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A Hybrid Torque Sharing Function with Controlled Commutation Period for Torque Ripple Minimization in SRM

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Abstract: The main drawback of the switched reluctance motor (SRM) is the torque ripples that restricts its suitability for high-performance applications. Several control techniques have been used to mitigate these torque ripples. Torque sharing function (TSF) is one of the most significant control techniques used for minimizing the torque ripples in SRM. Different TSFs have been developed for reduction SRM torque ripples. However, the difference between the incoming and the outgoing torque responses along with changing of the commutation interval (CI) with changing the motor speed makes the tracking operation difficult. In this paper, a hybrid TSF is proposed. The proposed TSF is formulated based on a linear function for the incoming phase and a nonlinear exponential function for the outgoing phase. Also, the control procedure of the TSFs is developed where the motor speed is become an input along with the rotor position and the reference torque. The CI is accurately adjusted enough for the commutating process. A look-up table model based finite element analysis (FEA) for 6/4 SRM is built. The results of the proposed method are compared with those of conventional TSFs. The effectiveness of the proposed control technique is verified by the simulation results.

Keywords: Switched reluctance motor (SRM), Torque ripple minimization, Torque sharing function (TSF), Commutation interval (CI).

1. Introduction

Switched reluctance motor is an electrical motor that has been widely used in recent years. It has a simple and durable structure, low inertia, inexpensive cost, fault tolerant, high torque per ampere ratio, high speed and a high performance with different applications [1-3]. Unless, the SRM suffers from an elementary drawback caused by its construction and excitation process, which is the higher torque ripples [4-6]. Recently, there are many techniques have been developed to reduce these ripples in the producing torque either by development the motor design or by employing modern control approaches [7-11]. Torque sharing function (TSF) is an effective approach to perform the control of reducing the torque ripples in SRM. TSF is used for distribution of the reference torque between all phases of the SRM, with ensuring that the whole of all phases torque is equal to the torque command [12, 13]. In the literature, many TSFs have been developed, such as linear, exponential, cosine and cubic TSFs [14-16]. However, in the beginning of the commutation, the generated torque response is linear and fast due to it produces near to the unaligned rotor position where the inductance has its minimum value. At the end of the commutation, the produced torque has a nonlinear slowly response because it generates near from the aligned rotor position where the phase inductance has its top value [17, 18]. In addition, changing the speed will also produce impairment of torque tracking performance because the outgoing phase is not attained its reference due to the tail of current with constant overlap angle [19]. Therefore, to ensure accurate control implementation, precise tracking of the torque reference with changing the speed is the challenge. An offline TSF is presented

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in [20] where the flux linkage characteristics of SRM that obtained from (FEA) are used to determine the optimal current profiles for torque ripple reduction. However, the produced torque is irregular at different motor operations. Applying positive compensating at the starting of the commutation for outgoing phase and negative compensating at the end of the commutation for the incoming phase is introduced in [21]. Nevertheless, with increasing the motor speed, the torque ripples have been increased. In [22], a logical nonlinear TSF for torque ripple reduction and efficiency improvement is presented. However, the increasing of logical conditions made the control algorithm more complicated. An improved TSF based genetic optimization algorithm beside PI compensator is introduced in [23], but slight results are introduced. In [24], direct instantaneous torque control (DITC) with torque sharing function is developed. The method attains low torque ripple but is restricted in its operation range, as the controller requires to be altered when the speed changes. Evaluating and comparing between different types of TSFs are presented in [25]. Also, the genetic optimization is used. The exponential form is preferred in the most cases. Torque sharing function based fuzzy logic control (FLC) and sliding mode is proposed in [26]. Using sliding mode and look-up table model beside FLC complicated the control system.

