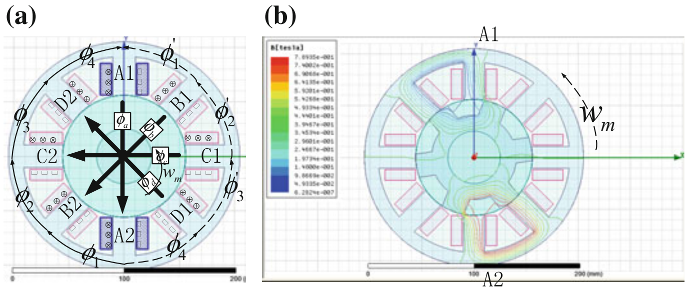

Fig. 13.3 Direction of induced magnetic flux

At a given moment ($\phi_d = \phi_a$) the magnetic flux density distribution of SR motor is shown in Fig. 13.3b, it can be seen that the motor magnetic circuit of short flux path excitation (SFPE) compared with LFPE, is much shorter. Such flux transitions happened four times in one electric cycle as shown in Fig. 13.2b.

$X \rightarrow Y$ indicate magnetic flux from X phase transfer to Y phase. $A \rightarrow B$, $B \rightarrow C$, $C \rightarrow D$ form LFPE while, $D \rightarrow A$, forms SFPE. This is because in the process of $D \rightarrow A$, A, D phase induction flux polarity direction is not consistent. That leads to changes in internal magnetic field and direction of the magnetic circuit of SR motor. It also changes magnetic induction intensity of SR motor. In addition, under the multi-phase excitation, the excitation mode of each phase is unbalanced. There exists at least one SFPE in SR motor with unipolar excitation during one electrical cycle.

In practice, even if each phase winding in a consistent and independent way to stimulate, the amplitude of each phase current is not identical. As shown in Fig. 13.2a, compared actually same current waveform of B, C, and D with A phase, the latter current amplitude is slightly higher than the other three. This inconsistent phase current waveform can cause the output torque $T = T_a + T_b + T_c + T_d$ and dc bus current i_{dc} ripple. Because the unbalance phase current only affects one phase of the motor. Therefore, the torque ripple and the motor bus current ripple caused by unbalance phase current is 1/n (n is the number of motor phase) times of the torque ripple when motor is running. That pulse is defined as low frequency torque ripple caused by phase current unbalance.

13.3.2 Current Imbalance Analysis

The induction magnetic flux polarity of typical four phase 8/6 SR motor is shown in Fig. 13.3a, stator yoke is divided into 8 sectors on average to determine the direction of the induced magnetic flux polarity. The axial symmetry of the magnetic flux is equal to the size of each part of the magnetic flux, such as the formula (13.5), each phase flux and the stator yoke of the various sectors of the magnetic flux as shown in Fig. 13.4.

