International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 7, No. 4, December 2016, pp. 1110~1124
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v7i4.pp1110-1124

A Novel Modified Turn-on Angle Control Scheme for Torque-ripple Reduction in Switched Reluctance Motor

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Article Info

Article history:

Received May 25, 2016
Revised Oct 30, 2016
Accepted Nov 11, 2016

Keyword:

Switched reluctance motor
Torque ripple reduction
Torque sharing functions
Turn-on angle control

ABSTRACT

In recent years, Switched Reluctance Motors (SRM) have been dramatically considered with both researchers and industries. SRMs not only have a simple and reliable structure, but also have low cost production process. However, discrete torque production of SRM along with intensive magnetic saturation in stator and rotor cores are the major drawbacks of utilizing in variety of industrial applications and also causes the inappropriate torque ripples. In this paper, a modified logical-rule-based Torque Sharing Function (TSF) method is proposed considering turn-on angle control. The optimized turn-on angle for conducting each phase is achieved by estimating the inductance curve in the vicinity of unaligned position and based on an analytical solution for each phase voltage equation. Simulation results on a four-phase switched reluctance motor and comparison with the conventional methods validates the effectiveness of the proposed method.

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1. INTRODUCTION

Switched reluctance motor is one of the earliest electric motor, which dating back to more than a hundred years ago. The name of this machine is based on its physical performance which is able to switch in variable reluctance. SRM is recognized due to its robustness, high reliability and simple mechanical structure [1]. In this machine Centralized wiring of the stator, make it unnecessary to use modern control techniques and sinusoidal analysis. Rotor and stator poles have saliency and concentrated wirings lead to severe torque-ripples and sonic noise. Hence, the most current research studies on SRM focus on reduce torque ripple and related noise problems [2]. The torque-ripple can be derived by nonlinear nature of torque-Current-angle (T-i-θ) relations and discrete mechanism of torque production in SRM. In commutation intervals, the torque transferred from an active phase which named outgoing phase to another adjacent phase named incoming phase [3]. Even though design procedure such as rotor and stator shaping were investigated in [4], control techniques have been more undertaken to keep the motor resultant torque with minimum ripples. This category can be divided to nonlinear control approaches [5]-[7], conducting angle control and advanced control methods such as DITC [8], DTC [9] and TSFs [10]. One of the most convenient torque control method, is torque sharing functions. In this method reference torque for each phase is considered as a predefined function so that the total phase torques remain at desired motor torque. Some conventional TSFs are: linear, cosine, cubic and exponential which have introduced and studied in references [11]. Introduced a family of torque sharing functions which minimized torque ripple and copper power loss as the secondary objective function based on the speed of motor operation. In recent years, many methods have been proposed to optimize the turn-on and turn-off angles to reduce torque ripple in switched reluctance motors. These methods can mainly be classified as artificial intelligence-based, self-regulation and analytical methods.

To maximize the ratio of torque to current in all operating points, [12] has proposed a neural network in which the reference current and speed were used as inputs and turn-on /off angles were used as outputs [13]. Introduced the method in which the turn-on/ off angles optimized by an adaptive fuzzy controller [14]. Proposed the method to determine commutation angle and reduce torque ripples with higher efficiency for SRM. An analytical equation respect to the self-inductance of each phase in the vicinity of the unaligned position introduced in [15], and an analytic turn-on angle according to related phase voltage and motor speed was calculated [16].

Proposed novel logical rules to modify the reference phase torque which can be applied on all types of TSFs. In this reference, torque errors of two adjacent phases which are participating in commutation area used to regulate the reference phase torque of the others so that the torque generated in this area remains constant. However, the modified method introduced in [16] didn't consider the ability to change the turn-on angle which can have major effects on torque ripple especially near the based speed. Moreover, maximum torque ripple-free speed region without turn-on angle control was limited to the low speed operation. In this paper, analytical approach considering the independency of phase inductance near the unaligned position respect to the phase current will be used to regulate the turn-on angle and modified logical rules will enhance the motor resultant torque so that the torque ripple reduced to the desired level. Torque generation principles in SRM presented in section II, TSFs and the modified rules provided in section III, turn-on angle control algorithm as well as the proposed modified TSF presented in IV and verifications will be made by simulation results in section V.

2. TORQUE PRODUCTION PRINCIPLES

Switched reluctance motors with salient poles on the rotor and stator and concentrated windings on stator poles are usually constructed without wiring or permanent magnet on the rotor laminated core. Torque Production on switched reluctance motor is based on the principle of tendency to the least reluctance in the magnetic flux path. In this motor energy conversion has the close relationship with the phase current in stator windings and the rotor position.

$$T(\theta,i) = \left.\frac{\partial W'}{\partial \theta}\right|_{i=const.} \tag{1}$$

According to the above equation, T is the torque generated by each phase, i represents the phase current, θ denotes rotor position and w' is the Co- energy. Ignoring the magnetic saturation effects and assuming Co-energy equal to the magnetic stored energy, the following equation is obtained:

$$W_f(\theta,i) = W'(\theta,i) = \frac{1}{2}L(\theta)i^2 \tag{2}$$

In this case, the instant torque of the machine can be easily achieved using the following equation.

$$T = \left.\frac{\partial W'}{\partial \theta}\right|_{i=const.} = \left.\frac{\partial}{\partial \theta}\left(\frac{1}{2}L(\theta)i^2\right)\right|_{i=const.} = \frac{1}{2}i^2\frac{dL(\theta)}{d\theta} \tag{3}$$

The above equation shows that the relation between motor or generator torque is independent of the current direction. In other words, the slope of inductance profile can determine the operating mode of this machine. In general, voltage equation for each phase can be represented by the following eqation:

$$V = Ri + \frac{d\lambda(\theta,i)}{dt} \tag{4}$$

According to equation (3), the generated torque at each phase is positive when the slope of the inductance profile is positive and it will be negative when the slope of inductance becomes negative. Figure 1 shows the instance for a 4-phase SRM inductance profile during the unaligned to the aligned position for various phase current values. In this figure, phase current ascending leads to magnetic saturation in the corresponding stator pole and decrease the phase inductance in the vicinity of aligned position. However, phase current amplitude doesn't have much effect on the inductance near the unaligned position.