In this paper, a hybrid TSF with controlled the commutation period for torque ripple reduction SRM is proposed. A linear reference for incoming phase and controlled exponential reference for the outgoing phase are combined to shape the proposed TSF. An online controlled of the overlap period based on the motor speed is developed. Robustness and effectiveness of the proposed method will be validated by simulation results at different conditions. This paper is structured as follows: Section 2 shows the modelling of the SRM. Section 3 introduces the conventional TSFs. However, the problem description is introduced in section 4. Section 5 illustrates the proposed TSF. Section 6 includes the simulation and comparison results. Section 7 is a conclusion.

2. Modeling of SRM

2.1. Steady state model

The phase voltage for any phase can be expressed as;

$$V = i.R + \frac{d\psi(\theta,i)}{dt} \tag{1}$$

$$\psi(\theta,i) = L(\theta,i).i \tag{2}$$

Where, V is the voltage applied to the phase winding, ψ is the flux linkage, R is the phase resistance and L is the phase inductance. The phase co-energy (W) is determined by mathematical integration of the $\psi(\theta,i)$ with respect to phase current:

$$W(\theta,i) = \int_0^i \psi(\theta,i)di \tag{3}$$

Then, the phase torque can be calculated by mathematical differentiation of the $W(\theta,i)$ with respect to the rotor position θ

$$T(\theta,i) = \frac{\partial W(\theta,i)}{\partial \theta} \tag{4}$$

By summing the phases developed torque, the total torque can be calculated as follow:

$$T = \sum_{k=1}^{3} T_k\left(\theta_k, i_k\right) \tag{5}$$

2.2. Dynamic model

For switched reluctance motor, the dynamic model equations can be deduced as the following:

$$\frac{d\psi(\theta,i)}{dt} = V - Ri \tag{6}$$

$$\frac{d\theta}{dt} = \omega \tag{7}$$

$$\frac{d\omega}{dt} = \frac{1}{J}\left(T - T_L - B\omega\right) \tag{8}$$

Where ω, J, B are rotor speed, moment of inertia and viscous damping constant respectively.

3. Torque sharing function

In torque sharing strategy, the conduction interval of each phase is split into two regions. In the first region, single phase is conducted but commutation between adjacent phases is applied in the second region. Also, the control is designed where the overall torque for different phases during the commutation process remains at specified level. Fig. 1 shows the block diagram for conventional torque sharing method. In conventional TSF method, the output signal depends just on the torque reference Tref and rotor position θ. The torque to current converter is used to convert the reference torque signal to the reference current signal.

The general TSF equation can be defined by [22]:

$$TSF(\theta)=\begin{cases} 0 & 0\le\theta<\theta_{on} \\ f_{up}(\theta).T_{ref} & \theta_{on}\le\theta<\theta_{on}+\theta_{ov} \\ \mathrm{T}_{ref} & \theta_{on}+\theta_{ov}\le\theta<\theta_{off} \\ f_{dn}(\theta).T_{ref} & \theta_{off}\le\theta<\theta_{off}+\theta_{ov} \\ 0 & \theta_{off}+\theta_{ov}\le\theta<\theta_{p} \end{cases} \quad (9)$$

Where

T_{ref} the reference torque,

$f_{up}(\theta)$ the rising TSF for the incoming phase,

$f_{dn}(\theta)$ the declining TSF for the outgoing phase,

θ_{on} turn-on angle,

θ_{off} turn-off angle,

θ_{ov} overlapping angle,

θ_{p} rotor pole pitch angle.

3.1. Linear TSF

In the linear TSF the rising and declining reference torque equations can be expressed as [25]:

