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Application of Switched Reluctance Motor in Electric Vehicle Drive System

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Abstract By studying the operating mechanism of switched reluctance motors, its application in electric vehicle drive systems is elaborated in detail, and the structure, operation strategy and control strategy of electric drive systems of switched reluctance motors are analyzed. Combined with the basic structure and working principle of the switched reluctance motor, its application in the field of electric vehicle driving is explained, and the current application of the switched reluctance motor in the driving field at home and abroad is introduced. According to the structure of the electric vehicle drive system and the driver's operating habits in the actual situation, the working process of the electric vehicle to adjust the switched reluctance motor during the starting, accelerating, decelerating, reversing, parking, uniform speed and other running actions is analyzed. According to the characteristics of the switched reluctance motor, its three operating characteristics are introduced respectively, and the speed regulation schemes of starting chopper control, natural commutation control, variable angle chopper control and single pulse control are analyzed in detail. Improve the feedback method of the drive system, analyze the startup control strategy of the electric vehicle in the acceleration starting mode, and propose two methods to stabilize the motor output torque by limiting the current upper and lower limits and the off time of the switch tube. The simulation verifies the correctness of the two methods.

Keywords Electric vehicle; switched reluctance motor; drive system; control system

Introduction

Switched reluctance motor is a new type of motor that was developed in the 1970s and developed rapidly in the 1980s. It has simple structure, easy control, high efficiency and energy saving, wide speed range, high fault tolerance, simple reliability and low cost. Switched reluctance motor has two basic characteristics: one is switching: the motor must work in a continuous switching mode; the other is reluctance: it is a double salient motor with variable reluctance circuits on the stator and rotor.

Compared with internal combustion engine cars, electric cars appeared earlier. As early as 1834, the world's first electric car came out. Electric cars became popular at the end of the nineteenth century, but with the invention of internal combustion engine cars, electric cars gradually disappeared from people's vision. It was not until the outbreak of the Middle East oil crisis in the 1970s that governments around the world began to pay attention to the use of new energy, and electric vehicles returned to people's vision. One of the leaders in the automotive industry of Toyota, Japan, began to develop electric vehicles in 1971. By the 1990s, basically every year the company would launch an electric vehicle, mainly hybrid electric vehicles. Honda Japan also regards the research and development of electric vehicles as one of its main research and development directions. Its main research and development projects include hybrid electric vehicles and fuel cell electric vehicles. General Motors in the United States also started its research on electric vehicles relatively early, and its main research direction is also hybrid electric vehicles and fuel cell electric vehicles. General Motors researched a wide range of vehicle types, including trucks, buses, cars and so on. It was an extended-range car that came out in the year. In the case of pure electric power, its driving range can reach 483km, and when the extended range is activated, the cruising range can reach 1000km. In addition, North American Ford, Italy's Fiat, France's Citroen, Germany's BMW and other auto manufacturers are also actively involved in the research and development of electric vehicles, and various electric vehicles continue to emerge in the market.

Application of Switched Reluctance Motor in Electric Vehicle Drive

The switched reluctance motor operates according to the "reluctance minimization principle". When a certain phase of the stator is energized, the magnetic field generated by the phase winding will generate a tangential pulling force according to the twist of the magnetic field lines, so that the adjacent rotor pole axis is based on the pulling force. The action rotates to a position aligned with the pole axis of the energized stator, which is the position where the magnetic resistance is the smallest. Figure 1 is a structure diagram of a four-phase 12/8-pole SRM. Only one phase is shown in the figure. Take the switched reluctance motor as an example. When the rotor magnetic pole center line coincides with the stator magnetic pole center line, the inductance of the phase winding Maximum, when the center line of the rotor slot coincides with the center line of the stator pole, the phase inductance is the smallest. The moving direction of the switched reluctance motor rotor is always opposite to the moving direction of the magnetic field axis, and has nothing to do with the direction of the current. According to the number of rotor teeth Nr and the number of motor phases m, the pole pitch angle t_r of the rotor can be calculated as:

$$t_r = \frac{2\pi}{N_r} \quad (1)$$

And the step angle ap for each phase on and off is:

$$a_p = \frac{2\pi}{mN_r} \quad (2)$$

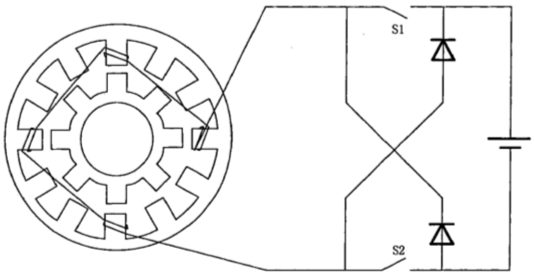

Figure 1: Structure diagram of switched reluctance motor

With the increasing proportion of electric vehicles in the automotive industry, switched reluctance motors have developed well in this field. As the drive motor of electric vehicles, it needs to meet the requirements of reliable structure, easy maintenance, adaptability to variable road conditions, frequent start and stop, wide speed range, and high torque at low speed. Switched reluctance motors perform in these aspects. It has great advantages and has been successfully applied to a variety of electric vehicles outside China.

In foreign countries, switched reluctance motors have been widely used in the driving direction of electric vehicles. In the early 1970s, the Ford Company of the United States first invested in the research of switched reluctance motor control systems. The structure of the switched reluctance motor speed control system studied by him is an axial air gap motor, which is used in a variety of electric vehicles. In 1975, the University of Leeds and University of Nottingham jointly developed a 50KW switched reluctance motor device and successfully applied it to electric vehicles. In the early 1990s, the UK had successfully developed a 300KW switched reluctance motor and applied it to the scraper conveyor, with very good results. The electric booster developed by Tridelta Company of the United States is driven by a small gasoline engine. When energy concentration and system efficiency are considered, the switched reluctance motor is a must.

In China, 110KW switched reluctance motors have been successfully developed for use in gangue winches, and 132KW switched reluctance motors are used for belt conveyor driving. Good starting and speed regulation performance are welcomed by workers. China also uses reluctance motors in the traction device of coal mining machines, and the operation test shows that the new coal mining machines perform well. In addition, switched reluctance motors have been successfully used in electric locomotives, which improves the reliability and efficiency of the operation of electric locomotives. The switched reluctance motor research group of Huazhong University of Science and Technology developed a pure electric car using SRM in the "Ninth Five-Year Plan" project, and will be applied to hybrid city buses in the "Tenth Five-Year Plan" project, and has achieved good operating results. Dongfeng's hybrid buses have already used switched reluctance motor systems. It is the first demonstration team in China to successfully use switched reluctance motor systems. The fuel-saving rate of the vehicle is as high as 25%, and the distance between failures has exceeded 10,000 kilometers. However, in the field of pure electric vehicles, the drive motors for electric vehicles on the market are mainly brushed DC motors. China's application of switched reluctance motors in small pure electric vehicles is still in the research and development stage.

Structure and Operation Analysis of Electric Vehicle Drive System Based on Switched Reluctance Motor

Electric Vehicle Drive System Structure of Switched Reluctance Motor

The drive system of a pure electric vehicle mainly consists of three parts: a motor drive module, a power supply module and an auxiliary module. The electric vehicle drive system based on switched reluctance motor studied in this paper mainly refers to the motor drive module. The motor drive module mainly includes a controller, a power converter, a closed reluctance motor, a mechanical transmission device and a braking device. In order to make the driver more accustomed to operation, the accelerator pedal, brake pedal and gear lever are retained in this design, but the clutch pedal is omitted. The accelerator pedal is actually a sliding rheostat. By changing the resistance, the voltage signal input to the controller can be changed to control the motor in real time; the brake pedal is basically the same as the brake pedal of a traditional car, and is mainly used to control mechanical braking. The device performs external mechanical braking; the gear position handle only retains the three gears of forward gear, neutral gear and reverse gear, and sends forward, parking and reverse signals respectively.

Operational Analysis of Electric Vehicle Driven by Switched Reluctance Motor

Under the control of the controller, the switched reluctance motor starts, accelerates, decelerates, reverses, stops, and runs at a constant speed according to the instructions given by the driver. The driver presses the start button to switch the power supply and the power converter. The electric vehicle enters the starting state. When the start button is not pressed, the gear handle, accelerator pedal and brake pedal will not work; after starting, the acceleration and deceleration are controlled by the same accelerator pedal. The acceleration command is given when it is irritated, and when it is lifted, Deceleration command; when the motor speed reaches the speed set by the driver, the car runs at a constant speed, and the controller calls different control methods according to different speeds; when the brake pedal gives a braking command, the motor enters the electric brake and When the mechanical brake is acting simultaneously, when the motor speed drops to zero, it enters the mechanical lock state. According to the specific functions that the electric vehicle needs to realize, the control situation that the switch reluctance motor drive system needs to realize is summarized as follows:

(1) Start: the driver presses the start button, the entire drive system is powered on, and the forward direction is given through the gear handle Or retreat the command, the accelerator pedal motor enters the start state, the controller calls the start control command to accelerate according to the acceleration and target speed set by the system, when the speed reaches the given speed, the start ends, and the controller makes the motor run through closed-loop adjustment In the hook speed state; if the given speed is greater than the startup speed set by the system startup program, after reaching the maximum startup speed, exit the startup program, and the controller calls the acceleration program to make the motor continue to accelerate until it reaches the given speed.

(2) Acceleration and deceleration: The system's acceleration and deceleration actions are completed by the controller internally processing signals such as given speed, feedback speed, and feedback current and calling specific control programs.

(3) Reversing: the gear lever gives a back instruction. If the motor speed is zero at this time, the reversing process is similar to the start process; if there is a positive speed at this time, the controller first calls the brake program to perform electrical braking, and waits. The speed drops to zero and then reverse start.

(4) Uniform speed operation: The motor can operate at a uniform speed within the range, and the actual control signal is given after adjusting the given speed, feedback speed and feedback current.

Control Analysis of Electric Vehicle Drive System Based on Switched Reluctance Motor

The electric vehicle drive system based on the switched reluctance motor is mainly composed of five parts: battery, switched reluctance motor, power conversion circuit, controller and detection circuit. The battery provides all the electrical energy for the operation of the electric vehicle, and the power conversion circuit provides the motor running time. The detection circuit includes a position detection circuit and a current detection circuit. The position sensor detects the relative position of the rotor. The speed of the position change reflects the speed of the speed change. The current sensor detects the current of each phase of the motor, and the speed signal and current signal are input to the controller. Processing calculations, and then the controller provides control signals to control the selection of the opening and closing angles of each phase of the motor and the judgment of the energization logic, so as to output the PWM wave through the isolation and amplification of the power conversion circuit to control the work of the switched reluctance motor.

The control process of a switched reluctance motor includes motor electric control and motor power generation control. The two are combined into one, which not only includes the process of converting electrical energy into mechanical energy, but also the process of returning mechanical energy to electrical energy. The main characteristics of this control system are: the same set of hardware circuits are used, and different control methods are used at different moments of energy conversion, so that the power generation process and the electric process are combined to achieve the purpose of energy saving. Controlling a switched reluctance motor is mainly to control its turn-on time, turn-off time, the maximum value and average value of each phase current, and the control of the bus voltage. Changing one of the parameters individually or changing multiple parameters at the same time will produce multiple controls. Methods, single pulse control method (APC), current PWM control method (CCC) and voltage chopping control method (CVC) are the more commonly used control methods.

Speed Control Strategy of Switched Reluctance Motor

According to the characteristics of the switched reluctance motor, its operating characteristics can be divided into three areas:

(1) Constant torque area: When the speed of the switched reluctance motor is lower than the critical speed ω_{rc}, the motor exhibits constant torque characteristics. In this area, due to the low speed, low back EMF, the phase current rises quickly, the current needs to be chopped control, and it can also be controlled by adjusting the effective value of the voltage applied to the winding.

(2) Constant power zone: When the motor speed is higher than ω_{rc} and less than ω_{sc}, the power of the motor can remain unchanged, and the torque of the motor will decrease with the increase of speed and enter the constant power zone. At this time, the angle position control method is generally adopted, and the speed is controlled by changing the opening time of the switching tube or changing the closing time of the switching tube.

(3) Natural characteristics area: When the speed is greater than ω_{sc}, since the bus voltage and the switching time and other parameters have reached the limit value, the motor will output according to its natural characteristics.

According to the operating characteristics of the switched reluctance motor, its speed regulation characteristics can be divided into three parts, current PWM control area (CCC), single pulse control area (APC) and series excitation characteristics area, as shown in Figure 2, ω_0 is the maximum speed limit for starting chopping, ω_{Cmax} is the maximum speed limit for CCC control. Under normal circumstances, current PWM control (CCC) control is used at low speed, and single pulse control (APC) control is used at high speed. In the design, attention must be paid to ensure the connection of the two modes.

