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Impact Analysis of Dwell Angles on Current Shape and Torque in Switched Reluctance Motors

Syeda Fatima Ghousia*
* Departement of Electrical and Computer Engineering, University of Windsor, Canada

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ABSTRACT

The reduction of torque ripple is the main target in research for designing a variable drive system with switched reluctance motors (SRM) for higher torque density and better efficiency. This ripple is due to the transition of excitation current between the adjacent phases. Precise control of turn-on and turn off angle is required to smooth the torque. In this paper, the effects of selecting the turn-on and turn-off angles are simulated in detail. It is observed that with the extended turn-on and turn off angles, the precise selection of turn-on and turn off angle can alter the shape of the excitation current in the stator coil and its point of overlapping with the adjacent coil. Therefore the transition between different phases can be smoothed out. The impact of this alteration on the excitation current and torque ripple as a function of different parameters of dwell angle is studied in detail in this paper. It is found that a sinusoidal current shape can also be obtained with the proper selection of these parameters.

Corresponding Author:

Syeda Fatima Ghousia
University of Windsor
401 Sunset Ave, Windsor, Ontario, Canada N9B3P4 (519)253-3000
e-mail: sfghousia@gmail.com

1. INTRODUCTION

There are many possible sources of torque ripple, vibration and acoustic noise in the SRM. The inherent vibration and acoustic noise are derived from the torque production mechanism, in which they are caused by the force between the excited stator teeth and the rotor. It contains a significant radial force component in addition to the required tangential component. A stator vibration is initiated when each time a phase winding was commuted. Not only magnetic and mechanical origin but also the control algorithm and the inverter system are considered to overcome these problems[1]. A multi-level switching technique has been used to reduce the radial attraction [2]. A systematic approach to waveform design is introduced with switching angle variations[3]. Design optimization of magnetic structure is also used to reduce resonance in the motor operation range [4, 5]. The winding topology and phase excitation methods were also considered [6]. The full-pitched winding, which was used to utilize the mutual torque, however, is disadvantageous to drive efficiency. The symmetrical excitation technique in a conventional winding is also disadvantageous to the developed torque. A detailed comparison of various techniques has been presented has been presented by[7].

This paper suggests a new method of current shape control and improving the torque ripple by using the continuously and non-linearly varying excitation current scheme without using multiple or variable voltage sources. It minimizes the acoustic noise and torque ripple by reducing the rapid change of radial MMF. The electromagnetic structure of an ac motor has been designed so as to be suitable for operation with a sinusoidal wave source. However, an SRM has an electromagnetic structure suitable to be operated with current pulse. This multi-level excitation is achieved simply by controlling the dwell angle parameters to control the shape of the individual phase currents in nearly sinusoidal waveform instead of square waveform without using any variable voltage source or using many voltage sources or even without using the split voltage source. Therefore there will be no hardware complexity or limitations. This excitation method has an additional overlap of more than 2-phases excitation region, before one phase is off compared with the conventional one-phase or two phase excitation method. In the overlapped excitation region, the rapid change of magneto-motive force (MMF) from the previous phase off sequence is distributed by the other two adjacent phases.

In the first session, the pulsation in static torque characteristics is discussed in detail. In the second section, the traditional mode of switching the phases is discussed with single level (constant value) excitation current with stator coils excited sequentially and one phase at a time. Later in the third section, the study of the machine with overlapping phases is presented i.e. adjacent poles are excited simultaneously, however the current levels are kept constant with negligible rise and fall time. It is found that although improved, the torque still has quite a significant amount of pulsation in it. In the last section, the impact of varying the dwell angle parameters such as turn-on and turn-off angles are studied in detail. With the variation of these angles, the current shape is altered almost into a sinusoidal shape. It is also noted that with the sinusoidal shape of the current, the current level in any of the two phases will never be same at the same time. Therefore, a current switching scheme is suggested which generates a multi-level and multi-phase multiphase excitation current without the complexity of the bipolar switching scheme.