$$f_{up}=\frac{\theta-\theta_{on}}{\theta_{ov}} \quad (10)$$

$$f_{dn}=1-\frac{(\theta-\theta_{off})}{\theta_{ov}} \quad (11)$$

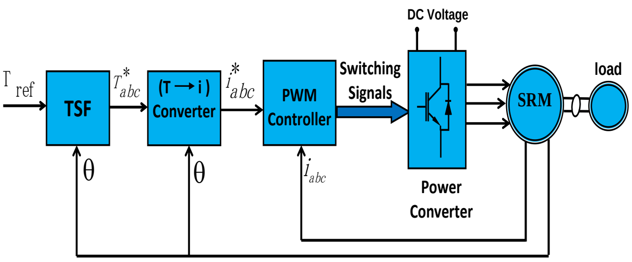

Figure. 1 The block diagram of conventional TSF method

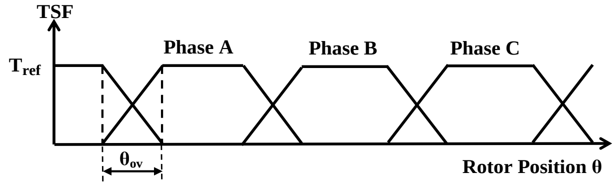

Figure. 2 Linear torque sharing function

Fig. 2 illustrates the profile of the linear TSF.

3.2. Cubic TSF

For the cubic TSF the rising and falling reference equations are expressed mathematically as [28]:

$$f_{up}=\frac{3}{\theta_{ov}^{2}}(\theta-\theta_{on})^{2}-\frac{2}{\theta_{ov}^{3}}(\theta-\theta_{on})^{3} \quad (12)$$

$$f_{dn}=1-\frac{3}{\theta_{ov}^{2}}(\theta-\theta_{off}+\theta_{ov})^{2}-\frac{2}{\theta_{ov}^{3}}(\theta-\theta_{off}+\theta_{ov})^{3} \quad (13)$$

3.3. Exponential TSF

Up and down reference torque in exponential TSF can be characterized by the equations [29]:

$$f_{up}=1-\exp\left(-\frac{(\theta-\theta_{on})^{2}}{\theta_{ov}}\right) \quad (14)$$

$$f_{dn}=\exp\left(-\frac{(\theta_{off}-\theta_{ov}-\theta)^{2}}{\theta_{ov}}\right) \quad (15)$$

3.4. Cosine TSF

In the cosine TSF the reference equations can be written as following [25]:

$$f_{up}=\frac{1}{2}-\frac{1}{2}\cos\left(\frac{\pi}{\theta_{ov}}(\theta-\theta_{on})\right) \quad (16)$$

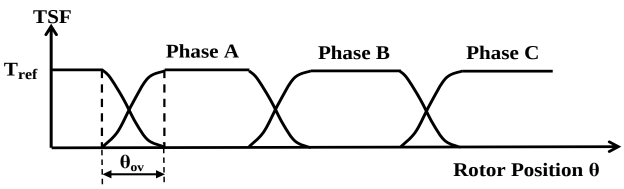

Figure. 3 Cubic torque sharing function

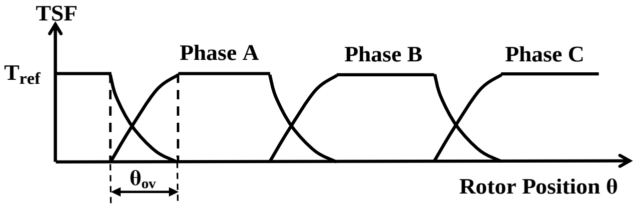

Figure. 4 Exponential torque sharing function

$$f_{dn} = \frac{1}{2} + \frac{1}{2}\cos\left(\frac{\pi}{\theta_{ov}}(\theta - \theta_{off})\right) \quad (17)$$

4. Problem description

Conventional excitation of SRM phases is to sequentially turn on one phase in unaligned position where the inductance is minimum (L_{min}) and turn off the phase in aligned position where the inductance is maximum (L_{max}) as shown in Fig. 6. Where β_s is the stator pole arc, β_r is the rotor pole arc, θ_{on} is the turn on angle and θ_{off} is the turn off angle.

Based on the above-mentioned excitation way, the produced torque for 3phase 6/4 SRM is illustrated in Fig. 7. It is obvious that the torque response has extremely linear response for the incoming phase and the torque response is closest to the exponential form for the outgoing phase.

