CHEMICAL ENGINEERING TRANSACTIONS

VOL. 66, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Songying Zhao, Yougang Sun, Ye Zhou

ISBN 978-88-95608-63-1; **ISSN** 2283-9216

DOI: 10.3303/CET1866212

Study on Optimization Technology of Instantaneous Torque Control Strategy for Switched Reluctance Motor

Shu Xiong[a,b*]

[a]College of Automation Engineering Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China
[b]School of Physic and Electronic Electrical Engineering of Huaiyin Normal University, Huai'an 223300, China
shuxiong2938475@163.com

The study deals with the instantaneous torque control of switched reluctance motor (SRM) so as to drive vehicle with electric power sources. The instantaneous torque control mode, torque regulation and direct instantaneous torque control (DITC) system of SRM are analyzed, and the optimization scheme is proposed. From the results and analysis, it is found that DITC mode can control the flux linkage of the motor more accurately by comparing the simulation results of the control system of SRM. The conclusion verifies the advantages of DITC.

1. Introduction

Nowadays, the fossil energy around the world is decreasing at a very surprising speed, and the natural environment of energy is deteriorating continuously. For the sake of continuous development, the human society has put forward the concept of new energy application. Under this concept, the research and development of electric vehicle is a problem worth paying attention to. At present, electric vehicle mainly rely on motors to drive, so the efficiency of motor drive directly determines the performance of electric vehicle. Under this premise, this study proposes SRM which not only has the advantages of simple structure, sturdiness and durability, but has a high starting torque and a relatively low starting current, as well as many controllable parameters compared with the traditional asynchronous motor. However, SRM has some disadvantages. For example, it will form large torque pulsation in the process of speed regulation because of the effect of its doubly salient structure.

In order to improve the disadvantages of SRM, the instantaneous torque control technology is adopted to reduce the torque pulsation and improve the performance of driving system of SRM. In order to study this technology, that simulation models of current chopping control (CCC), direct torque control (DTC) and DITC are built by using Matlab / Simulink, and the superiority of the control method is verified by analyzing and comparing the simulation results.

2. Literature review

Switched reluctance motor is abbreviated as SRM. Its development can be traced back to 1980s, which is a new type of motor rising on the development of science and technology. It has the characteristics of single structure, high efficiency and reliability. In 1842, British researchers Davideen and Aberdeen used electromagnets and mechanical switches to produce a motor similar to that of switched reluctance motors. Due to the immature conditions at that time, the operation was unstable and the reliability was poor, it was not paid attention to. Until 1960s, because of the wide application of high-power thyristors to various fields, SRM has been further developed. In 1969, S.A. Nasar, a famous American scholar, presented the concept of "switched reluctance motor" for the first time in his paper, and further elaborated two prominent features of SRM: switching nature: SRM must work in a continuous switching state; magneto-resistance: SRM mechanism is double salient. The fixed rotor has a variable reluctance circuit. The earliest SRM speed control system was developed by Ford Motor, USA. In 1980, Lawrenson introduced the whole speed regulation system of SRM for the first time in more detail. The working principle and design advantages of the system are

Please cite this article as: Xiong S., 2018, Study on optimization technology of instantaneous torque control strategy for switched reluctance motor, Chemical Engineering Transactions, 66, 1267-1272 DOI:10.3303/CET1866212

analyzed and illustrated. At the same time, this means that switched reluctance motor has been internationally recognized for the first time and is of great significance. In 1983, Tasc Drives of UK first launched SRD series OULTON products. In 1984, Tasc Drives Company developed the tram driving system. This product has reached an unprecedented high level on many performance indicators. At the same time, it has attracted wide attention from experts and scholars in the field of electrical drive.

There are many researches on switched reluctance motor in foreign countries. Kermanipour and Ganji studied axial flux switched reluctance motor (AFSRM). Because AFSRM has a high torque / weight ratio, it can be applied in many occasions, especially well applied in electric vehicles and aerospace systems. But the torque ripple is usually a disadvantage of AFSRM, so Kermanipour and Ganji proposed a new torque structure for double sided AFSRM, which makes the torque ripple decrease significantly (Kermanipour and Ganji, 2015). Labiod and others studied the speed control of switched reluctance motor (SRM) using direct torque control (DITC) torque ripple suppression. The reference value of instantaneous torque is generated by the speed control of the PI controller. The hysteresis controller is used in comparison between the reference torque and the estimated torque. In addition to selecting the different turn off angle, the performance of the torque ripple is improved. The latter realizes the switching signals needed by the converter to achieve desired results. SRM has highly nonlinear characteristics. Under nonlinear magnetic properties, the finite element method (FEM) is used to determine the static characteristics, which makes it difficult to control, but makes the result closer to the reality. Labiod compared the different turn off angles through the computer, and improved the torque ripple performance of the switched reluctance motor (Labiod et al., 2015). Moron and others explored the performance of an instantaneous torque control method, which showed the application of switched reluctance motor (SRM) in the field of motor drive (Moron et al., 2012).