2. BEHAVIOR ANALYSIS OF SRM

SRM is still struggling for its deserved position in the market because of an inherently existing drawback in its traditional configuration which causes torque ripple, the acoustic noise and vibrations. Therefore, the inherent torque characteristics of the SRM are discussed with respect to the rotor position compared to the excited stator pole. Fig 1 Shows a typical 8/6 SRM and its torque vs. speed characteristics. A detailed analysis of an 8/6 switched reluctance machine operation in its traditional form is required to understand the process of torque generation process.

2.1 Governing Equations of SRM

There are two main equations represent the mathematical model of a switched reluctance motor. The voltage equation of a particular winding, obtained by neglecting the coupling effect between phases, can be expressed as

$$\mathrm{v} = \mathrm{Ri} + \frac{\mathrm{d}\lambda(\mathrm{i},\theta_\mathrm{r})}{\mathrm{dt}} = \mathrm{Ri} + \mathrm{L}(\theta_\mathrm{r})\frac{\mathrm{di}}{\mathrm{dt}} + \mathrm{e}(\mathrm{i},\theta_\mathrm{r},\omega_\mathrm{r}) \tag{1}$$

Where *v*= winding terminal voltage, *i* = winding current, *R*= winding resistance, *L*= winding inductance, and *e*= back electromagnetic force (EMF). Torque developed per phase by assuming a linear magnetic system in a SRM can be derived from the co-energy, W_c as follows,

$$\mathrm{T_e}(\mathrm{i}) = \left[\frac{\partial \mathrm{W_c}(\theta_\mathrm{r})}{\partial \mathrm{x}}\right]_{\mathrm{i=constant}} = \frac{\partial \frac{1}{2}\mathrm{L}(\theta_\mathrm{r})\mathrm{i}^2}{\partial \theta_\mathrm{r}} = \frac{1}{2}\mathrm{i}^2\frac{\partial \mathrm{L}(\theta_\mathrm{r})}{\partial \theta_\mathrm{r}} \triangleq \mathrm{K}(\theta_\mathrm{r})\mathrm{i}^2 \tag{2}$$

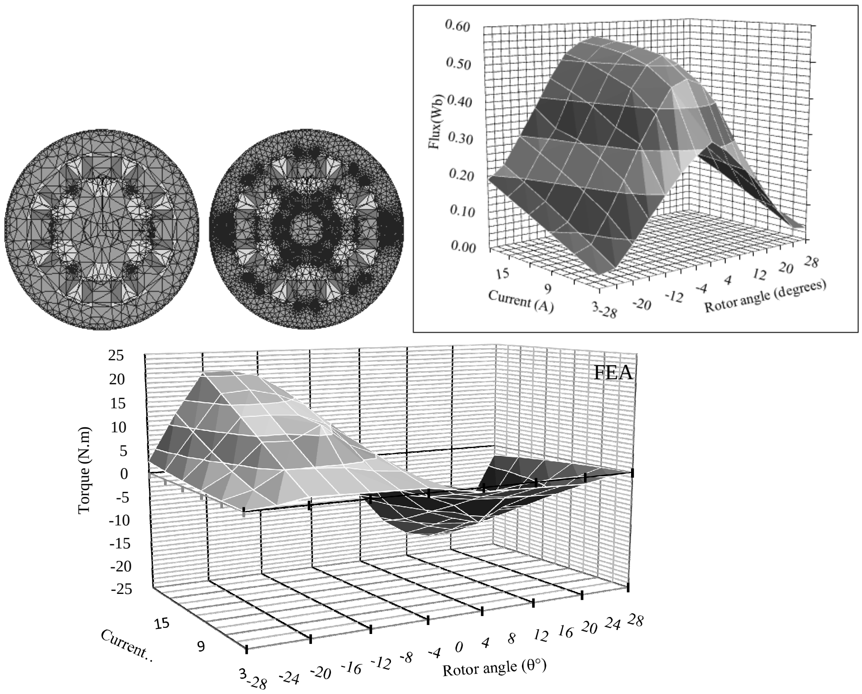
$K(\theta_r)$ denotes the torque generation constant. The composite generating torque T_e and mechanical equation of an SRM can be derived by summing the torques produced by all phases.

$$T_e(i) = \sum_{i=1}^{4} T_{ei}(i) = T_L + B\omega_r + J\frac{d\omega_r}{dt} \tag{3}$$

T_L is the load torque, J is the moment of inertia and B is the damping ratio.