Furthermore, the actual motor current for the outgoing phase is met difficulty to track its reference when the motor speed is changed. With fixed overlap angle, the commutation interval (CI) is become smaller than the current need to fall to zero with increasing the motor speed as shown in Fig. 8. It can be noted that the incoming phase torque is typically tracked its reference which is linear TSF.

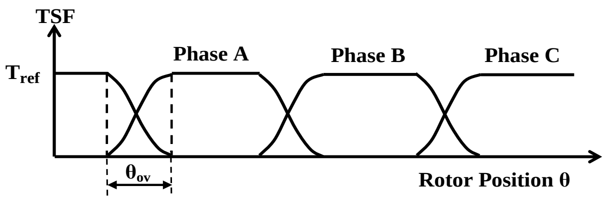

Figure. 5 Cosine torque sharing function

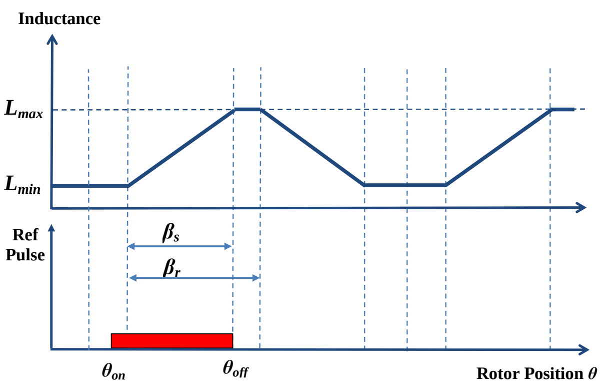

Figure.6 Phase inductance profile of the SRM

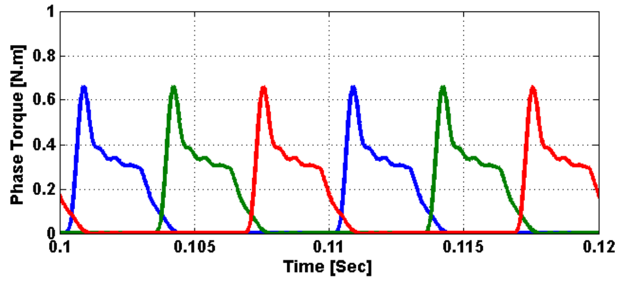

Figure. 7 Phase torque response for 6/4 SRM

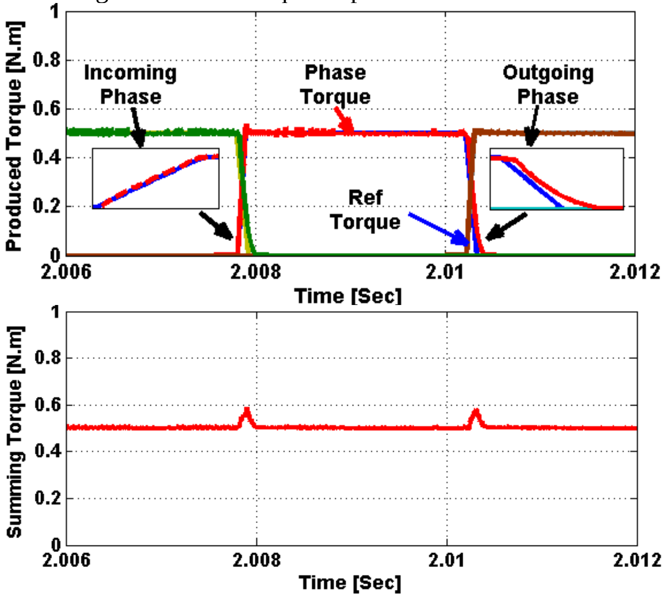

Figure. 8 Phase and total torque at high speed

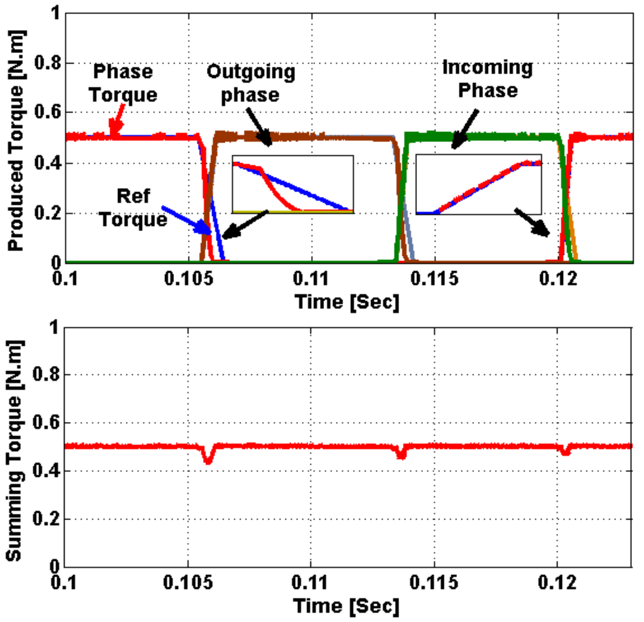

Figure. 9 Phase and total torque at low speed during the starting

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However, the outgoing phase torque is failed to track the reference due to both reasons. The first reason, the CI is become smaller with increasing the speed and the other reason is the exponential torque response while the reference of TSF is linear.

Contrariwise at low speed, the CI is become larger than the required time that the current for the outgoing phase is needed for decaying to zero as introduced in Fig. 9. Also, it can be observed that the response of the incoming phase is matched its reference accurately while the outgoing phase torque response is arrived early and has exponential form. As result of the previous reasons, high torque ripples are produced in the both cases.

5. Proposed TSF

As explained above, the traditional TSFs result undesirable oscillations in the torque production because the outgoing phase fails to track its reference. For compensating these oscillations at different motor operation, the proposed TSF is improved. The proposed TSF can be expressed by the following equation;

