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A Review of Torque Ripple Control Strategies of Switched Reluctance Motor

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Abstract

Doubly salient, single energized Switched Reluctance motor is eminently suited for Industrial application of variable speed control .SRM drive is most suited for low cost and variable speed operations. But the major drawback in Switched Reluctance Motor is High torque ripple, mechanical vibration and Acoustic noise. Due to its nonlinearity and doubly salient structure torque ripple becomes inevitable. This paper discussed about the outset of torque ripple and the appropriate methods used so far to diminish the torque swell in Switched Reluctance Motor. Results obtained from the review of all the Torque ripple Minimization techniques are presented. From the results it has been concluded that DTC and DTC with PI &Genetic PI controller gives the least torque ripple when it is used in Switched Reluctance motor drive.

Keywords: Acoustic noise, Converter, Current Control, Torque Control,

INTRODUCTION

The stator and rotor of SRM have projected poles. Stator winding produce magnetic field and the rotor don't have windings, commutator and brushes. The speed of SRM is more compared to stepper motor. The preferable qualities of induction motor drives and dc commutator drives are combined in this motor. The torque produced in this motor is related to square of the winding current. Due to its simple construction, SRM becomes more considerable than other types of motor for industrial applications. Progressive growth in modern control techniques in Power Electronics and Processors, leads to variable speed industrial applications using SRM. The main drawback of SRM is the non-uniform and pulsed attribute of torque creation which leads to torque swell and which in turn gives rise to acoustic noise. This paper focuses on the torque ripple concept and some of the methods that was adopted to reduce the torque flutter in SRM drive system

TORQUE RIPPLE CONCEPT

The electromagnetic and electro dynamic equipment, switched reluctance motor that converts electrical energy to mechanical energy. Due to flow of current through phase winding the rotor has a tendency to line up with the stator , it delivers a torque that tends to align the rotor to a least reluctance position[1-2]. Torque is delivered by the propensity of its versatile part to adjust itself to its less reluctance value area. Due to three reasons Torque swell is produced in SRM. The foremost reason is due to its magnetic mechanical structure. Second reason is due to its non- direct attributes of inductance and third reason is negative torque due to tail current(ref).

Expression of the torque can be derived using the derivative of the co energy (w') with the rotor position(θ) at a given value of current(i)

$$\boldsymbol{Tph = \frac{\partial W'(\theta,i)}{\partial \theta} / i = constant} \qquad \text{---------(1)}$$

Where Co-energy $w'(\boldsymbol{\theta, i}) = \int_0^i \boldsymbol{\lambda di}$

The instantaneous torque of SRM is expressed by the summation of all individual phase torques.

$$T_{inst}(\theta,i) = \sum_{k=0}^{n} \boldsymbol{Tphk(\theta, i)} \qquad \text{----------(2)}$$

Where k is the number of phases in the machine.

Average torque of the SRM drive can be calculated by integrating the equation (2)

$$Tavg = \boldsymbol{1/T \int_0^T Tinst.dt} \qquad \text{-------------(3)}$$

The ripples in the Torque can be defined as the difference between the maximum and minimum instantaneous torque expressed as a percentage of average torque during steady state condition.

$$\text{Torque ripple} = [T_{inst}(max) - T_{inst}(min)]/T_{avg} * 100 \qquad \text{-------(4)}$$

$$\text{Co energy } (W') = \text{Field Energy } (Wf) = \frac{1}{2} Li^2 \ J \qquad \text{-----------(5)}$$

$$\text{Therefore, Torque} = \frac{1}{2} i^2 \frac{dL}{d\theta} \qquad \text{-----------(6)}$$

From (6) it is clear that Torque does not depend on the direction of current, it depends only on the polarity of dL/dθ. When rotor is aligned to the stator, positive (motoring) torque is produced, independent of the direction of current. When the rotor comes out of alignment, the torque is negative (braking or regenerative). In synchronism with the rotor position, the current must be switched on and off. The period of conduction should not exceed the step angle. At the instant of commutation, a small amount of overlap is desirable to minimize the torque swell in the form of notches in the instantaneous torque waveform. Too much commutation overlap results in positive impulses of torque and this will add to the average torque, and they enforce transients on the coupling, shaft, load [1]. Due to this reason, SRM has high mechanical vibration and noise.