2.2 Static Characteristics of SRM

In this section, the air-gap torque produced on phase 1 as a function of the rotor position and excitation current as calculated by the finite-element model is shown is Fig.1. Figure 1(a) shows the geometrical FEA model, 1(b) shows flux vs current and rotor position, and 1(c) shows the generated torque in single phase excitation scheme.It is also clearly understandable that since the torque is continuously varying like sinusoidal with the rotor position between the negative and positive maximum values. The value of torque varies directly with the amount of excitation current. Also the rotor position with respect to the stator pole has a contribution in deciding the amount of torque. Therefore, a fine and detailed study of this can help us in determining the requirement of precise control of the overlapping between adjacent phases. It also shows that sinusoidal shape excitation current gives smoother torque. The torque ripple generation is considered as the major source of acoustic noise and vibration, therefore, reduction in torque ripple will also reduce the vibration and acoustic noise significantly.



(c)

Fig. 1: FEA Analysis of the switched reluctance machine (a) Initial and final solution 2D mesh (b) Static flux Characteristics (c) Static torque characteristics

3. ORIGIN OF TORQUE RIPPLE, VIBRATION, AND ACOUSTIC NOISE IN SRM

3.1 Sources of Torque Ripple

Although there are many inherent structural advantages, the doubly-salient structure and non-ideal switched square wave winding current give the SRM higher torque ripple, and thus lead to the generation of higher vibration and acoustic noise. In addition, the rotor position and current dependent winding nonlinear inductance makes its torque and dynamic behavior highly nonlinear. Therefore, these are the main four causes of torque ripple generation. For performing the development of key technologies, it is indispensable to understand thoroughly the key features of an SRM. Figure 3 shows the switching sequence, dwell angle as well as the dynamic behavior of SRM. The sequentially generated current waveforms produces large torque ripple due to the large commutation at the fully aligned between the adjacent poles. Also due to the switching control which generates non-ideal square waves yield ripples in each phase. Fig [2] shows the basic electrical configuration and switching sequence of SRM.

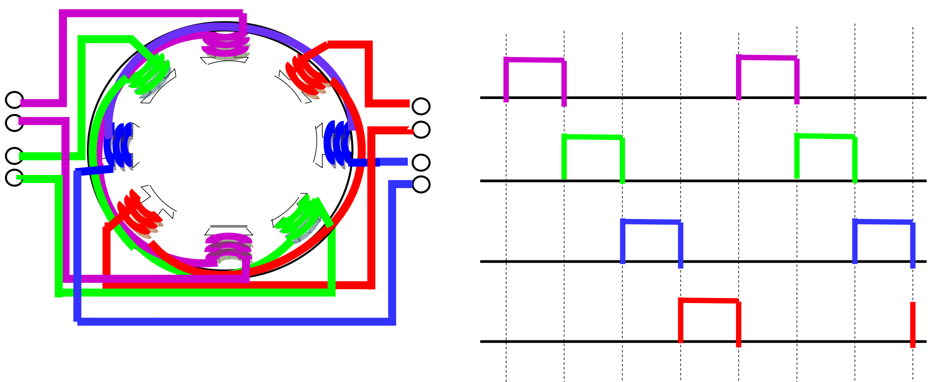


Fig. 2 Phase Connections and single phase excitation sequence

3.2 Sources of Vibration and Acoustic Noise

The generation of acoustic noise is an inherent characteristic of all electric motor but is particularly severe in SRM. Due to the rapid change of MMF during commutation, radial vibration of the stator is the dominant source of acoustic noise. These mechanical vibrations are dominantly increased when a large harmonic component of the radial force with resonant force which tries to reduce the gap separation between stator and rotor poles, especially when both poles approach alignment. This tendency, while exciting for all positions of the rotor during the excitation of a phase, is particularly prevalent at the aligned position, where the reluctance is lowest and the flux is highest. A rapid change of current, particularly associated with a declined range of inductance, induces a vibration. The magnitude of the vibration is directly proportional to the gradient and the magnitude of the exciting current. In addition, vibrations increase as a rotor pole approaches alignment with a stator pole for a given current magnitude. Table 1 shows the specification of the SRM used in simulation of the test runs of this study.