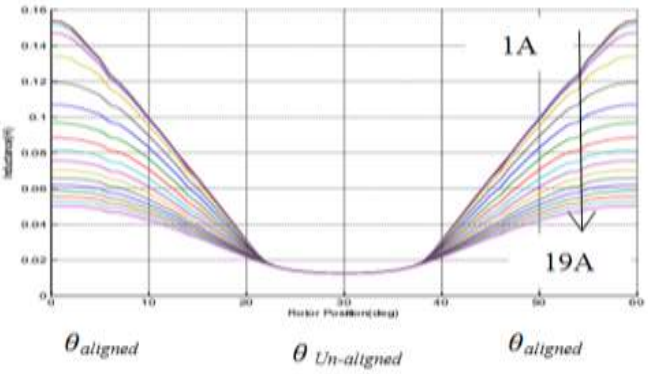

Figure 1. Inductance Profile of Considered 4-Phase SRM Versus Current and Rotor Position Variations

In motor mode operation, current in each phase starts to conduct from the unaligned position and where the slope of inductance becomes positive. As Figure 1 shows, when the stator and rotor poles placed where they have maximum air gap distance, the lowest inductance will be obtained. While, in the aligned position, the inductance will be the greatest value due to the minimum air gap between stator and rotor poles. In the neighboring aligned and unaligned positions, the slope of inductance is negligible and thus the potential for torque production is low based on equation (3). Therefore, applying phase voltage in the vicinity of unaligned position can dramatically increase copper losses while no torque production will be achieved.

3. TORQUE SHARING FUNCTIONS (TSFs)

One of the most simple and effective method in order to minimize torque ripples at the switched reluctance motor is torque sharing functions (TSFs) scheme. In this method, the reference torque is divided in to reference torque functions corresponding to each of the phases, so that the resultant motor torque remains at desired reference value. Considering this concept, the conduction current in each phase can be divided in to two areas which are named: Single-phase conduction and the adjacent phase commutation areas. In the commutation area, two adjacent phases have been excited and are simultaneously active. Figure (2) shows four different conventional torque sharing functions such as, linear type, cosine, cube and exponential type which are obtained from equations (5) to (8). The turn-on angle and commutation interval has significant effects on torque control performance. In other words, turn-on angle should be controlled based on the motor speed due to the dependency of motor internal back-EMF with operational speed and considering the limitation of converter voltage. At low speed, the reference torque tracking in both incoming and outgoing phases can be occasionally well performed. While, increscent in rotor speed can have significant influence on the magnitude of motor Back-EMF and deteriorate the torque control in both phases in commutation area due to considering the limitation of converter voltage.

$$T^{*}_{ph} = T_{ref} \cdot f_{Linear}$$

$$f_{linear} = \begin{cases} \dfrac{(\theta - \theta_{on})}{\theta_{ov}} & \theta_{on} \le \theta \le \theta_{on} + \theta_{ov} \\ 1 & \theta_{on} + \theta_{ov} \le \theta \le \theta_{off} - \theta_{ov} \\ \dfrac{(\theta_{off} - \theta)}{\theta_{ov}} & \theta_{off} - \theta_{ov} \le \theta \le \theta_{off} \end{cases} \quad (5)$$

$$T^{*}_{ph} = T_{ref} \cdot f_{\text{cosine}}$$

$$f_{cosine} = \begin{cases} sin^2(\dfrac{\pi}{2}(\dfrac{\theta - \theta_{on}}{\theta_{ov}})) & \theta_{on} \le \theta \le \theta_{on} + \theta_{ov} \\ 1 & \theta_{on} + \theta_{ov} \le \theta \le \theta_{off} - \theta_{ov} \\ sin^2(\dfrac{(\theta_{off} - \theta)}{\theta_{ov}}) & \theta_{off} - \theta_{ov} \le \theta \le \theta_{off} \end{cases} \quad (6)$$

$$T^*_{ph} = T_{ref} \cdot f_{cubic}$$

$$f_{cubic} = \begin{cases} \frac{3}{\theta_{ov}^2}(\theta - \theta_{on})^2 - \frac{2}{\theta^3_{ov}}(\theta - \theta_{on})^3 & \theta_{on} \le \theta \le \theta_{on} + \theta_{ov} \\ 1 & \theta_{on} + \theta_{ov} \le \theta \le \theta_{off} - \theta_{ov} \\ 1 - \frac{3}{\theta_{ov}^2}(\theta - \theta_{off} + \theta_{ov})^2 + \frac{2}{\theta^3_{ov}}(\theta - \theta_{off} + \theta_{ov})^3 & \theta_{off} - \theta_{ov} \le \theta \le \theta_{off} \end{cases} \quad (7)$$

$$T^*_{ph} = T_{ref} \cdot f_{Expon}$$

$$f_{Expon} = \begin{cases} 1 - Exp(-\frac{(\theta - \theta_{on})^2}{\theta_{ov}}) & \theta_{on} \le \theta \le \theta_{on} + \theta_{ov} \\ 1 & \theta_{on} + \theta_{ov} \le \theta \le \theta_{off} - \theta_{ov} \\ Exp(-\frac{(\theta_{off} - \theta_{ov} - \theta)^2}{\theta_{ov}}) & \theta_{off} - \theta_{ov} \le \theta \le \theta_{off} \end{cases} \quad (8)$$

According to the above equations θ_{on} and θ_{ov} and θ_{off} are, respectively turn-on angle, overlap between adjacent phases and each phase conduction turn-off angle.