Due to the change in current between the phase windings, SRM has very high torque ripple and it mainly depends on turn off and turn on angles.

Many views have been proposed in recent years to minimize the torque ripples in SRM and this paper will give the review of torque ripple control strategies adopted in switched reluctance motor.

TORQUE RIPPLE MINIMIZATION METHODS IN SRM:

In SRM, to diminish torque swell is excessively troublesome and many research have experienced to lessen the torque swell. Diverse control techniques were proposed for various applications. Torque swell can be viably minimized, by legitimate selection of the control strategy for a specific design of motor. This paper exhibits the survey of all the control procedures that can be connected to Switched Reluctance Motor. Different Control strategies are converter control , Direct Instantaneous Torque Control, Advanced Direct Instantaneous Torque Control method, Indirect torque control, Optimization of phase current profile, on line and off line optimizing the current waveform, ,Iterative learning control, Adaptive control algorithms, Sliding mode control, Adaptive Intelligent fuzzy method are adopted to minimize the torque ripple in Switched Reluctance Motor.

A. Indirect torque control method:

Indirect Torque control method(ITC), by controlling the current, torque is controlled. But conversion from torque to current is not direct, due to torque dependence on rotor position(θ). Two methods are used for conversion from torque to current .One method is storing T-i-θ relationship in a look up table and another one is by using Artificial Neural Network(ANN) method. The detriment of ANN method is intensive online computation. Even though lookup table method requires large online memory, it is simple and ease for implementation, so this method is commonly used. Process flow diagram of ITC is shown in Fig.(1).

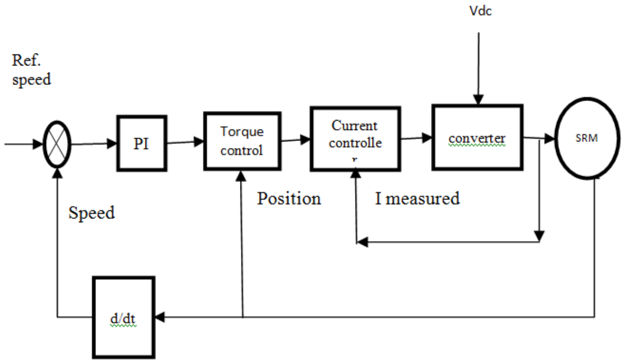

Figure 1. Process flow diagram of ITC

Torque controller generates individual phase torques references such that addition of winding torque is equal to reference torque. Reference current is generated for each phase from look up table and assigned to a current controller. Current controller used is either hysteresis controller or Fixed frequency PWM controller[40].

B. Direct Torque Control Method

In this method, SRM torque is directly controlled and there is no need for torque to current transformation. Fig (2) shows the Process flow diagram of DTC.