In China, switched reluctance motors were also paid enough attention to. Cao and others studied the double winding bearingless switched reluctance motors (BSRMS). In traditional switched reluctance motors (SRMS), a winding is attached to the stator windings, whose main purpose is to realize the suspension function. Due to the existence of hysteresis current control in the present double winding BSRM control strategy, it is necessary to deduce the expression of the winding current, and some constraints are introduced, which increases the difficulty of the design of the current control algorithm. In order to solve these problems, Cao and others proposed and developed the concept of direct torque control and direct control of suspension force, called direct torque control (DTC) and direct force control (DFC), which greatly reduced torque ripple (Cao et al., 2017). Zhang and others thought that torque ripple was a disadvantage of switched reluctance motor and considered that the DTC strategy could reduce ripple. DTC is a kind of Bang-Bang control, and the result is limited. The error level can be measured by fuzzy control to achieve better results. Zhang and others simulated the CCC strategy, DTC strategy and fuzzy direct torque control strategy. The simulation results show that the DTC strategy reduces the ripple of CCC to a certain extent and combines with fuzzy control with, having better results (Zhang et al., 2013).

Zeng and others discussed the smoothing method and considered that torque ripple of switched reluctance motor (SRM) was the main drawback of the industrial application of these motors. Although several smoothing methods were proposed by predecessors, the STO worked well only in a certain range of torque and speed due to the limitation of the power supply voltage and peak current. Based on previous work, Zeng extended the STO range to determine the maximum smooth torque range at every speed, and defined the relationship between the maximum smoothness torque and speed as a smooth torque speed characteristic (STSC), which was used to evaluate torque utilization (Zeng et al., 2014). Ye and so on studied a low ripple torque control method of switched reluctance motor (SRM) speed regulating system using torque separation function (TSF). In the process of commutation, two working modes of online TSF are defined: in mode I, the absolute value of the flux change rate (ARCFL) of the entry phase is higher than that of the ejection phase; in mode II, the ARCFL of the ejection phase is higher than that of the entry phase. In order to compensate for the torque error caused by the not ideal tracking of the phase current, the proportional integral compensator with the torque error is added to the torque reference of the output phase in mode II and input phase II. Therefore, the total torque is determined by the phase with a lower ARCFL rather than the phase with a higher ARCFL in the conventional TSFS. The maximum torque ripple speed of the proposed TSF increases to ten times that of the conventional TSFS. Finally, the operation of the proposed TSF and three-phase 12/8 SRM with 2.3 kW and 6000 rpm in the linear magnetic and saturated magnetic regions is verified by simulations and experiments. The results show that the proposed TSF has higher average torque and lower torque ripple than traditional TSFs (Ye et al., 2015). Zhao discussed the phase current on the basis of three independent current sensors of switched reluctance motor (SRM), and explored the conditions of arrival and stability of the sliding mode control (SMC) method, and applied it to the SRM speed control loop to compensate torque pulse of the torque output. The proposed sliding mode controller has better performance than the traditional PI controller and is more effective for external disturbances (Zhao et al., 2013).

In 1993, the switched reluctance motor group was formally established in China. According to international conference and articles published by scholars at home and abroad, it can be found that the development of switched reluctance is very fast and the technology is more and more mature. But at present, the research on transient torque control of switched reluctance motor is less. This paper studies the optimization strategy of switched reluctance motor transient torque control, and also provides reference and help to the future research direction in this respect in China.

3. Methods

3.1 Instantaneous torque control mode of SRM

The traditional control method can't solve the problem of large torque pulsation. In order to control the large torque ripple of driving system of SRM more efficiently. This study designs a method which can control the torque ripple effectively according to the instantaneous torque control theory of SRM. The instantaneous torque control theory includes the DTC theory and DITC theory. On this basis, a torque distribution method is proposed to control the instantaneous torque of SRM, which reduces the large torque ripple of driving system of SRM to a certain extent.