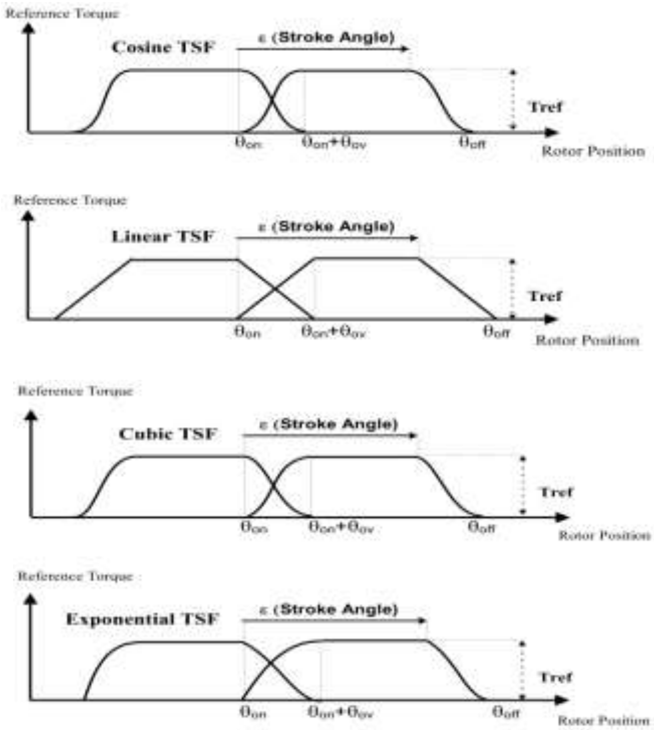

Figure 2. Four conventional TSFs: Cosine, linear, Cubic and exponential types

4. TURN-ON ANGLE CONTROL WITH MODIFIED TORQUE SHARING FUNCTIONS

When the stator and rotor poles have the maximum air gap distance from each other, the inductance magnitude has the minimum value while in the same axial position, the inductance will be maximum magnitude as depicted in Figure 1. In this figure the measured inductance values plotted using curves in different rotor positions by applying the various phase currents. It can be shown that starting from unaligned position and in neighboring area of this point; the inductance curves for different phase currents have approximately the same pattern. However, increasing rotor position toward the aligned position has significant effect on inductance curves due to the magnetic saturation in rotor and stator poles. In the vicinity of unaligned position, the inductance curves can be estimated according to equation (9) and be considered only by rotor position [15]. In other words, phase current doesn't have much influence on inductance value.

$$L = ae^{(\theta - b)/c} \tag{9}$$

Where, L is inductance, θ is position of the rotor and a, b and c are parameters determined by curve fitting. The above equation shows that (3) can be most accurate at the vicinity of unaligned position where the inductance curve is only the function of rotor position. Increasing rotor speed leads to raise the internal motor back-EMF and reference current or torque tracking can substantially deteriorated. This will reduces the effectiveness of TSF schemes to overcome torque ripples produced by commutation between adjacent phases. Many previous works considered some different relations for the turn-on angles based on the motor speed. However, the proposed methods were proportional to the motor parameters approximately. The constant values in (9) are respectively equal to 0.0088, 1.1 and 9.66 for the motor considered in this paper. Using some simple manipulations (10) can be derived.

$$\theta_{on} = \theta_c^i - c\ln\left(1 + \frac{a}{c}\frac{\omega . i}{v_S} e^{-\frac{(b - \theta_c^i)}{c}}\right) \tag{10}$$

In this equation, θ_c^i represents the position where two adjacent phases in the commutation region produce similar torque at the same phase current. In other words, θ_c^i is the position in commutation region where incoming and outgoing phase generate the half of reference torque at the same current level. Figure 3 shows the approximate approach to find the θ_c^i for different reference torques.

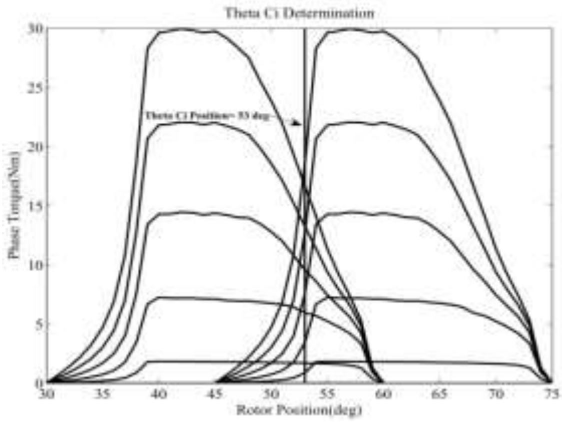

Figure 3. θ_c^i Determination for the Considered 4-Phase SRM

It is noteworthy to mention that before θ_c^i (from unaligned position to θ_c^i) the slope of inductance curve will be much greater than after this position (from θ_c^i to aligned position) and the required phase voltage to track the reference phase torque in incoming phase will be more increased. Due to the limitation of converter voltage in practice, torque phase error will be inevitable and may lead to noticeable torque ripple in motor resultant torque. In other hand, reducing turn-on angle will cause to excessive phase current magnitude due to the lower value of phase inductance at the beginning of incoming phase conduction period and increasing the copper loss. Therefore, in this paper, the analytic equation is proposed for turn-on angle control based on reducing the phase torque error in incoming phase at θ_c^i . Considering equation (9), the inductance derivative function respect to the rotor position and produced phase torque are obtained which shown by (11) and (12):

$$\frac{dL}{d\theta} = \frac{1}{c} a e^{(\theta - b)/c} \tag{11}$$

$$T_{ref} = \frac{1}{2}\left(\frac{1}{c} a e^{(\theta - b)/c}\right) i_{ref}^2 \tag{12}$$

Where T_{ref} is the reference phase torque derived from the torque sharing functions. From this equation, reference phase current at the center position θ_c^i can be obtained using the following relation:

$$i_{ref} = \sqrt{\frac{2T_{ref,in}}{\left.\frac{dL}{d\theta}\right|_{\theta=\theta_c^i}}} \tag{13}$$

In this equation, *Tref*, in is incoming reference phase torque which should be considered the half of motor reference torque at θ_c^i. By substituting the relation (13) in (10), the turn-on angle obtained analytically respect to motor speed. As speed increases, the turn on angle value decreases toward the unaligned position so that phase current can capable to follow the reference current in incoming phase. The authors proposed the scheme in [16] to modify the conventional TSFs in order to enhance the effective controlled torque-speed region. In the proposed algorithm, torque error in incoming torque control loop was added to the reference torque of outgoing phase at the constant turn-on and turn-off angles. This may leads to increase the phase current magnitude in outgoing phase where the phase inductance becomes maximum value respect to the rotor position which cause to entering the tail current in outgoing phase to the negative torque region due to the negative slope of inductance area. In this paper, turn-on angle control taking the analytic function proposed by (10) into account to overcome this drawback. The effects of receding turn-on angle on phase current can be represented as depicted in Figure 4.