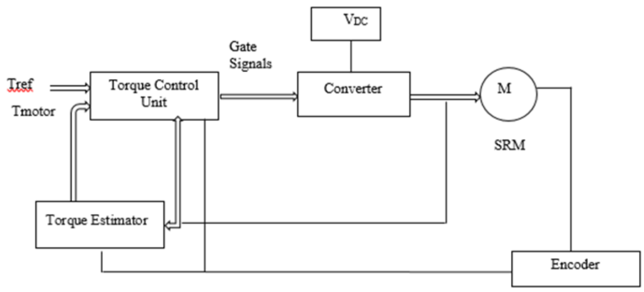

Figure 2. Process flow Diagram of DTC

Because of the nonlinear qualities of SRM, torque at that instant can be determined from the stored static T-i-θ characteristics. The torque profile is resolved from the rotor position and current or flux linkage and current. Torque calculated at the instant is compared with the reference torque. But this method requires large online memory. Usage of this technique is troublesome because of its mind boggling exchanging rules, uncontrolled exchanging recurrence and high examining rate. The effectiveness of the method can be judged by calculation and control of torque developed by the machine[4].In this technique , torque is the control variable and hence DTC experience the torque mistake momentarily with quick unique reaction and viably limits the torque ripple. [18]. DTC scheme also eliminates the use of current controller. DTC can also be used to drive constant torque load[27]. Instantaneous response to torque command was achieved in five phase SRM using DTC method[35]. Torque is additionally controlled by controlling the extent of flux linkage and the adjustment in speed of the stator flux vector[31].Torque is maintained within the hysteresis band by modifying the switching sequence of phases for Electric Vehicle application[10].DITC based Modular SRM was designed for Automotive applications [4].

C. Torque Sharing Function

To make the overall torque of SRM to become a constant value, torque sharing function (TSF) is used. During the commutation period, torque reference is distributed uniformly to two adjacent phases. Torque sharing functions is categorized as linear, sinusoidal, cubic and exponential TSF. Input of TSF block is torque and this input torque is distributed as individual torque reference T_k^* for each phase depending on the rotor position. Individual phase torques are converted into current by T-I block and the switching angles are controlled by power converters. Downside of TSF strategy is we can't foresee the most extreme speed in torque swell free execution of motor. To beat the disadvantage specified above altered TSF technique was proposed[2].Genetic algorithm based TSF was proposed in[41].Figure (3) shows the Process flow diagram of Torque control using TSF concept.

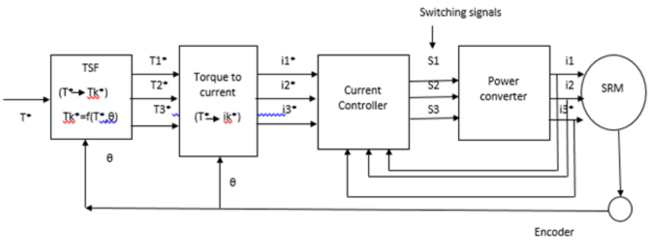

Figure 3: Process flow diagram of TSF method

D. Intelligent Control Techniques

Intelligent control is a type of control technique that use different Artificial Intelligent computing methods like Neural network, Fuzzylogic, Machine Learning, Evolutionary computing and genetic algorithm. Dynamic response of SRM drive can be brought to a desired value by using different intelligent controllers. [8].

Fuzzy Logic Control :

Conventional PI,PID controllers are replaced by Fuzzy logic controller. Nonlinear controllers are designed using Different schemes can be implemented with Fuzzy logic control and it is robust too. Torque ripple in SRM can be reduced by Fuzzy Logic Controller with current compensation algorithm.[15]. TSF concepts was also introduced in FLC [38].Unity torque is maintained at any condition. If there is any mistake in forming the TSF it can also be tracked and torque can be monitored. Torue in high speed region cannot be controlled by this method. This is the main drawback. Torque density of motor increases in adaptive fuzzy control method. [44].The controller produces a smooth torque from base speed of motor till it reaches its high speed. Also Torque density of the motor increases in this work. Fuzzy Sliding mode controller was incorporated in [16]. For SMC, objective function has been chosen as torque ripple and based on this function, DC link voltage of the converter is adjusted by the Fuzzy sliding mode controller. So that the torque ripple is properly reduced and there is no change in speed output. Turn on angle and turn off angles of position sensor will be the deciding factors of the SRM's smooth torque .The turn off angle of the position sensor can also be controlled to get desired torque value[51].

Neuro-Fuzzy Compensator Control :

There are numerous mixtures of methodologies in soft computing, the one that has highest priority at this area is Fuzzy logic and neural networks leading to Neuro-Fuzzy systems. Observations are made and rules are framed in such systems .ANFIS based torque control was proposed in[54].Current profiles are generated for a particular torque reference by online learning to reduce torque ripple. In a current managed speed control loop, compensating signal is added to the PI controller output so that the analysis was made in the effects of changing the membership functions of neuro-fuzzy compensation.