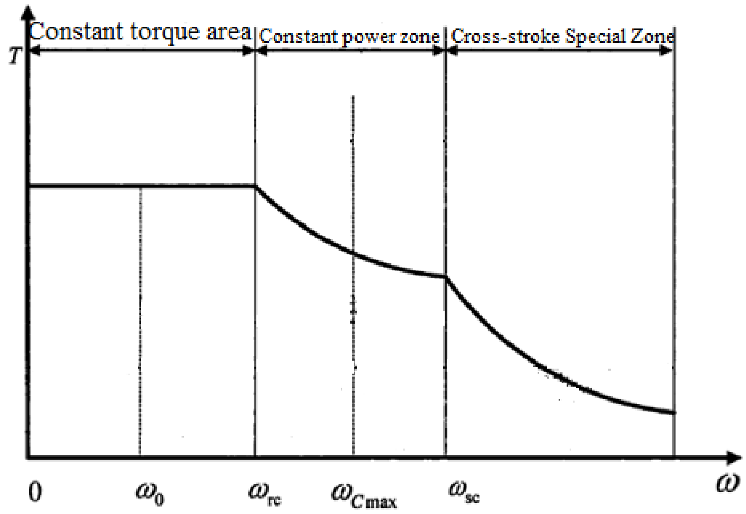

Figure 2: Switched reluctance motor control method

In order to ensure a good connection between the two modes of conversion, the speed control methods at different speeds can be subdivided, and the two methods can be combined at medium speed to form a complete speed control scheme: (1) Start the chopper switch There are two main ways to start reluctance motors, single-phase energized starting method and two-phase energized starting method: single-phase energized starting method refers to a constant current to one phase winding of the motor when starting, with the difference of the rotor angle , The electromagnetic torque produced by the motor is also different; the two-phase energized start mode means that at each moment of start, there are two energized at the same time, and the starting torque is the sum of the torques produced by the two-phase windings. In general, if the parameter settings are reasonable, the two-phase start will increase the average torque at start and increase the load capacity of the motor, and the two-phase start can reduce the torque ripple. Under the same load torque, the two phases are energized the starting phase current will be less than the current amplitude of single-phase power-on starting.

(2) The natural commutation is in the range of 500~1500r/min, and the single-phase energization is maintained, and the natural commutation method is adopted. Each phase is energized between the inductance 0°~15°, the opening angle is 0°, and the switching off the angle is 15°, and the current PWM control method is used for control. Because the speed is not high, it will not cause the current to flow to the area where the inductance begins to drop and generate negative torque.

(3) The variable-angle chopping speed keeps increasing, the phase current rise time will be shorter, and the natural commutation may be turned off before the current reaches a sufficient amplitude, so when the speed is present, the system uses the turn-on The control method of angular premise and fixed cut-off angle gradually advances the cut-off angle by a certain angle as the speed increases, so that the phase current can have sufficient rise time and can generate greater torque.

(4) Single pulse control (APC) When the motor speed is in the range of 2500~3000r/min, in order to prevent the phase current from continuing to flow to the inductance drop zone and generate the braking torque, the opening angle and the closing angle are used to move to the premise at the same time. way to control.

The single pulse control method means that the bus voltage does not change. In order to improve the phase current waveform, the turn-on and turn-off moments of the main switching device in the power conversion circuit are changed, that is, the energization time of each phase winding is changed to realize the control of the motor speed. When the motor runs at a high speed, when the bus voltage is constant, when the speed drops, in order to prevent the torque from falling too fast, it is necessary to change the energization time of the phase winding by changing the values of the opening angle θ_on and the closing angle θ_{off}, So as to obtain the required large current. When the opening angle θ_on changes, the parameters such as the maximum value and effective value of the current waveform will change accordingly, and the relative position of the inductance waveform and it will also change, so the output torque and speed of the motor will also be changed. When the turn-on angle θ_{on} is fixed, the change of the turn-off angle θ_{off} can control the turn-on time. If θ_{off} is too small, the phase current will end prematurely; if θ_{off} is too large, negative torque will be generated. It is the relationship between T_e and θ_{on} and θ_{off} in APC mode.

The main characteristics of angular position control are: the torque adjustment range is large, it can be turned on at the same time, and the efficiency of the motor is high. However, the maximum current in this control method is mainly determined by the rotating electromotive force of the motor, so it is not suitable for low-speed operation.