$$TSF = \begin{cases} 0 & 0 \le \theta < \theta_{on} \\ \left((\theta - \theta_{on})/\theta_{cov}\right)T_{ref} & \theta_{on} \le \theta < \theta_{on} + \theta_{cov} \\ T_{ref} & \theta_{on} + \theta_{cov} \le \theta < \theta_{off} \\ \text{1-exp}\left(-\left((\theta - \theta_{off})/\theta_{cov}\right)^2 * k\right)T_{ref} & \theta_{off} \le \theta < \theta_{off} + \theta_{cov} \\ 0 & \theta_{off} + \theta_{cov} \le \theta < \theta_p \end{cases} \quad (18)$$

Where k is exponential constant and θ_{cov} is the controlled overlap angle which depends on the motor speed.

In the improved TSF, the rising function is expressed by a linear function in line with the incoming torque response in the previous results. The falling function is formulated by an exponential function which closest to the torque response of the outgoing phase. Also, the falling function has a constant k which controls of its shape as shown in Fig. 10.

In addition, the controlled overlap angle θcov is formulated by the following equation;

$$\theta_{cov} = a_0 + a_1\omega + a_2\omega^2 \quad (19)$$

Where ω the motor speed and a_0, a_1, a_2 are the overlap controlled function constants. The optimum overlap angle is determined for each speed from 50 rpm up to 2000 rpm by step 50 rpm. After that the curve fitting tool is used to get the nonlinear overlap control function which links between the overlap angle and the motor speed. By this way, the overlap angle and subsequently the commutation interval (CI) are regulated continuously with speed change. The concept of the proposed method is presented in Fig. 11. It can be obvious that the output of TSF is become not only depends on the reference torque Tref and rotor position θ but also depends on the motor speed ω. So, an online tuning of the overlap