Based on the analysis of the working principle of SRM, it is concluded that DC current is applied to each phase of the motor, and the phases are independent and don't influence each other. Stator phase winding voltage equation of SRM is: $\mathrm{U} = \mathrm{Ri} + \frac{d\psi(\theta,i)}{dt}$

Where,

U ——Phase voltage of stator

R ——Phase resistance of stator

i ——Phase current of stator

θ——Phase voltage of stator

$\psi(\theta,i)$——Phase winding flux linkage of stator of a motor

It can be found from the above formula that the change of the current lags behind the change of the flux linkage, so it can be considered that the current remains basically unchanged when the the winding flux linkage changes. Meanwhile, the torque equation of SRM can also be obtained according to the law of conservation of energy. That is, part of the energy eW from the power source is transferred into the magnetic field to become fW, and another part acts on the load to become mechanical energy mW, so the formula $W_e = W_f + W_m$ is obtained. Part of the power from the power source is dissipated by the winding resistance of the stator phase of the motor.

As can be seen from the above formula, when the current of stator phase keeps constant, that is, when the amplitude of stator flux linkage is constant and the stator flux linkage leads θ , the conversion rate of flux linkage with angle is greater than zero, and the torque is also greater than zero, then the motor is in an accelerated state; when the stator flux linkage lags behind θ, the conversion rate of the flux linkage with angle is smaller than zero, and the torque is smaller than zero, the motor is in braking state.

The special working environment of electric vehicle requires that SRM needs to adapt to the change of various load conditions of the vehicle in real time. The change of load torque can not only reflect the dynamic load situation of the motor, but also has obvious influence on the dynamic characteristic parameters of the motor. Figure 1 is a changing curve showing the change of smoothness coefficient and equivalent power coefficient of target torque with load torque under different rotational speeds when the turn-on angle and the turn-off angle of SRM are fixed at 6° and 24° respectively, as shown in Figure 2 and Figure 3.

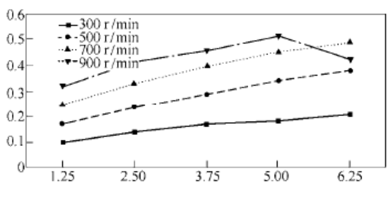

Figure 1: The effects of the load torque at various speeds

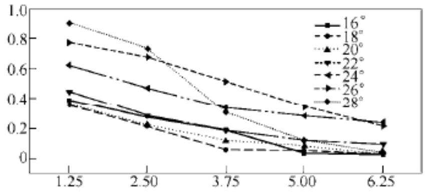

Figure 2: Load torque

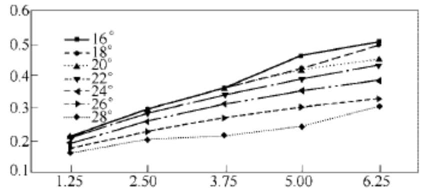

Figure 3: Equivalent power coefficient

It can be seen from the analysis of Figure 1 that the smoothness coefficient of torque decreases with the increase of load torque, and the change at high speed is relatively smooth while the change amplitude at low speed is relatively large; the value of the equivalent power coefficient increases with the increase of the load torque. Under the same load condition, the greater the rotation speed is, the greater the value of the coefficient is.

3.2 Torque regulation

In order to more clearly describe the relationship between torque and voltage flux linkage, a control vector table 1 is obtained based on Figure 4. In the table, T↑ and T↓ represent the increase and decrease in torque demand respectively; ψ↑ and ψ↓ represent that flux linkage needs to be increased and decrease respectively.

Table 1: Direct torque flux vector table

	angle	T↑↓ψ	T↑↑ψ	T↓ψ↑	T↓ψ↓
Region Ⅰ	[0°~0°)	V3	V2	V6	V5
Region Ⅱ	[60°~120°)	V4	V3	V1	V6
Region Ⅲ	[120~180°)	V5	V4	V2	V1

3.3 DITC system of SRM

As a new control theory method, DITC of SRM can efficiently control torque pulsation. Compared with the traditional control strategy, DITC keeps the torque constant not by controlling the space voltage vector, calculating the control unit of flux linkage, looking for the power-on logic unit but by the torque share function which has been pre-stored in advance. However, due to the nonlinear electromagnetic characteristic of the salient structure of SRM, it is impossible to control the torque ripple and fix the torque distribution function curve efficiently under any command. Therefore, on the basis of this theory, this study proposes a method which can realize DITC efficiently. In this method, the torque distribution is determined according to the real-time running state without giving a specific TSF graph so that the fast reversing can be realized. Therefore, the purpose of efficient DITC can be achieved only by selecting reasonable turn-on angle and turn-off angle and implementing proper torque distribution for each phase to stabilize the total instantaneous torque output value of SRM.