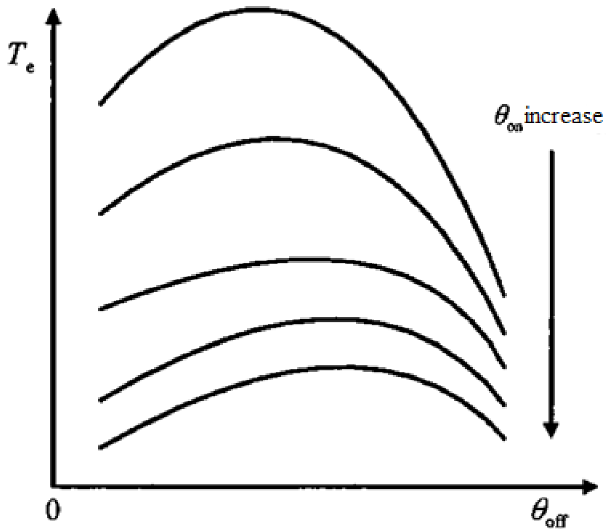

Figure 3: The relationship between T_e and θ_{on}、 θ_{off} in APC mode

Start Control Strategy of Switched Reluctance Motor

In order to ensure that the electric vehicle can reach the set speed in a short time when starting, the feedback mode of the system can be improved, and the traditional speed-current loop double closed loop is changed to the acceleration-current double closed loop control, which is called acceleration start mode. The starting method is to replace the speed ring with the acceleration ring, which can speed up the speed adjustment during the starting process.

When the driver gives a start command, the system mechanical brake is released, the controller starts according to the preset acceleration and the target speed given by the accelerator pedal, and the current loop performs current PWM control. When the electric vehicle reaches the set speed, Enter the state of constant speed operation, the controller controls the motor to run at a constant speed according to the comparison between the feedback and the given, and waits for the next instruction to be given.

It can be seen from the definition of acceleration that acceleration refers to the change in speed per unit time, and the motor controller determines the value of acceleration by measuring the change in speed in the same time interval. The controller gives a given acceleration when starting, and through the adjustment of the acceleration loop, the output of the acceleration loop is used as the input of the current loop. The current loop is adjusted by PI and the input controller controls the motor.

Current PWM control method (CCC) means that when the motor starts or runs slowly, the rotating electromotive force can only produce a small voltage drop, which will cause the phase current to increase quickly, and the maximum current may exceed the power and shutoff device or the allowable range of the motor itself, so it is necessary to limit the maximum value of the current pulse. At this time, it is necessary to use a control method to limit the maximum value of the current to obtain a more stable torque output. CCC control does not directly control its turn-on and turn-off angles, but performs current PWM control at a specific position of each turn-on phase. Control is generally carried out in the inductance change area. In order to make the output torque of the motor more stable, the value of the current must be limited by turning on and turning off the main switch for multiple times, so that it can only change within a certain range. There are usually the following two implementation methods.

① Limit the upper and lower limits of the current. When detecting that the current is greater than the upper limit I_max given by the system, the controller will send a command to control the power switch to turn off; when it detects that the current is less than the lower limit I_min given by the system, the controller sends a command to control the power switch to turn on. When the phase winding inductance is small, the switching tube's operating frequency is relatively high; when the phase inductance is large, the operating frequency will become smaller, and the chopping conditions of the upper and lower limits of the current limit are shown in Figure 4.

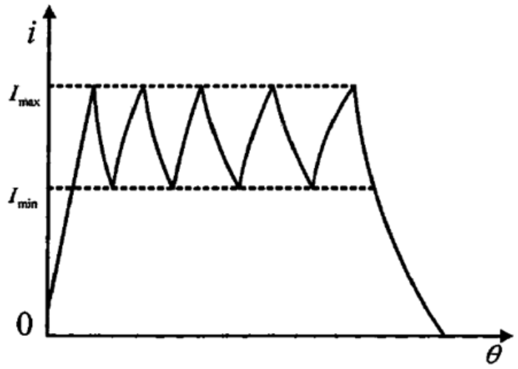

Figure 4: Chopper diagram for limiting current upper and lower limits

The maximum current and the time when the switch is turned off are certain. When the detected current reaches the maximum current I_max given by the system, the controller sends a control command to control the power switch to turn off. After the Δt time has elapsed, the controller reissues a command to control the power switch to turn on, and so on. Figure 5 shows the phase current chopping diagram in this mode.