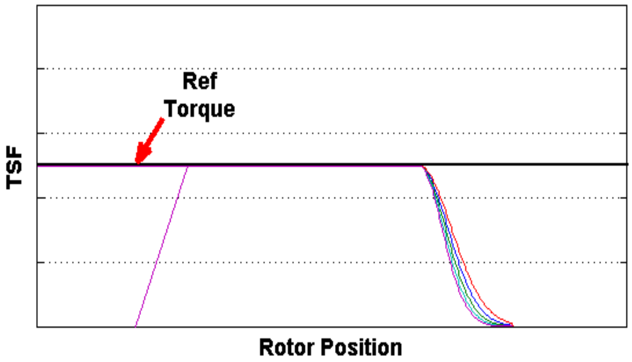

Figure. 10 The profile of the proposed TSF

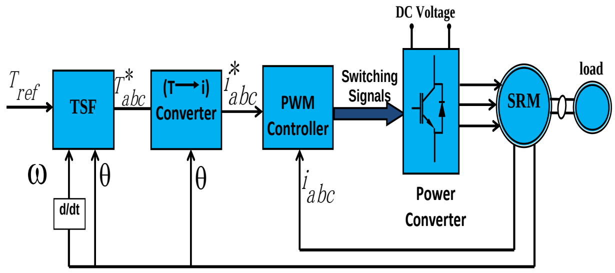

Figure. 11 The proposed TSF for torque ripple minimization in SRM

angle will be occurred with changing the motor speed and the overlap angle will be precise enough for commutation process.

After the reference torque is determined by the proposed TSF, the individual current references will be extracted from torque–current–position characteristics that are gotten from FEA. Then the hysteresis current controller will be used to control the feedback current to track its reference current.

6. Simulation results

The produced torque of each phase and the overall torque for all phases are executed in the Matlab/Simulink software based on the block diagram of the proposed TSF abovementioned. To verify the effectiveness and robustness of the proposed technique, the results are compared with the results of conventional linear TSF. In the both techniques under comparison, the turn on angle, the turn off angle and the torque reference are the equal. Additionally, the conventional linear TSF has fixed

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overlap angle but it depends on the motor speed in the proposed hybrid TSF. The both methods are tested and compared over a wide speed range. The simulation parameters for the system are introduced in Table 1.

6.1. Operation under the rated speed

To examine the proposed technique at different motor speeds under the rated, the starting operation is the best choice for this examination. In the conventional linear TSF the overlap is kept constant at 2.6 degree and the torque reference is chosen at 0.625 N.m. The turn on angle and turn off angle are 8 degree and 38.1 degree respectively. In the beginning of the starting operation of the linear TSF, the CI is larger than the time that the current is needed for falling to zero as shown in Fig. 12. Also, the response of the outgoing phase has a nonlinear response that is different from the linear response of the TSF. Therefore, the torque ripple is bigger and nearly equal 15% of the reference torque. With increasing the speed toward the rated speed, the CI is decreased and it is become closer to what current needs to decay to zero. So, the torque ripples decrease with increasing the speed toward the rated speed but the response of the outgoing phase still cannot track its linear reference.

Table 1. Simulation parameters

Item	Value
Voltage, V	100 V
Phase Resistance, R	8.6 Ω
Moment of inertia, J	0.01 kg.m2
viscous damping constant, B	0.005 N.m.s
No of stator poles N_S	6
No of rotor poles N_r	4
No of phases m	3