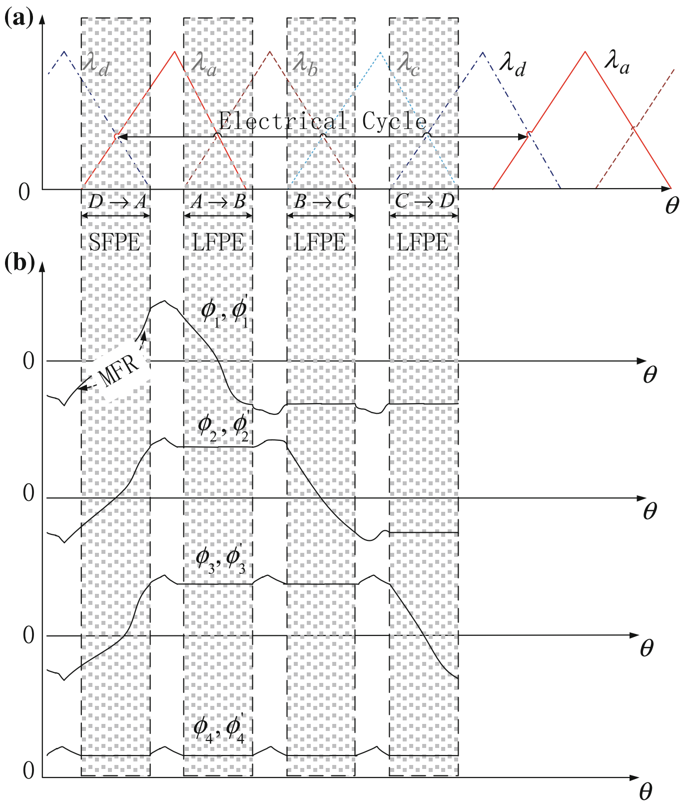

Fig. 13.4 Sector flux waveforms

$$
\begin{aligned}
\phi_1 = \phi_1' &= \frac{1}{2N}(\lambda_a - \lambda_b - \lambda_c - \lambda_d) \\
\phi_2 = \phi_2' &= \frac{1}{2N}(\lambda_a + \lambda_b - \lambda_c - \lambda_d) \\
\phi_3 = \phi_3' &= \frac{1}{2N}(\lambda_a + \lambda_b + \lambda_c - \lambda_d) \\
\phi_4 = \phi_4' &= \frac{1}{2N}(\lambda_a + \lambda_b + \lambda_c + \lambda_d)
\end{aligned}
\tag{13.5}
$$

Impact of rotor and stator poles on saturation affects is for all phases which do not the reason of unbalanced currents. Mutual inductance is usually ignorable in SRM of long flux path. Moreover, in order to attenuate mechanical vibrations, back iron of SRM is usually designed thickly in order to form a solid structure. Therefore, without causing saturation in rotor and stator poles, magnetic flux has enough space in the back iron to any consecutive phases to cross over. Accordingly, mutual inductance effect result of saturation in back iron also be neglected since it impacts all phases identically and does not cause the unbalanced currents. As shown in Fig. 13.4b, the magnetic flux polarity ϕ_1 reversal (MFPR) during the flux transition moment $D \rightarrow A$. There will be six MFPRs in the whole period $D \rightarrow A$, but only two times during the period $A \rightarrow B$, $B \rightarrow C$ and $C \rightarrow D$.

Under same conditions, core loss of long magnetic path is larger than that excitation in short path. The magnetic flux polarity reversal (MFPR) of the stator yoke in the whole SFPE mode is n-1 times of that in LFPE. So the core loss in SFPE mode of the stator yoke and whole motor is much larger than in LFPE mode. As in practice, more power is needed to deliver to phase through the phases involved in SFPE to supply the extra core loss. So, SFPE needs windings to provide additional energy to compensate more core loss of the motor. The imbalanced phase reveals a little higher peak current. Thus, iron core loss of the stator yoke section is the cause of the motor phase current imbalance and low frequency torque ripple.

The developed torque, phase current waveform, bus current and the phase inductance of unipolar exciting 12/8 three-phase SR motor without the current balancing technology are shown in Fig. 13.5, in an electric cycle, each phase excitation power in sequence, flux transition occurs in the overlap interval of the adjacent two-phase current. The current of three phases is placed in the same phase position as shown in Fig. 13.5b, A phase current is observed to have a higher amplitude, which is not balanced in the other two phases. The motor bus current and each phase winding inductance curve in Fig. 13.5c, d. Low frequency current ripple and the output torque ripple mark in Fig. 13.5c, e, can see the effect of phase current imbalance on the motor operation.

For three-phase SR motor, three flux transitions occur in an electric cycle, respectively as $A \rightarrow B$ (LFPE), $B \rightarrow C$ (LFPE) and $C \rightarrow A$ (SFPE). In $C \rightarrow A$, A phase winding inductance is much larger than that of in C phase. At this point, A phase winding is required to provide additional energy to motor to meet additional core loss caused during the flux transition of SFPE. A phase is carried unbalanced phase current, which is reflected in Fig. 13.5a, b, has higher peak value and lager amplitude compared with other two phases. Figure 13.5e shows that output torque is affected by imbalance of phase current. The torque of srm is $T_e = \frac{1}{2} i^2 \frac{dL}{d\theta}$, proportional to the square of the current, makes effect of unbalanced current on the output torque curve is more obvious.