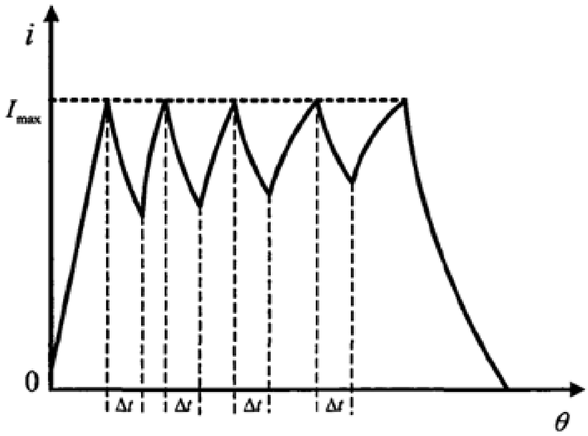

Figure 5: Chopper diagram for limiting current upper limit and off time

Current PWM control can control the output torque in a relatively stable range, which is suitable for control occasions where the maximum current is relatively large. However, the current change range in CCC control is small. When the motor output torque needs to change significantly, it is difficult to automatically adjust the current chopping value, which will make the entire system respond slower to this sudden change.

Simulation of Switched Reluctance Motor in Different Control Modes

According to the above-mentioned switched reluctance motor speed control strategy, the current chopping control (CCC) method and the single pulse control (APC) method are used to simulate the different states of the switched reluctance motor.

This article uses Maxwell software to model and simulate switched reluctance motors. The simulated motor model is a three-phase 12/8-pole switched reluctance motor with a rated power of 2.2KW, a rated speed of 3450r/min, a rated voltage of 280V, and a normal operating temperature of 75°C.

First, establish a two-dimensional model of the switched reluctance motor based on the basic parameters of the motor, set the solution parameters in Maxwell, and prepare for solution, as shown in Figure 6.

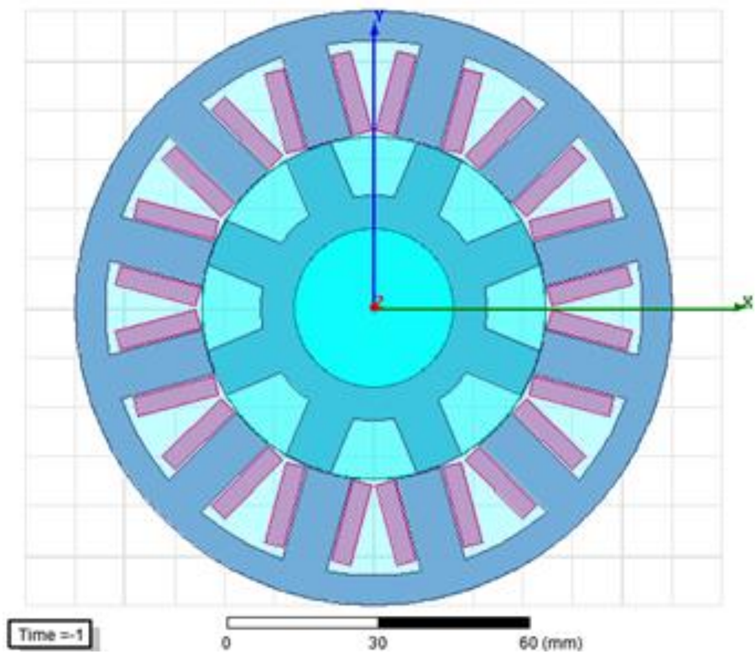

Figure 6: Modeling diagram of switched reluctance motor

Simulation of Switched Reluctance Motor Current Chopping Control (CCC)

It can be seen from Figure 2 that in the constant torque area of the motor, since the motor speed is low and the motor back EMF is small, the phase current needs to be chopped and limited, which is called the current chopping control (CCC) method. The external circuit diagram of a three-phase switched reluctance motor using CCC control mode is shown in Figure 7.