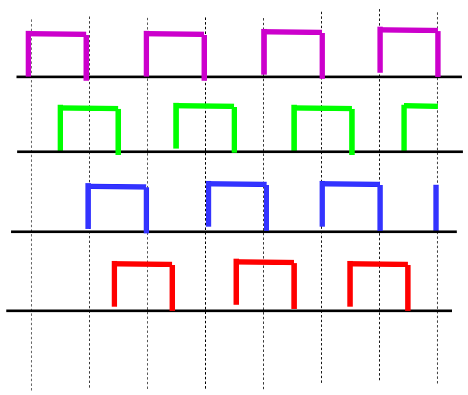
Table 1 Basic operating conditions of the SRM used in simulation

S. No.	Parameters	Specifications
1	Type	8/6 poles
2	Power rating	100 hp
3	Converter type	(2(n+1)
4	Loading Condition	No-Load
5	Measurement speed	5000-7000 rpm

4. PULSATION IN TORQUE WITH THE OVERLAPPING PHASES

4.1 Multiphase excitation operation

With the overlapping of the excitation current of the adjacent phases, the ripple at fully aligned position can be reduced. This multiphase switching sequence is shown in Fig 3. Conventionally, the overlap between the adjacent phases can be throughout the phase (50% of the time with the previous pole excitation and 50% of the time with the next pole excitation). Figure 3(a) shows the overlapping excitation. Fig. 3(b) displays the excitation current conduction angle in each phase. This conduction angle is also known as the dwell angle. It can be seen from the figure that the current flows after the middle of the unaligned position and is stopped before the fully aligned position.



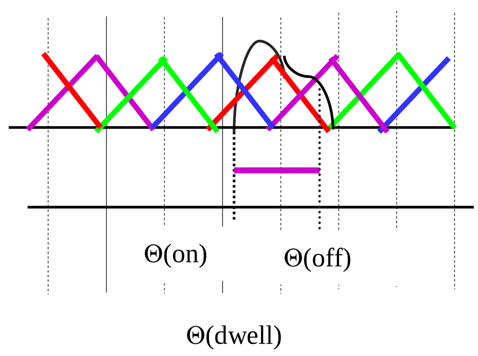
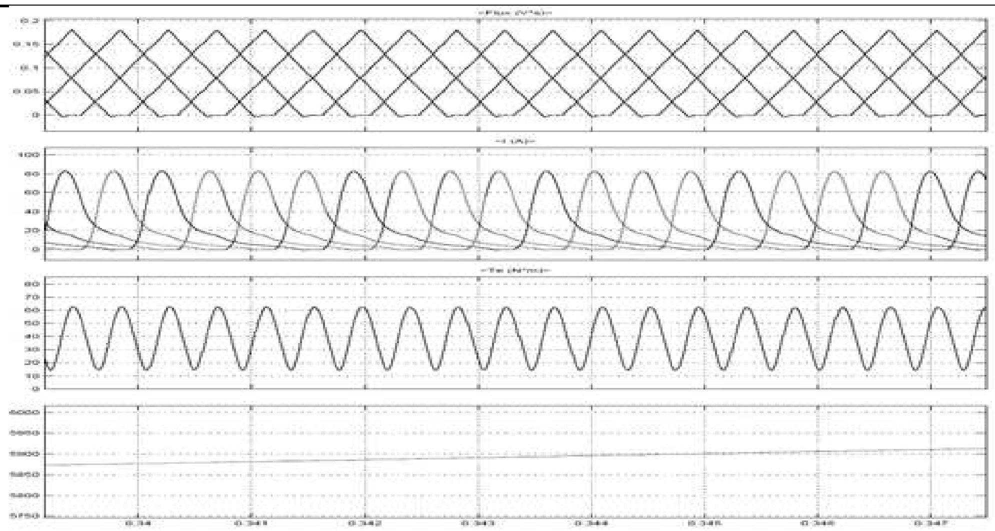