13.4 Phase Current Balance Control

Based on the above discussion, unbalanced phase current caused low frequency output torque ripple of the motor and fluctuation of the bus current. In order to eliminate this kind of fluctuation, this paper develops a kind of phase current balancing method, by changing the coil winding mode or the power switch tube topology, LFPE mode during magnetic flux transition is converted into SFPE mode. This balancing technology regulates phase current direction to ensure similar

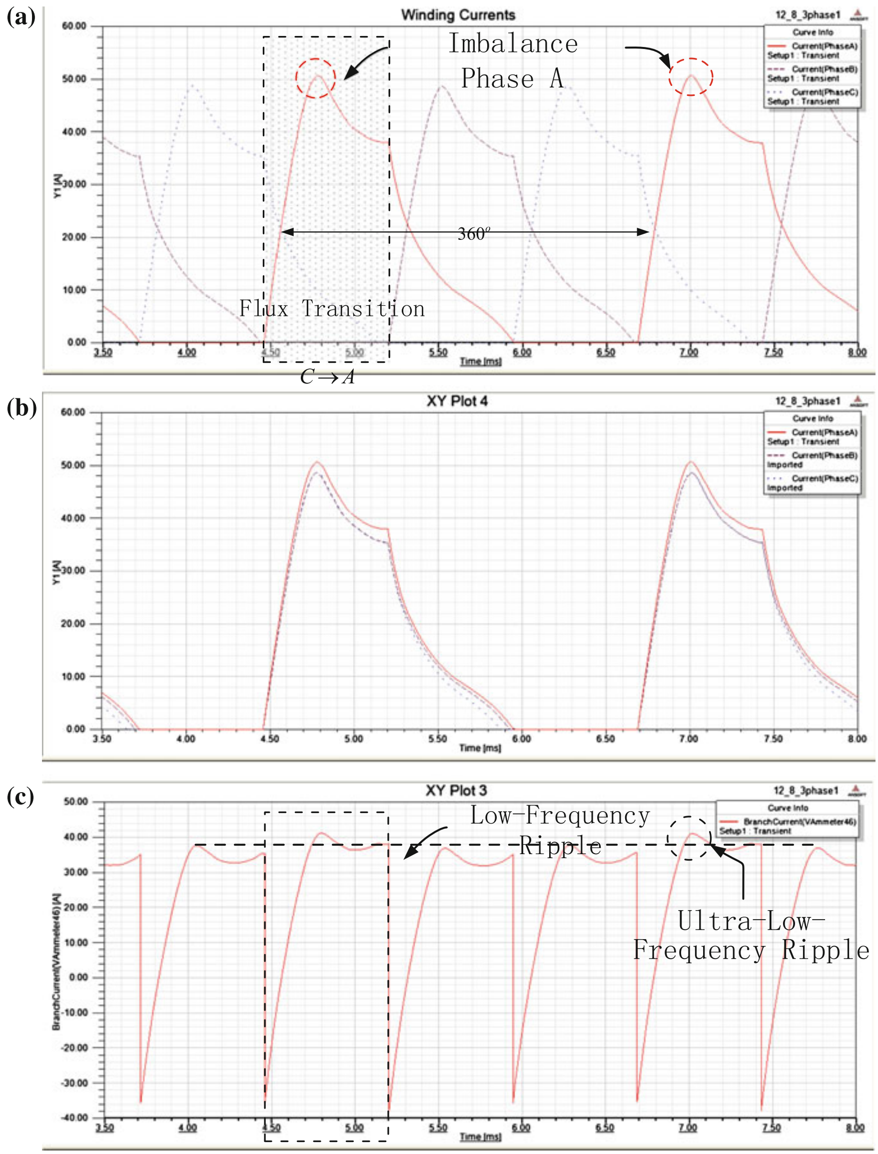

Fig. 13.5 SR motor output curve without current balancing strategy

magnetic flux path pattern for adjacent phases, is applicable to 3 phase and 4 phase SR motor.

Unipolar excitation SR induction flux polarity can be arbitrarily selected, traditional 12/8 three-phase and 8/6 four-phase switched reluctance motor in each coiling winding mode and induced polarity as shown in Figs. 13.6 and 13.7.