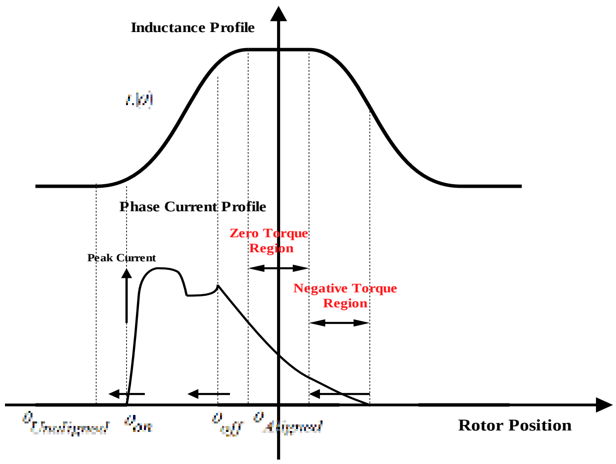

Figure 4. Receding Turn-on Angle Effects on the Shape of Phase Currents

The modification scheme regulate reference torques based on the errors exist on incoming and outgoing torque control loops [16]. Figure 5 shows the modification concept which will be used in this paper to minimize torque ripple in motor resultant torque. In order to implement this concept to modify the reference phase torques for any TSFs, Table (1) can be simply applied on the control system.

The control block diagram of switched reluctance motor drive using modified turn-on angle control scheme is depicted in Figure 6. In this figure reference torque which can be either generated by speed control loop or applied directly will be divided to the reference phase torques based on the considered TSFs. Turn-on angle control will also modified by (10) and affect both on TSFs and power converter signal pulses. The obtained θ_c^i considered as 53 degree for outgoing phase and 38 degree for incoming phase based on values from Figure 3.

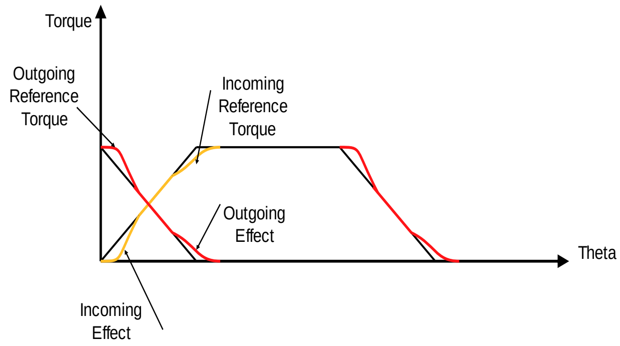

Figure 5. Simple Modification Scheme used to Compensate Torque Error in Phase Torque Control Loop

Table 1. Logical Rules for Modification Scheme

Condition	Step	Incoming and Outgoing Reference torques
$T < T^*$	First	$T_{k+1}^* = T_{K+1,TSF}$
	Second	$T_k^* = T_{K,TSF} + \Delta T_{k+1}$
$T > T^*$	First	$T_k^* = T_{K,TSF}$
	Second	$T_{k+1}^* = T_{K+1,TSF} + \Delta T_k$

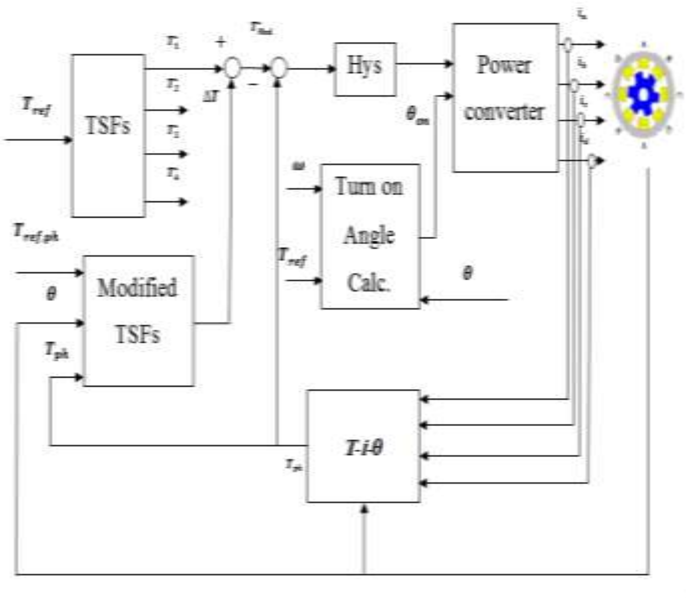

Figure 6. Control Block Diagram of Modified Turn-on Angle Scheme

5. SIMULATION RESULTS

In order to validate the effectiveness of the proposed method to reduce torque ripple and compare with the previous works, a four-phase switched reluctance motor, with the specifications given in the appendix is considered. The proposed method is simulated using MATLAB software. In the first case, conventional TSFs are simulated considering fixed turn-on angle for constant load torque. Figures (7) to (10) represent the results obtained for phase currents, flux linkages, torques and the motor resultant torque at 1200 rpm speed for four conventional TSFs.

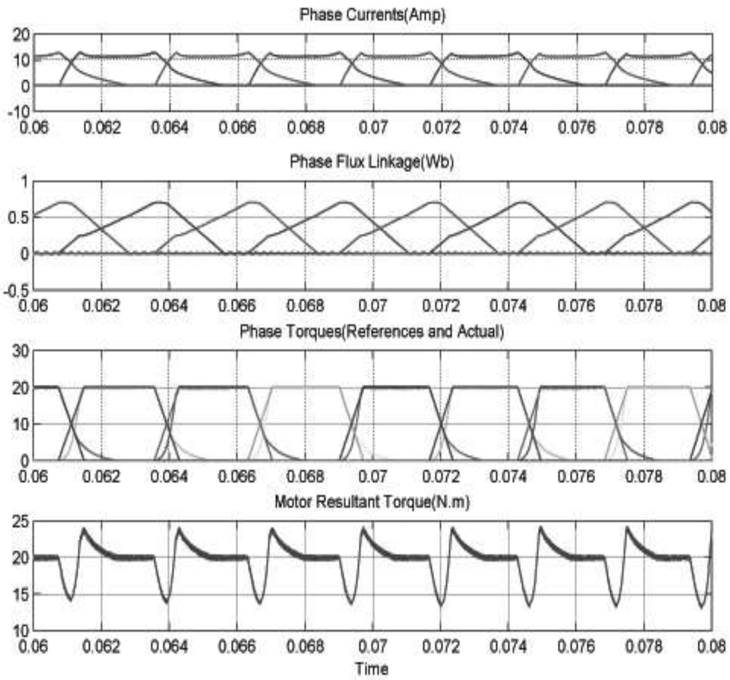

Figure 7. Phase Currents, Flux Linkages, Phase Torques and Motor Resultant Torque for Linear TSF at Speed 1200 rpm and 20Nm Reference Torque