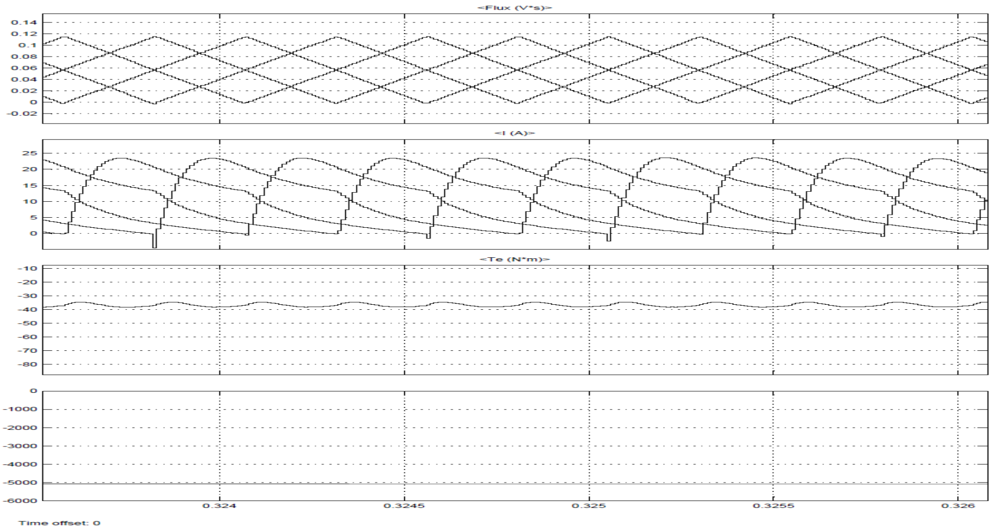
Fig. 3 Dwell angle parameters. (a) Multiphase excitation switching scheme (Dwell angles overlapped with adjacent pole). (b) traditional profile of dwell angle (turn-on and turn-off).

Fig 4(a)-(b) shows the impact of overlapping the independent phase currents. There can be light over lap i.e. the previous pole excitation is stopped within 25% of the on-time of the current pole and similarly the next pole can be excited within the last 25% of the time. 10% overlap is also studied in the same section. Therefore, a relationship between the amounts of overlapping between the phases and the torque ripple and density is presented in this section.



(a) Narrow-overlap between the phases

(b)



(c) Wider-overlap angle between the phases

Fig. 4: Impact of suggested overlapping angle range among phases in terms of the current and torque ripple as well as the speed of the machine.

4.2 Multi-level Excitation

In spite of current flow in adjacent coils, another way is to vary the current in the coil as required. In this method, a decreased or increased amount of supply voltage is provided to compensate for the large commutation torque ripple. This also includes the bi-polar (3 level square wave current) switching technique to control the current profile in the excited winding. However the idea is not very desirable due to the use of many voltage supplies or split voltage supply which will increase the complexity of the voltage supply. If the sinusoidal voltage is applied to the stator windings with the required phase difference then either numerous ac supply voltage sources have to be used or otherwise some compromise has to be done in the other key features of the SRM which distinguishes it from other motors in competition. For example, motor efficiency and fault tolerant features have to be compromised which is very desirable for electric vehicle applications. Therefore, However, if we the multi-level current is supplied in different windings by controlling the turn-on and turn-off timings of the conduction period, a gradually varying current profile can be obtained. There can be light over lap i.e. the previous pole excitation is stopped within 25% of the on-time of the current pole and similarly the next pole can be excited within the last 25% of the time. 10% overlap is also studied in the same section. Therefore, a relationship between the amounts of overlapping between the phases and the torque ripple and density is presented in this section. Due to the non-ideal square current waveform, the impact ofdifferent current levels in different coils can also be found from Fig 5.