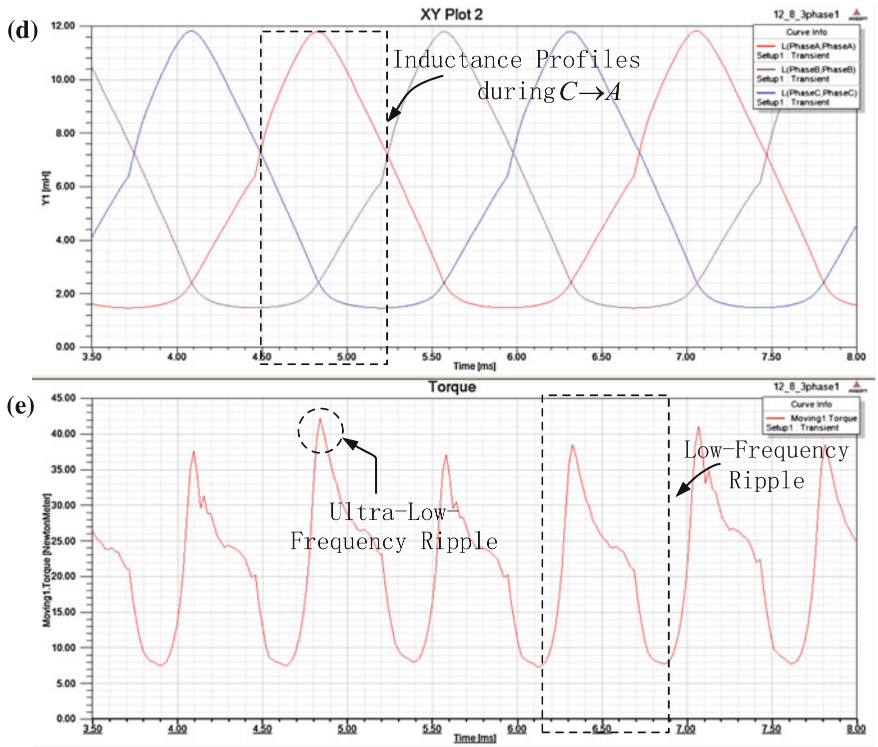

Fig. 13.5 (continued)

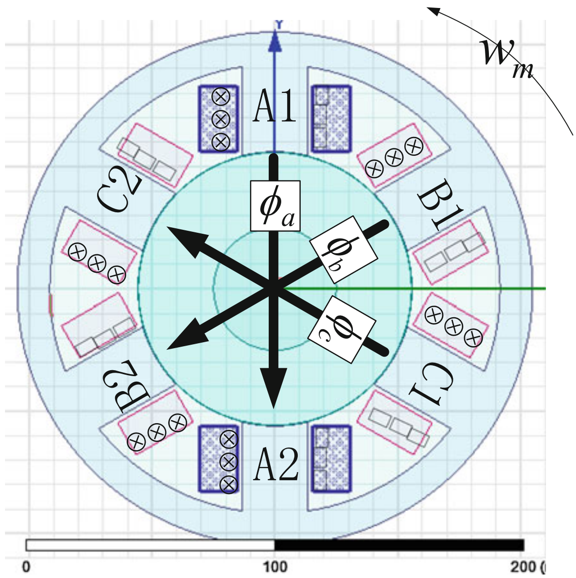

Fig. 13.6 6/4 induced polarity

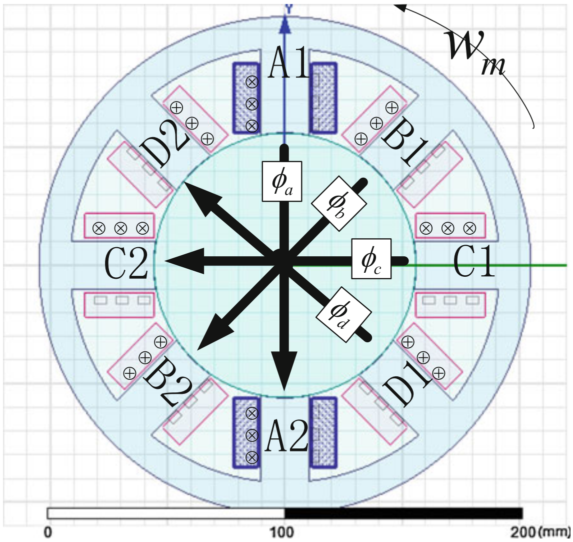

Fig. 13.7 8/6 induced polarity

13.4.1 Motor Current Balancing Strategy with Odd Phase

Induced flux polarity of switch reluctance motor is determined by coiling winding mode. Current direction and induced flux polarity in all phases of SRM can be arbitrarily set up. But, as current direction is assigned, it will be fixed when the machine is under operation. As shown in Fig. 13.6, flux polarity of motor from top to bottom is NNNSSS, in transition period between two adjacent phases when one phase cut and the next phase conduction, $N \leftrightarrow N$ formed LFPE and $N \leftrightarrow S$ formed SFPE, that inconsistency cased unbalanced current. As shown in Fig. 13.8, by