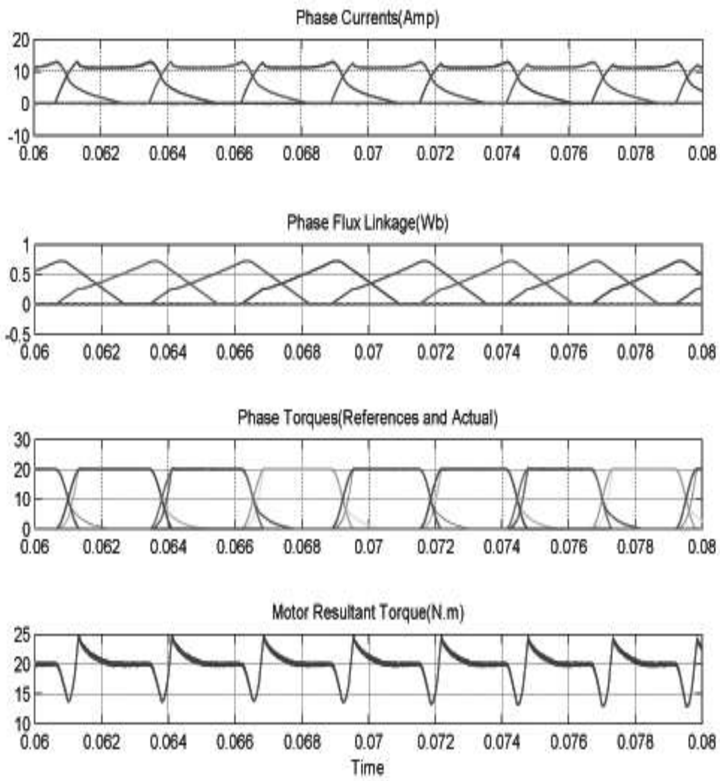

Figure 8. Phase Currents, Flux Linkages, Phase Torques and Motor Resultant Torque for Cosine TSF at Speed 1200 rpm and 20Nm Reference Torque

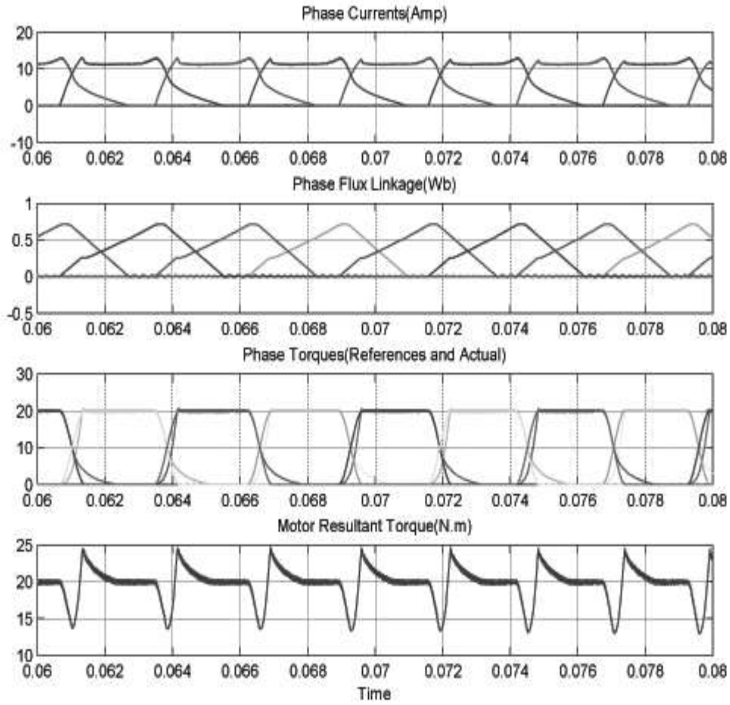

Figure 9. Phase Currents, Flux Linkages, Phase Torques and Motor Resultant Torque for Cubic TSF at Speed 1200 rpm and 20Nm Reference Torque

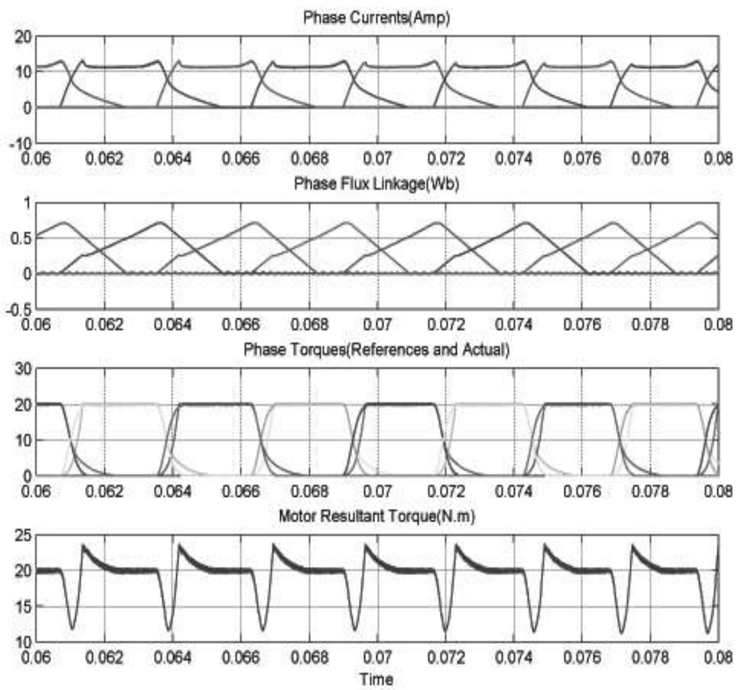

Figure 10. Phase Currents, Flux Linkages, Phase Torques and Motor Resultant Torque for Exponential TSF at Speed 1200 rpm and 20Nm Reference Torque

Considering equation (10) for turn-on angle control scheme without taking the modification rules into account, the simulation results obtained represented as following Figures from (11) to (14).