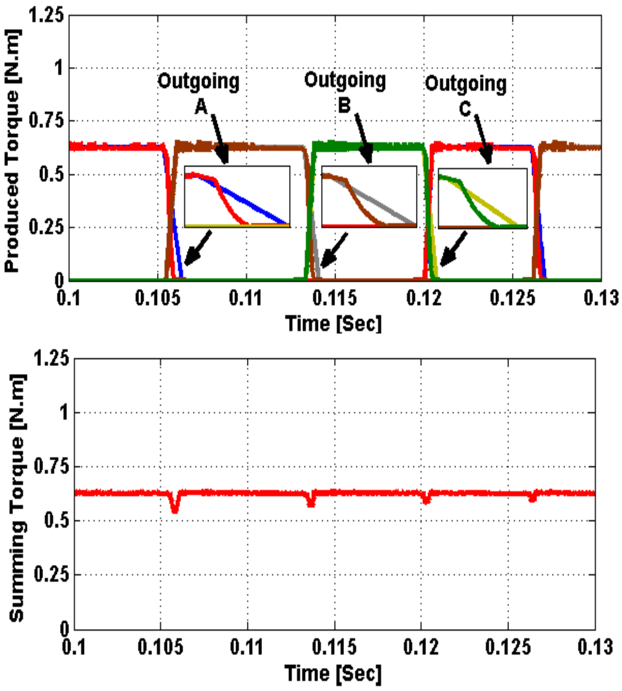

Figure. 12 The torque response during the starting using conventional TSF

In the proposed hybrid TSF, the turn on angle, turn off angle and the reference torque are taken the same values as the conventional TSF. The overlap angle has been tuned during the change of motor speed from 1.3 degree at the first torque pulse up to 2.72 at rated speed. Also, the exponential constant k has been adjusted to 4.95 in order to get falling exponential reference that matches the response of the outgoing phase. According to these modifications of the proposed TSF, the response of the output torque is improved as shown in Fig. 13. It can be observed that the response of the outgoing phase is typically matched its exponential reference in the proposed TSF at different motor speeds during the starting operation. Also, the torque ripples are reduced to less than 2% of reference torque by using the hybrid TSF and tuning the overlap angle as well as adjusting the CI.

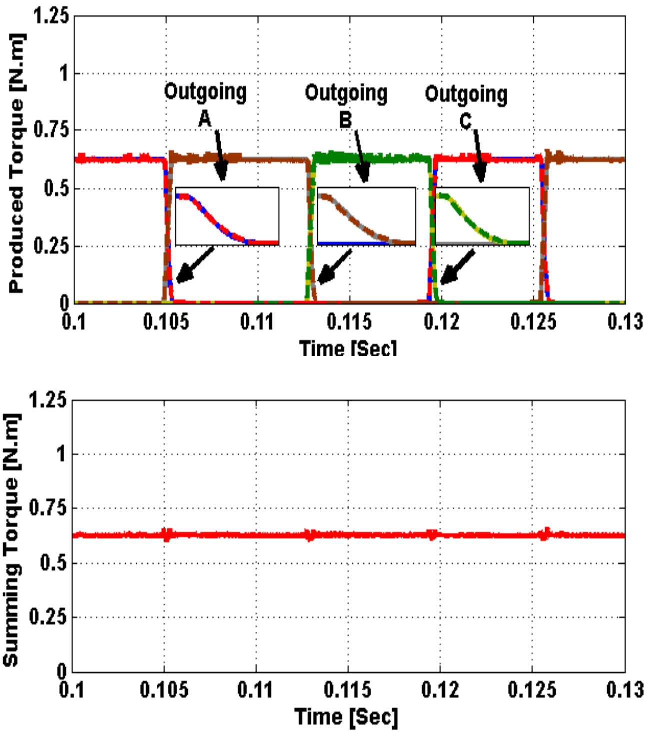

Figure. 13. The torque response during the starting using proposed TSF

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6.2. Operation over the rated speed

The proposed system is also checked over the rated speed to validate its robustness. The turn on angle, turn off angle and the torque reference are unchanged. Also, the overlap angle is remained constant at 2.6 degree for the conventional TSF. The response of the traditional linear TSF is introduced in Fig. 14. It can be shown that the response of the outgoing phase is gone away its reference with increasing the speed. At the same time, the shape of falling down response differs from the reference response. As result of these reasons, the torque ripples increase as the motor speed increases and the ripples reaches around 20% of the reference torque.