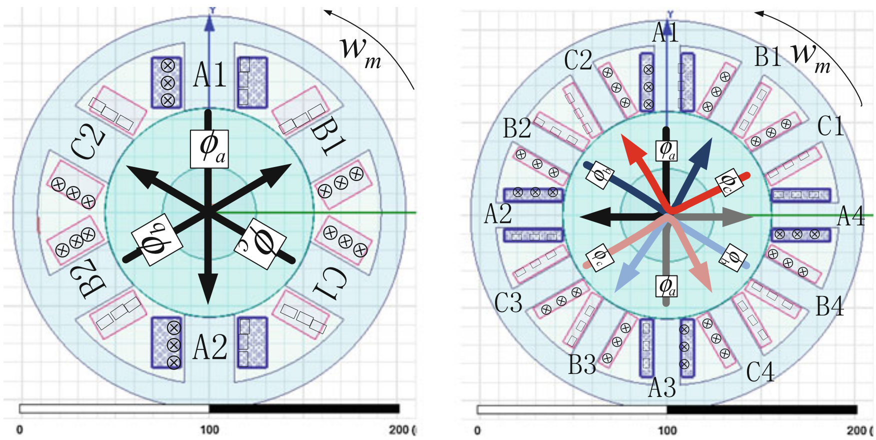

Fig. 13.8 Change the magnetic flux polarity by winding

changing the B phase winding coiling mode to change the current direction, and B phase induced magnetic flux polarity reversal. This motor stator poles formed NSNSNS. Only exists SFPE during flux transition, phase current waveform balance, low frequency torque ripple can be eliminated. This method is only applicable to the switched reluctance motor with odd phase.

The obtained phase current, bus current and output torque waveforms by two-dimensional finite element simulation are shown in Fig. 13.9. As can be seen, ripple of bus current and motor output torque is eliminated and phase currents are balanced.

13.4.2 Motor Current Balancing Strategy with Even Phase

For the even phase of the switched reluctance motor, 8/6 pole four phase switched reluctance motor coiling winding mode and induced magnetic flux polarity is shown in Fig. 13.7, induction flux polarity of stator pole from top to bottom in turn, NNNNSSSS. In order to make magnetic flux path pattern during flux transition only in SFPE or LFPE mode, change a single phase current direction is not feasible. In order to solve this problem, adds a control path in each phase of the motor power converter, the motor in the period of two adjacent electric cycles is excited by current with direction of one positive and one negative which have the same absolute value and waveform. So the magnetic flux polarity of the motor is changed to NSNSNSNS, and the magnetic flux path pattern of SFPE is formed. As rotation direction and output torque direction of the switched reluctance motor are not related to the direction of excitation current, this method will not affect the output power and torque of the switched reluctance motor. The excitation voltage of A phase switched reluctance motor with conventional unipolar excitation and current balancing strategy are shown in Fig. 13.10.

The single phase and the whole power converter topology of the power converter are shown in Fig. 13.11, adding a loop on each phase power switch tube circuit. During the operation of the motor, the switching frequency of each circuit is half of the original configuration.

Phase current, bus current and motor output torque waveforms by two-dimensional finite element simulation are shown in Fig. 13.12. It can be seen that the phase currents are balanced. Low frequency torque ripple of bus current and motor output torque ripple is also eliminated.

The output torque is put in the frequency domain as shown in Fig. 13.13a, b. It can be seen from Fig. 13.13a the harmonic frequency of producing output torque ripple frequency of switched reluctance motor is 350 Hz, which is caused by the switching of each phase, is determined by phase number of motor and motor speed. In the 1/4 of the torque ripple frequency, low frequency torque ripple caused by the phase current unbalance is observed. Compared with Fig. 13.13a, b, the balance strategy has a good effect on the elimination of low frequency torque ripple of motor output torque.