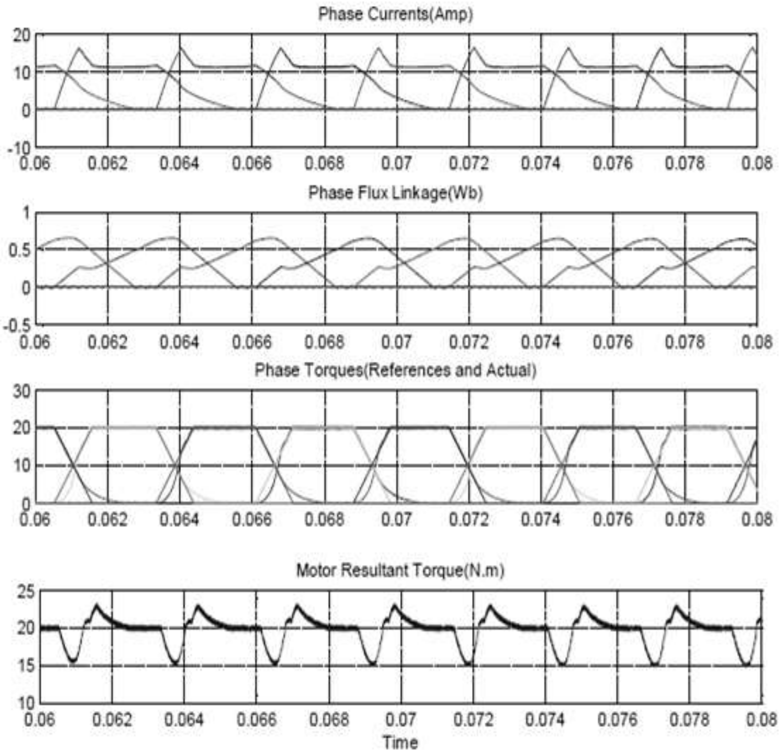

Figure 11. Phase Currents, Flux Linkages, Phase Torques and Motor Resultant Torque for Linear TSF at Speed 1200 rpm and 20Nm Reference Torque with Turn-on Angle Control Scheme

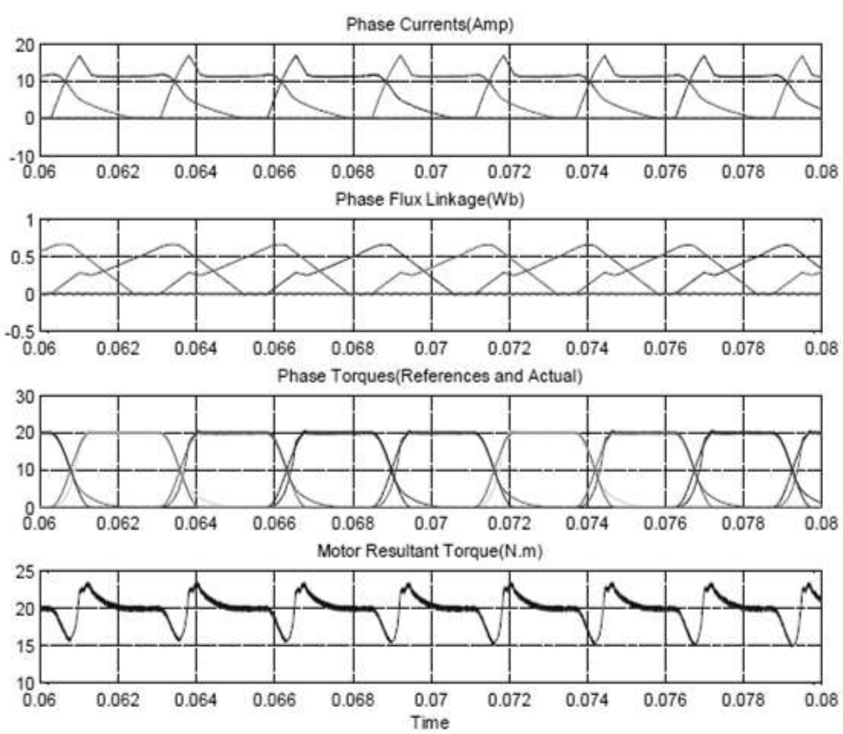

Figure 12. Phase Currents, Flux Linkages, Phase Torques and Motor Resultant Torque for Cosine TSF at Speed 1200 rpm and 20Nm Reference Torque with Turn-on Angle Control Scheme

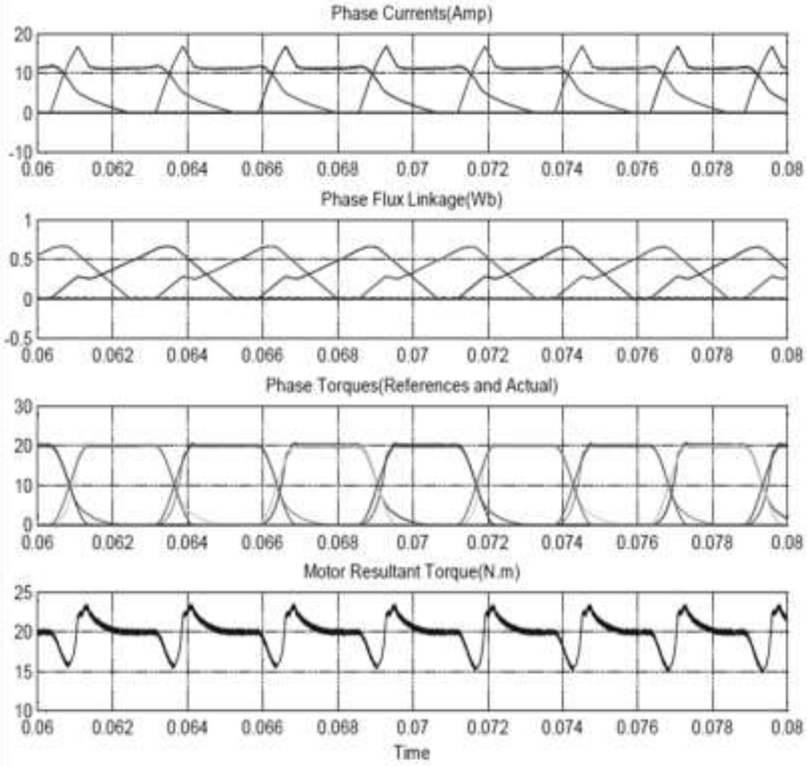

Figure 13. Phase Currents, Flux Linkages, Phase Torques and Motor Resultant Torque for Cubic TSF at Speed 1200 rpm and 20Nm Reference Torque with Turn-on Angle Control Scheme