Sliding Mode Control

A non-linear control technique that changes the system behavior by applying a control signal that makes the system under consideration to slide along the normal behavior of the system is called Sliding Mode Controller . A discontinuous control signal is applied to the system so that it slides along the system's normal behavior. SMC used in [55] controls the sum of the squares of the phase current by using two current sensors and analog multiplier. Low frequency oscillations are controlled by SMC technique. Continuous SMC provides better results compared to PI or Fuzzy in reducing torque ripple. Noise reduction can also be achieved by SMC[7].But speed control range cannot be defined in this paper.

Optimization Method

Bacterial Foraging optimization technique is a naturally inspired optimization. Apart from Genetic Algorithm, Evolutionary programming, Evolutionary strategies ,BFO find optimum placement of stator and rotor where the torque ripples are less [39]. Another control called Evolutionary control algorithm was also proposed for SRM motor to reduce the torque ripple[45]. Genetic algorithm is used for tuning the controller parameter.

Converter Control

Power converters are used in SRM drive to control the sequence of switching of phase windings. In order to reduce the torque swell, positive torque must be increased and the negative torque should be decreased. Asymmetric bridge SRM converters have two switches per phase. This converter topology gives the most adaptable and successful control to the present waveforms of SRM however with most increased number of switches [54].Bidirectional DC-DC LUO converter was designed [55] and the voltage gain can be increased on stage by stage using voltage lifting technique. By implementing this converter efficiency can be improved [56].A low cost Compact converter with less number of switches was proposed[57] to reduce the torque swell .This converter has less switching loss and faster commutation compared to classical converter. Two switch per converter (TSP) and Resonance Three Switch per phase (RTSP) was discussed in [56]. Resonant phenomenon was used in order to de-energize the winding after switching off the phase windings. Hence the torque ripple reduced significantly.

Analysis of all the Torque ripple Techniques Used

Comparison table of the results of Torque ripple reduction techniques is shown in Table 1.

Table 1. Comparison of Results

Techniques used	**Reduction in %**
Without any controller	77%
PID controller	56%
PI controller	45%
Converter control	40%
Optimization control	40%
Sliding mode control	36%
Torque sharing function concept	25%
Intelligent control technique	25%
Direct torque control	10%
DTC with PI	8.8%
DTC with Genetic PI	6.9%

Without any controller ,torque ripple is high as 77%.With the use controllers torque ripple % has been considerably reduced as shown in Table 1.With Conventional controllers like PI and PID controllers it has been reduced to 45%.By designing different types of converters like TSP,RTSP ,LUO converters form SRM ,torque ripples can be minimized up to 40%.Design of Sliding Mode controllers reduces the torque ripple by 36%.Torque sharing function design and Intelligent controller design like Fuzzy and Neural, ANFIS controllers reduces the torque ripple to 25%.Direct control of Torque in SRM reduces the ripples by 10%. Direct torque control with PI reduces the ripple by 8.8%.Direct torque control with Genetic PI further reduces the torque ripple by 6.9%.

CONCLUSION

An overview of various torque ripple minimization techniques is presented in this paper. Reason for torque swell concept is explained first and the indirect torque control methods are discussed. Torque sharing function methods are discussed followed by Direct torque control techniques. Torque to current controller is eliminated in this method. Intelligent controllers like Fuzzy, Neural, Neuro-fuzzy controller are also studied to minimize the torque swell. Sliding mode controller is used to obtain the smooth electromagnetic torque if the SMC function is properly chosen. BFO technique is also used to meet the objective. This technique gives the best position of stator and rotor where torque is reduced. Torque ripple can also be minimised by current profiling. Comparison of the different torque ripple minimization techniques is done and the torque ripple percentage obtained from each technique has been analysed .From the review of torque ripple minimization methods it is concluded that Direct Torque control method and DTC with PI and Genetic PI gives the least torque ripple percentage. Each method discussed above has its own advantages and drawbacks. Choice of the method depends on the application of Switched Reluctance Motor drive system

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