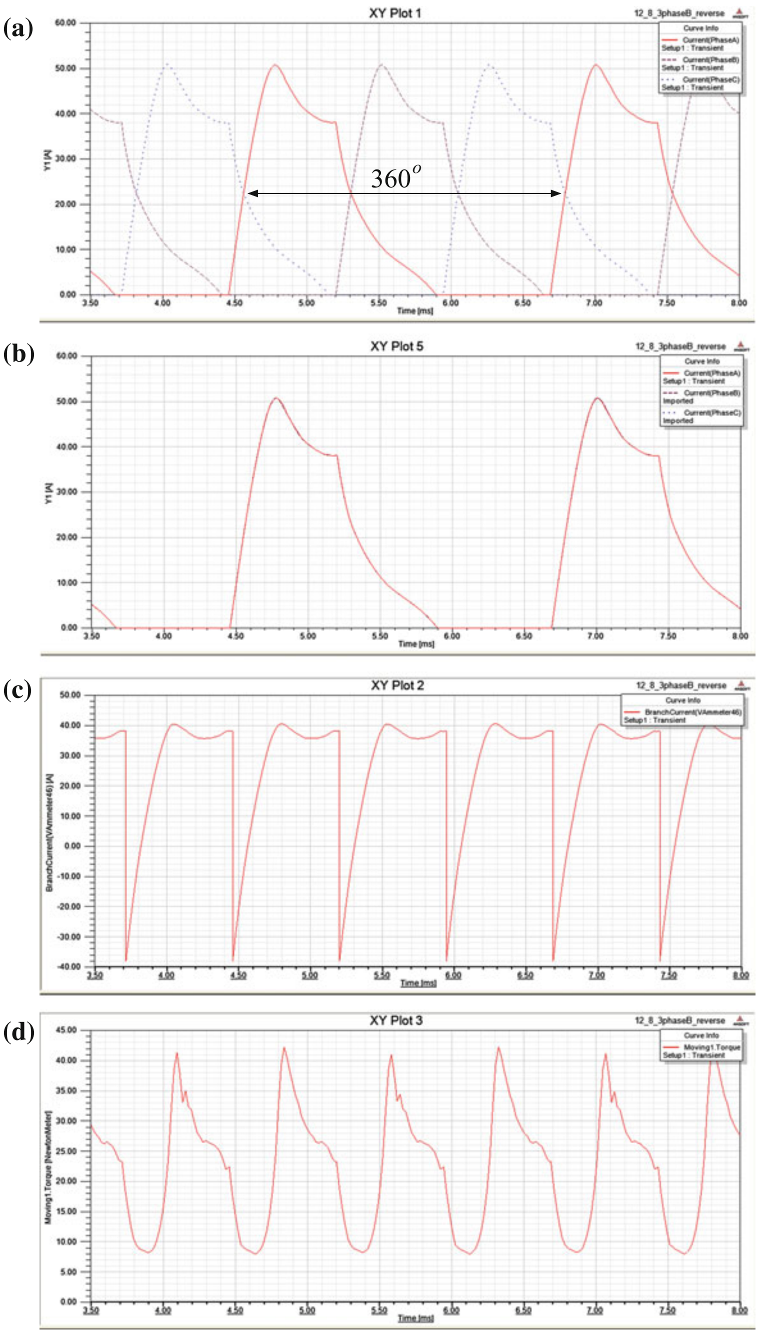

Fig. 13.9 Phase current/bus current/output torque curve

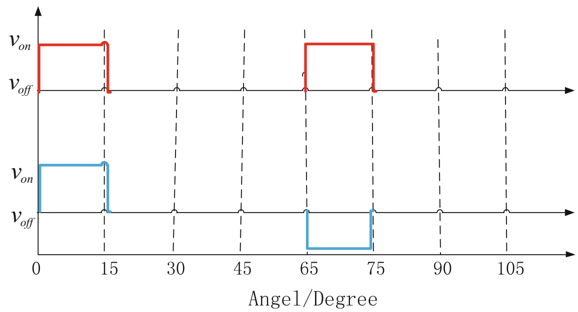

Fig. 13.10 Current excitation mode

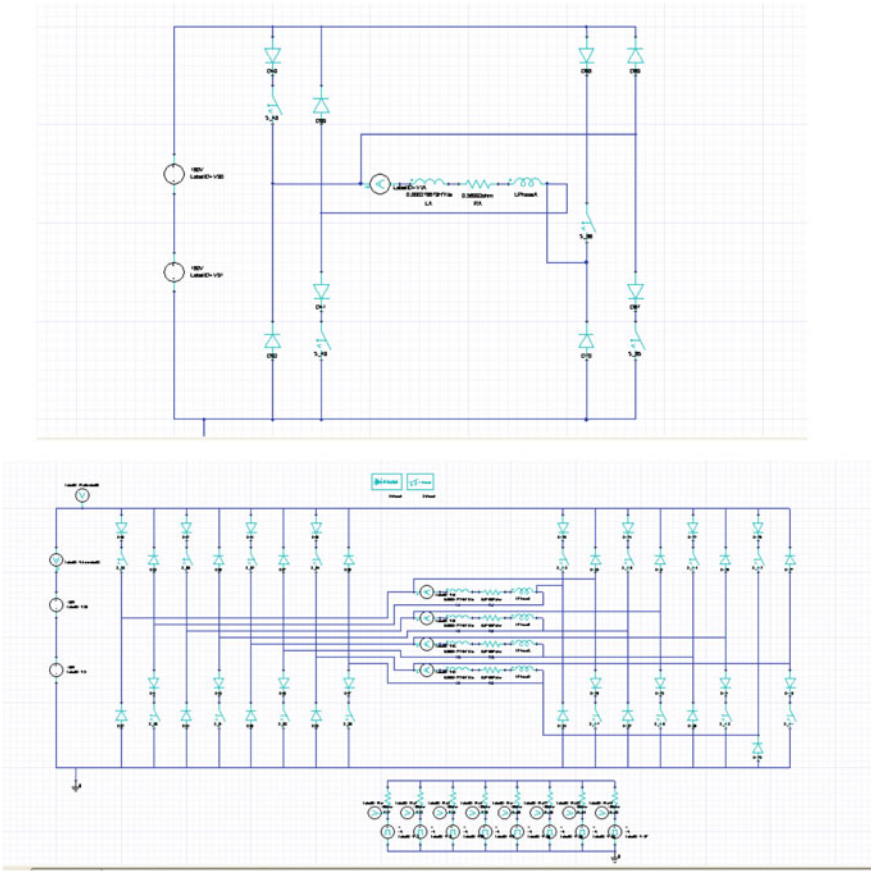

Fig. 13.11 Topology of power converter

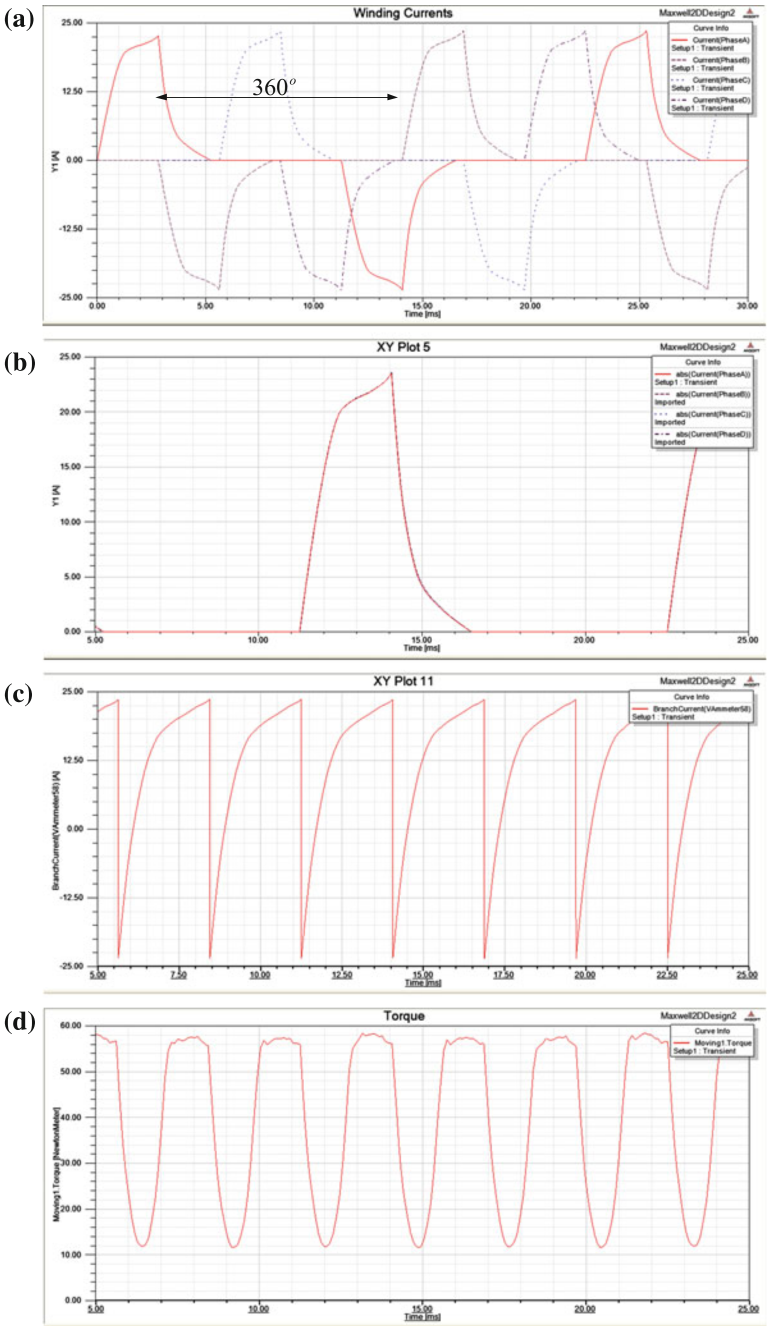

Fig. 13.12 Performance output curve of even phase SR motor

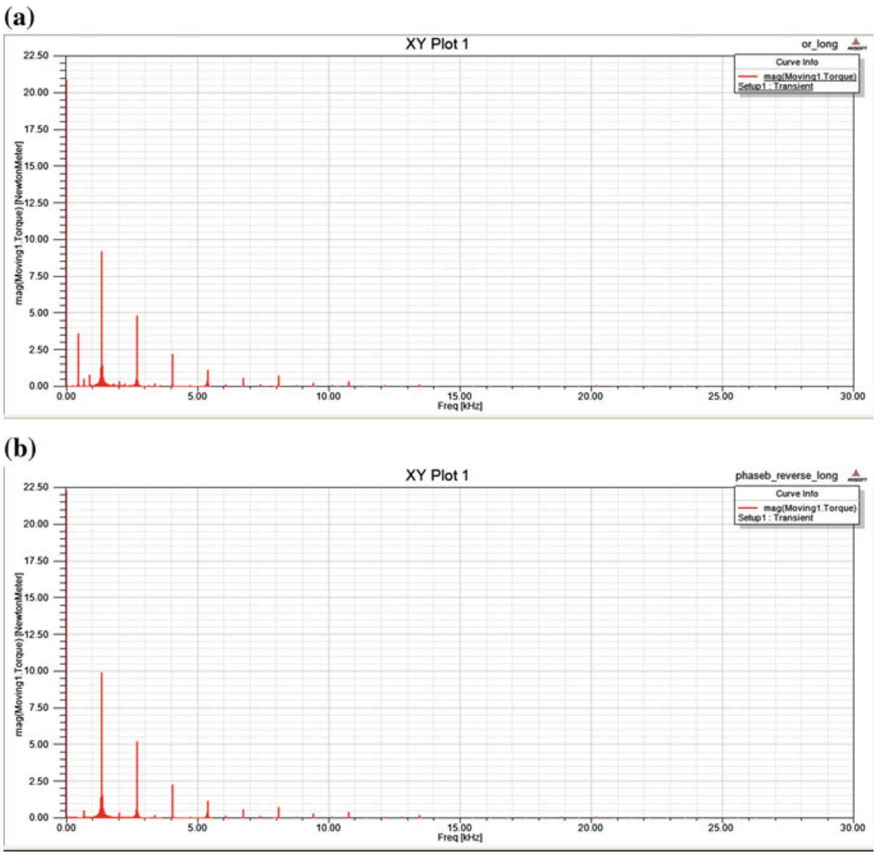

Fig. 13.13 Frequency domain of output torque

13.5 Conclusion

In this paper, problem of low frequency torque ripple of in-wheel-motor is analyzed in detail from energy viewpoint. An elimination of the current balancing strategy is developed, and the main conclusions are as follows:

(1) Unipolar excitation switch reluctance motor exist different magnetic flux polarity reversal (MFPR) during flux transitions, due to the MFPR directly in part of the energy distribution of core. This difference, results phase currents unbalanced, that one phase has higher or lower peak current amplitude, leads to the emergence of low frequency torque ripple.
(2) A phase current balancing strategy is proposed, this technique changes current direction of each phase for even phase machine and changes winding coiling mode for odd machine to ensure similar magnetic flux path pattern for adjacent phases, which exhibits a wonderful current balancing performance for not only

3 phase but also 4 phase machines, and low frequency torque ripple can be eliminated which can significantly alleviate the motor output torque ripple, improve motor performance. Thus, improve vertical and longitudinal driving performance of the four wheel drive electric vehicle.

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