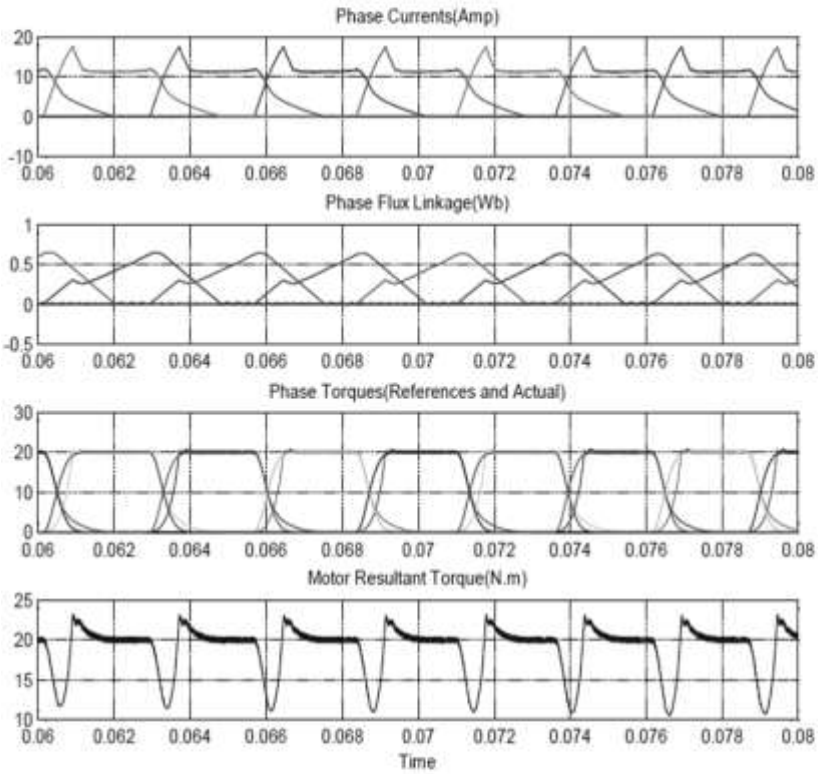

Figure 14. Phase Currents, Flux Linkages, Phase Torques and Motor Resultant Torque for Exponential TSF at Speed 1200 rpm and 20Nm Reference Torque with Turn-on Angle Control Scheme

Considering the both modification rules and turn-on angle control scheme both together, simulation results for the same conditions are presented as follows by Figures (15) to (18):

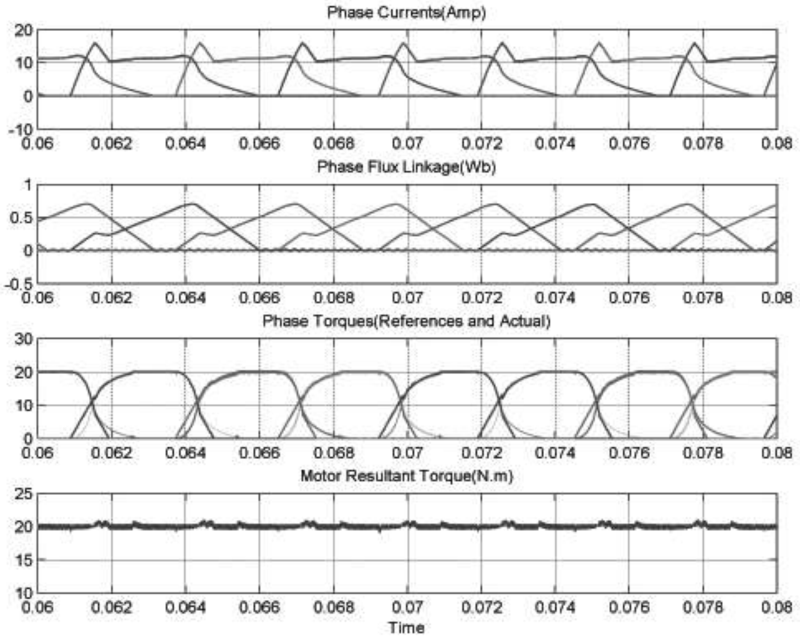

Figure 15. Phase Currents, Flux Linkages, Phase Torques and Motor Resultant Torque for Linear TSF at Speed 1200 rpm and 20Nm Reference Torque with Modification Rules and Turn-on Angle Control Scheme

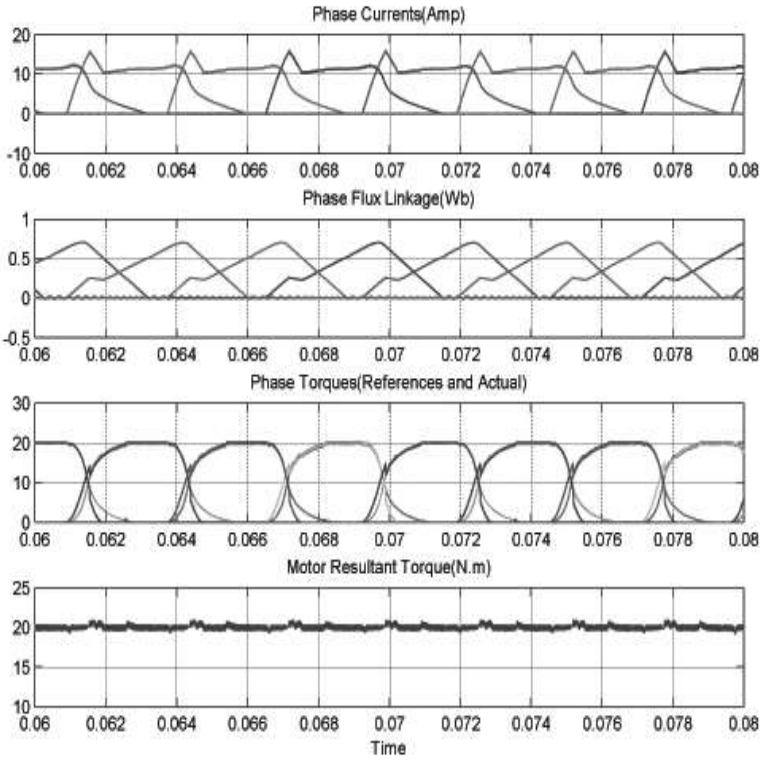

Figure 16. Phase Currents, Flux Linkages, Phase Torques and Motor Resultant Torque for Cosine TSF at Speed 1200 rpm and 20Nm Reference Torque with Modification Rules and Turn-on Angle Control Scheme