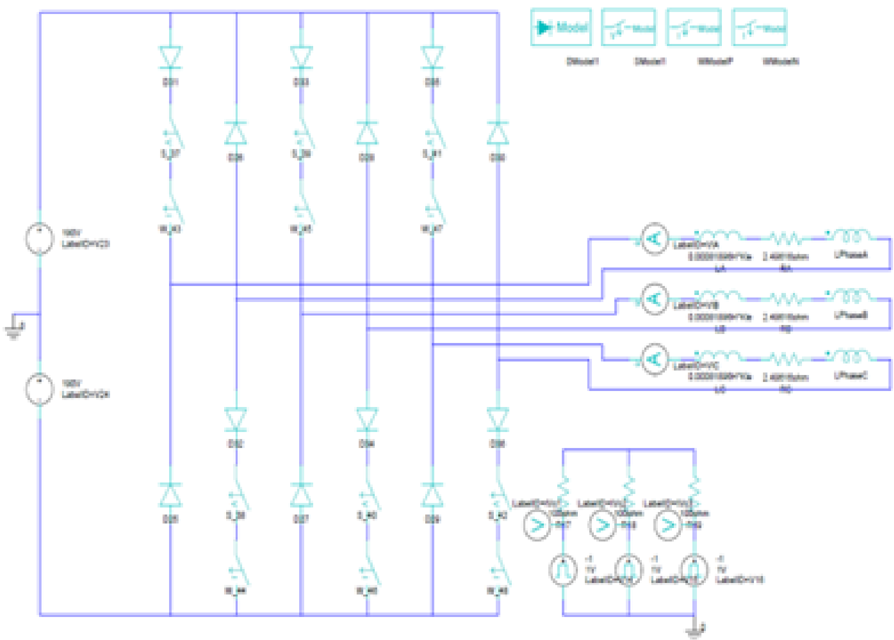
Figure 7: CCC control drive circuit diagram of switched reluctance motor

In the current chopping control mode, the constant torque state of the motor is simulated, and the simulation results are shown in Figure 8 and Figure 9. Figure 8 shows the motor torque waveform in CCC control mode. It can be seen from the figure that the output torque ripple of the motor in CCC control mode is quite large, which is in line with the large torque ripple of the switched reluctance motor. Figure 9 shows the phase current waveform of the motor. It can be seen from the figure that after each phase is turned on, the current rises sharply, which is consistent with the ideal curve. When the motor commutates, the current of the previous phase drops sharply. Because once the power switch is turned off, the voltage applied to both ends of the winding has an amplitude equal to that of the DC bus voltage, but in the opposite direction -Us, forcing the SRM to complete the commutation in a short time. After each phase is cut off and turned on, the respective freewheeling loops that pass through are freewheeling. After the previous phase is cut off and turned on, the next phase will be turned on after commutation, and the front and back do not affect each other. This is another major advantage of SRM. SRM phases can work independently of each other, with good stability, high reliability, and certain fault-tolerant operation capabilities.

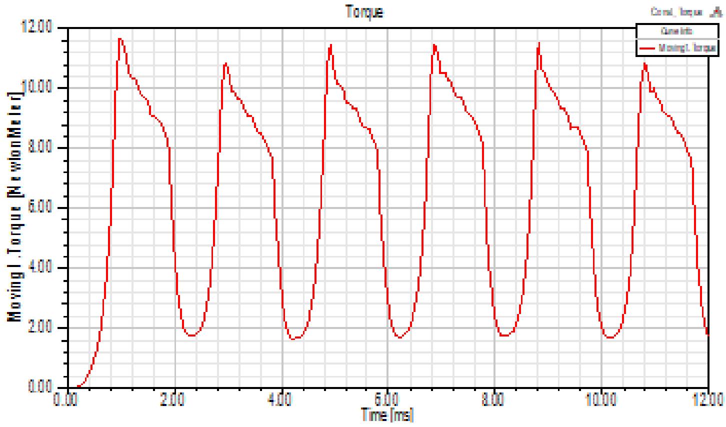

Figure 8: Motor torque waveform in CCC control mode

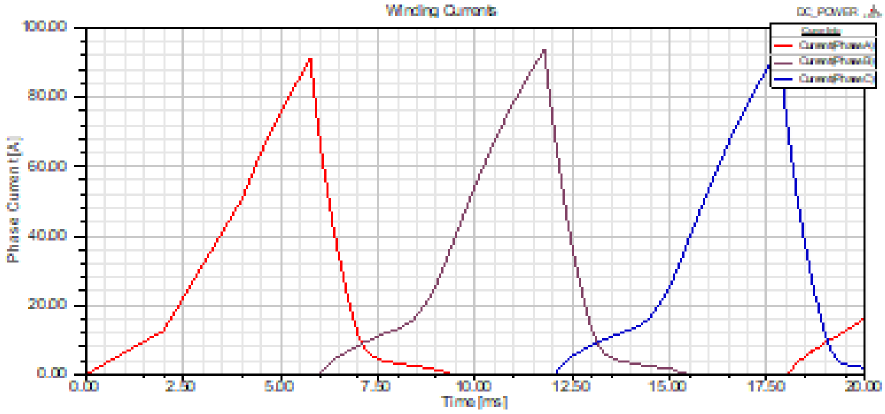

Figure 9: Motor phase current waveform in CCC control mode

In the constant power area, the constant power characteristic is obtained by adjusting the switch on and off angles, which is a single pulse control (APC) method. In the APC mode, the built model motor is simulated in a constant torque state, and the simulation results are shown in Figure 10 and Figure 11.