The system structure mainly includes SRM, torque distribution unit, hysteresis comparator, logic switch table, power converter and position detection unit. When SRM is powered on, the torque distribution unit obtains the three-phase currents AI, BI, cI and the position angle which passes through the torque distribution unit. And then the torque hysteresis device transmits the deviation of the actual torque and the reference torque to the logic switch table to select the turn-on angle and the turn-off angle. Finally, the actual speed of the motor is controlled by PWM output from the power converter. In the control structure, an inner ring torque ring and an outer ring speed ring form a double closed-loop control mode. In the whole system flow, the torque control hysteresis unit is the core unit.

Figure 4 are curves showing the change of the motor torque performance parameters with the change of the turn-on angle under different rotational speeds, where the values of the turn-off angle and the load torque are set to be 26° and 1.25N·m respectively.

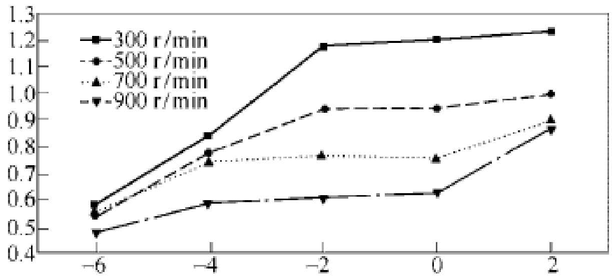

Figure 4: Torque smoothness coefficient

4. Results and Analysis

4.1 Control system simulation of SRM

The common verification methods are software verification and hardware verification. Hardware is easily disturbed by external conditions and affected by its own performance, so the ideal experimental results are usually not obtained. Therefore, the software verification method is usually adopted. In general, MATLAB simulation software is used to realize the software verification, and software simulation method can automatically find out the defects of the control system according to the parameter setting and the performance that is close to that of the actual device. Therefore, the software verification has great advantages in terms of cost and time. In addition, the processing speed of the software simulation is faster than that of the hardware system, and the control method that can be realized by software simulation may not necessarily be realized by hardware system. On the other hand, although software emulation can provide a similar environment to hardware, it is not possible to be exactly the same and the error is inevitable. This study will first use software simulation, and then use hardware system to verify the feasibility. Therefore, to verify the feasibility and accuracy of DITC technology, it is necessary to analyze the mathematical model of SRM and simulate it based on MATLAB/Simulink. Thus, the simulation models of CCC, DTC and DITC are established respectively, and the simulation results of the three control systems are compared on the premise that the SRM model is consistent with the motor load, which shows that the decrease of torque ripple under DITC effectively suppresses the torque pulsation.

4.2 Comparison of simulation results

Under the condition that the power supply voltage and the load are the same, the static-coordinate synthesized flux linkage is obtained in the simulation, and then the synthesized flux linkage trajectories obtained under three different control modes are compared. It is found that the flux linkage trajectory under CCC is similar to an irregular triangle shape with no rule to be found. The flux chain linkage under DTC is approximately an ellipse, and the flux linkage size is controlled near the given value. However, the flux linkage trajectory obtained by DITC is a circle, indicating that DITC can better control the amplitude of flux linkage in the range of given flux linkage and hysteresis width. Therefore, the DITC mode can control the flux linkage of the motor more accurately and reduce the amplitude vibration of the flux linkage.

When the SRM is just powered on, the torque is very large under the three control modes for better starting of the motor. Figure is the torque oscillogram under CCC. It is found that when the motor runs smoothly, the waveform has edges and corners, indicating that the torque pulsation is still large and doesn't decrease with the smooth operation of the motor. The torque oscillograms of DTC mode and DITC mode are shown below respectively. From the simulation results, both of them can control the torque pulsation to a certain extent. However, a careful observation finds that DITC torque is more stable and torque pulsation is smaller. The fluctuation is approximately a straight line, which indicates that the DITC can better restrain the torque pulsation.

5. Conclusions

This study mainly analyzes the mathematical model of SRM control theory, introduces the principle and system structure of instantaneous torque control of SRM, and designs the torque distribution unit, the power converter unit and the power logic switch table. In particular, the torque hysteresis controller is designed and explained. The simulation models of CCC, DTC and DITC are established and their simulation results are compared under the unified premise. The comparison shows that the decrease of torque ripple under DITC can effectively restrain the torque pulsation.

Then the Matlab simulation software is introduced, and the CCC model, DTC model and DITC simulation model of SRM are established in Simulink. The simulation results of the three algorithms are compared and analyzed to verify the superiority of DITC technology. The results show that both of them can restrain the torque pulsation to some extent. However, careful observation finds that DITC torque is more stable and torque pulsation is smaller, and the fluctuation is approximately a straight line, which indicates that DITC can better restrain the torque pulsation.

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