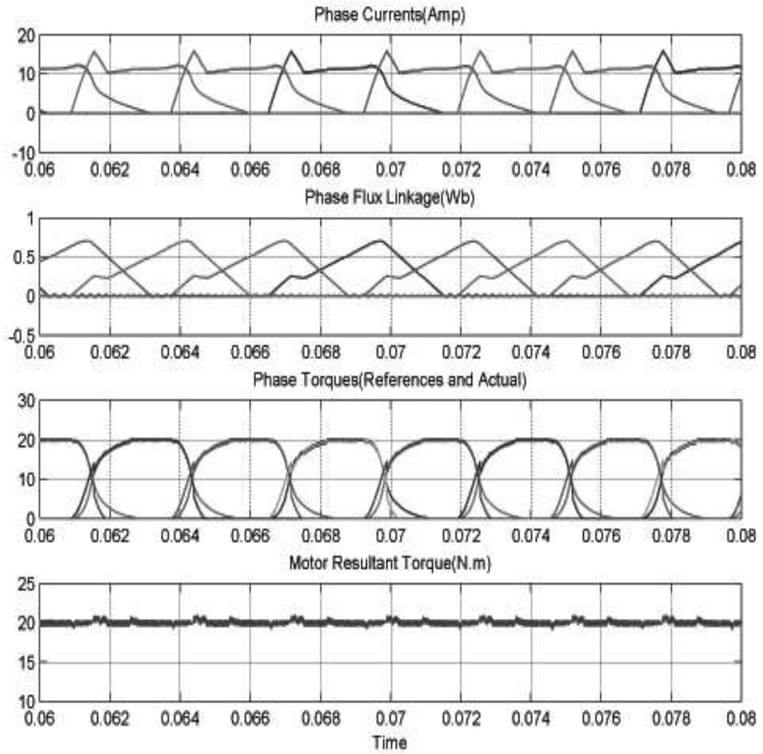

Figure17. Phase Currents, Flux Linkages, Phase Torques and Motor Resultant Torque for Cubic TSF at Speed 1200 rpm and 20Nm Reference Torque with Modification Rules and Turn-on Angle Control Scheme

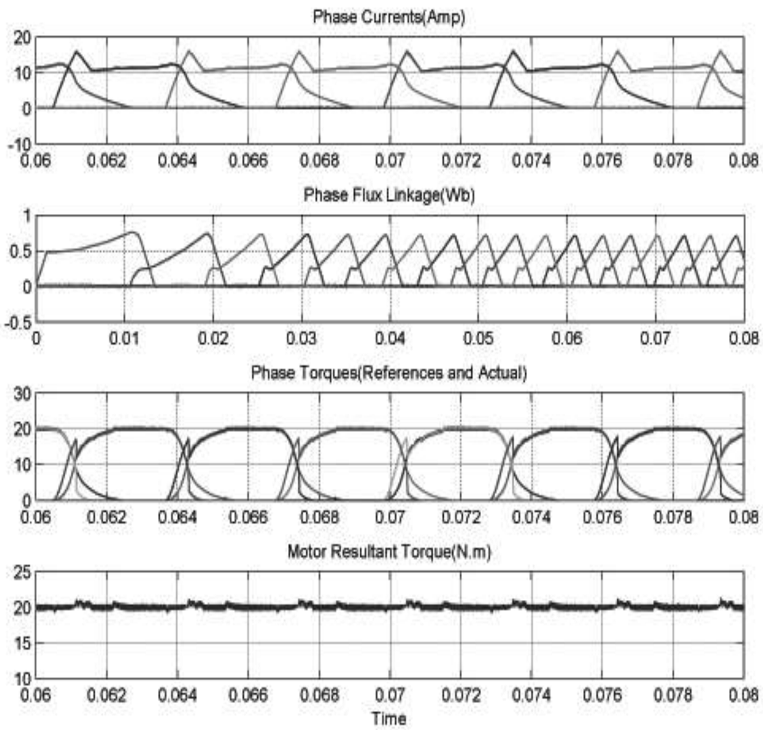

Figure 18. Phase Currents, Flux Linkages, Phase Torques and Motor Resultant Torque for Exponential TSF at Speed 1200 rpm and 20Nm Reference Torque with Modification Rules and Turn-on Angle Control Scheme

It can be seen from the above figures, torque-ripple reduced significantly and the proposed scheme can enhance the effectiveness of TSFs at higher speed compared with the conventional types. Figure (19) shows the average motor torque versus rotor speed for some different considered conditions.

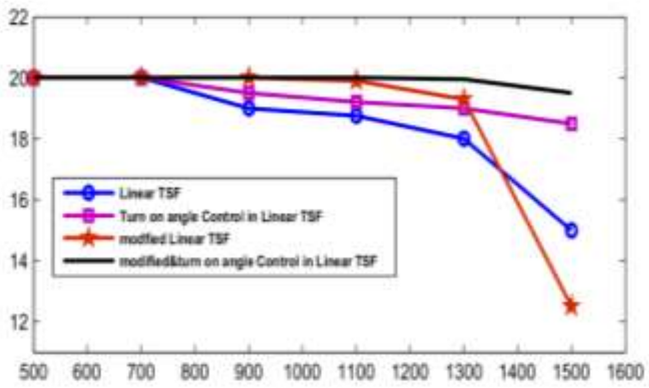

Figure 19. Average Motor Torque Versus Rotor Speed for Different Conditions: Conventional Linear TSF, with Turn-on Angle Control, with Modification Rules and Both Modifications and Turn-on Angle Control Schemes

It can be achieved from Figure (19), applying only the modification rules can lead to increasing outgoing phase current which can cause to entering the tail current to the negative torque region and reduce the average torque dramatically. This is happened over the 1300 rpm where the slope of corresponding curve reduced with greatest amount. Using the proposed scheme, this was prevented and overall performance of control method for all TSFs is enhanced.

6. CONCLUSION

SRMs not only have a simple and reliable structure, but also have low cost production process. However, inherent discrete torque production of SRM as well as intensive magnetic saturation in stator and rotor cores are the major drawbacks of utilizing in variety of industrial applications and also causes the inappropriate torque ripples. In this paper, the turn-on control method along with some simple modification rules is presented to enhance the effective controlled torque-speed region. The results showed that neither individual turn-on angle control nor modification rules can reduce torque ripples when the operational speed increased. Turn-on angle control strategy doesn't guarantee the zero torque error operation in incoming phase torque control loop. Moreover, excessive receding turn-on angle can leads to increasing phase peak current and copper loss. On the other hand, modification rules can increase the outgoing reference phase current which cause to entering the tail current to the negative torque region and reduce the efficiency and average torque dramatically. The proposed scheme showed that either turn-on angle control and modification rules can enhance the maximum ripple-free operation speed of an SRM and can be applied for all types of TSFs.

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