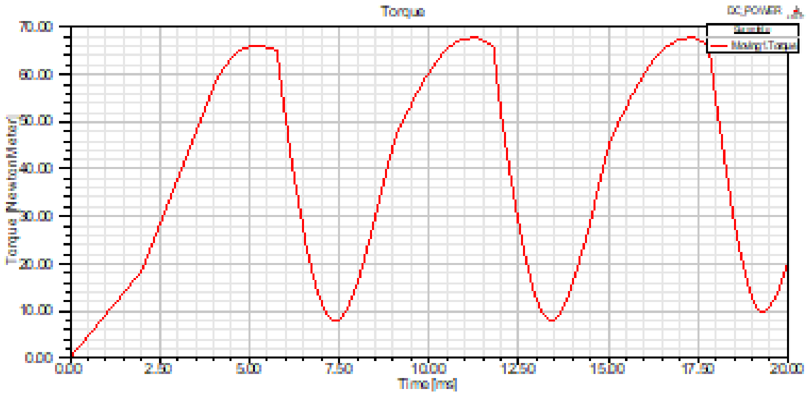

Figure 10: Motor torque waveform in APC control mode

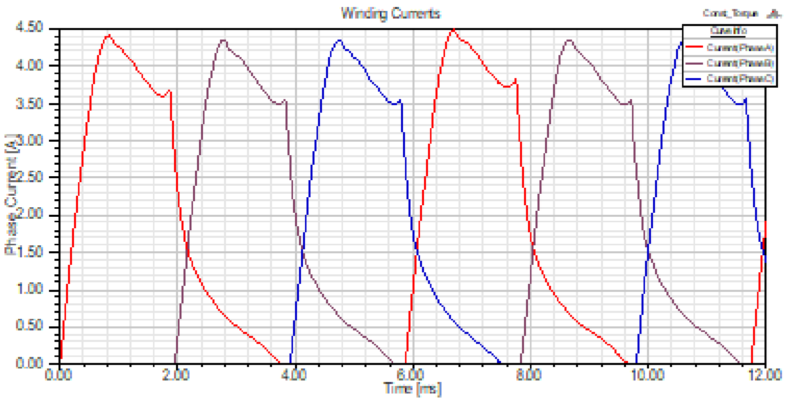

Figure 11: Motor phase current waveform in APC control mode

Judging from the simulation results of the two control modes, the torque waveforms of the motors in the two control modes are different, and the phase current waveforms are also different. Therefore, in practical applications, the switch reluctance motor drive control system needs to reasonably select the motor control method according to the instantaneous working conditions of the motor.

Conclusion

By studying the operating mechanism of the switched reluctance motor, this article elaborates its application in the electric vehicle drive system, and analyzes the structure, operation strategy and control strategy of the electric vehicle drive system of the switched reluctance motor.

(1) Combining the basic structure and working principle of the switched reluctance motor, it explains its application in the field of electric vehicle driving, and introduces the current application of the switched reluctance motor in the field of driving outside China.

(2) Combining the structure of the electric vehicle drive system and the operating habits of the driver in the actual situation, the working process of the drive system adjusting the switched reluctance motor when the electric vehicle is starting, accelerating, decelerating, reversing, stopping, and constant speed is analyzed.

(3) According to the characteristics of the switched reluctance motor, its three operating characteristics are introduced, and the speed control schemes of start chopping control, natural commutation control, variable angle chopping control and single pulse control are analyzed in detail.

(4) Improve the feedback mode of the drive system, analyze the electric vehicle start control strategy of the acceleration start mode, and propose two methods to stabilize the motor output torque by limiting the current upper and lower limits and the switch-off time.

(5) A three-phase switched reluctance motor is simulated and analyzed by CCC control and APC control respectively.

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