For the proposed hybrid TSF, the exponential constant k is kept constant at 4.95 but the overlap angle is changed from 2.72 degree at rated speed up to 3.21degree at speed equal to 1.33 of the rated speed. Based on the proposed strategy, the response of the produced torque upper the rated speed is enhanced as illustrated in Fig. 15. It can be detected that the torque ripples are minimized to less than 2% of the reference torque. This improvement in the output torque is occurred due to the online modification of the overlap angle along with the good matching between the torque response and its hybrid reference.

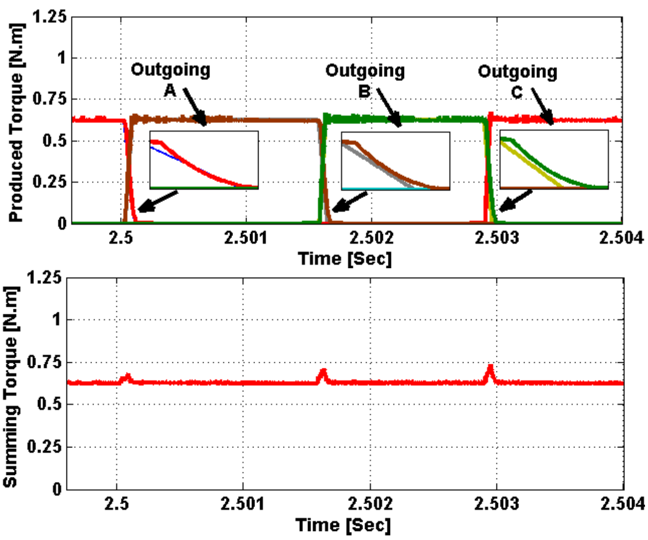

Figure. 14 The torque response of conventional TSF over the rated speed

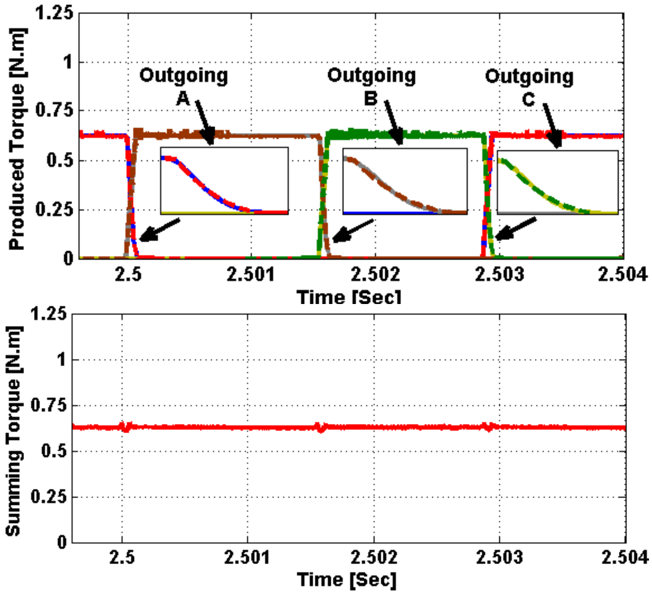

Figure. 15 The torque response of the proposed TSF over the rated speed

7. Conclusion

In this paper, torque ripple minimization technique for switched reluctance motor based on a hybrid TSF is introduced. In the proposed Technique the TSF has been designed based a linear function for the incoming phase and a nonlinear exponential function for the outgoing phase. The exponential reference for the falling function in TSF has been also controlled to match the machine torque response. In addition, the overlap angle in the TSF has been formulated as a function of the motor speed. Therefore, the CI has been accurately tuned over a wide speed range of the motor operation. Based these modifications of the TSF, the proposed method has been examined under and above the rated speed of the motor. The simulation results of the proposed technique have been compared with the results of the traditional linear TSF. The comparison illustrates that the proposed TSF has reduced the ripples into less than 2% of the total output torque over a wide speed range. However, the ripples in the conventional linear TSF have reached in some cases to 20%. So, the proposed TSF introduces a valuable technique to improve the behavior of SRM working under torque ripple minimization. In the future, one of the optimization techniques will be used for online tuning of the overlap angle based the motor speed.

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