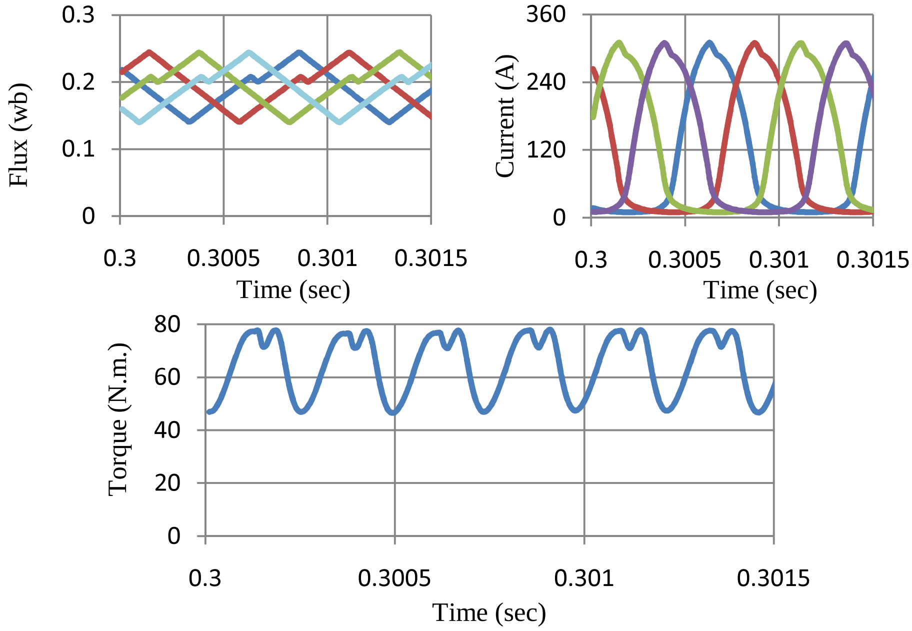


Fig.5. Multiphase excitation of SRM with sinusoidal phase current (a) flux (b) excitation current (c) torque.

5. THE PROPOSED CONTROL OF EXCITATION CURRENT

In this section, a multi-level combined with multiphase excitation method is proposed for shaping the excitation current and torque ripple reduction as well as the vibration. An SRM is excited by multiphase excitation that combines different current amounts in different coils in the process of building up magnetic energy and or demagnetization, thus combining more than 2 phase currents simultaneously to control the required current profile. In a phase torque generation region, the next phase is excited before the phase turn-off, and then the overlapped excitation region is produced. After building up of the next phase current, the previous phase is gradually demagnetized. In the overlapped excitation and demagnetizing region of the previous phase, the next phase winding will absorb the magnetic energy of demagnetizing phase during phase commutation. The absorption of the magnetic energy speeds up phase commutation as well as smoothing the commutation.

5.1 Significance of Dwell Angle Parameters

There exist three key tunable parameters, namely the turn-on, the turn-off angle and the width of the dwell angle. Selection of these parameters can help in shaping the excitation current. The shape of the current can be varied by means of the reference current. However, a continuously and smoothly varying excitation current shape can be achieved by the proper selection of the three key tunable parameters. The dwell angle parameters are traditionally controlled through a closed-loop feedback system using rotor position sensor. The block diagram of the system is shown in Fig. 5.

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Fig. 6 shows the block diagram of the system. Fig 7 shows the relative parameters for single windings and the dwell angle parameters are selected such that the current looks like sinusoidal waveform in each phase sequentially. A change of the exciting current, i.e., change of MMF, induces a vibration. Therefore, if the change of MMF is reduced, a vibration will be reduced.

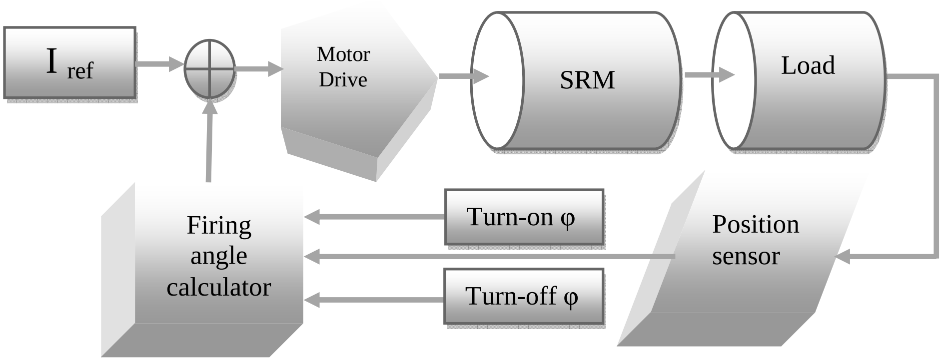

Fig 6. Block diagram of the feedback control system of the SRM drive.

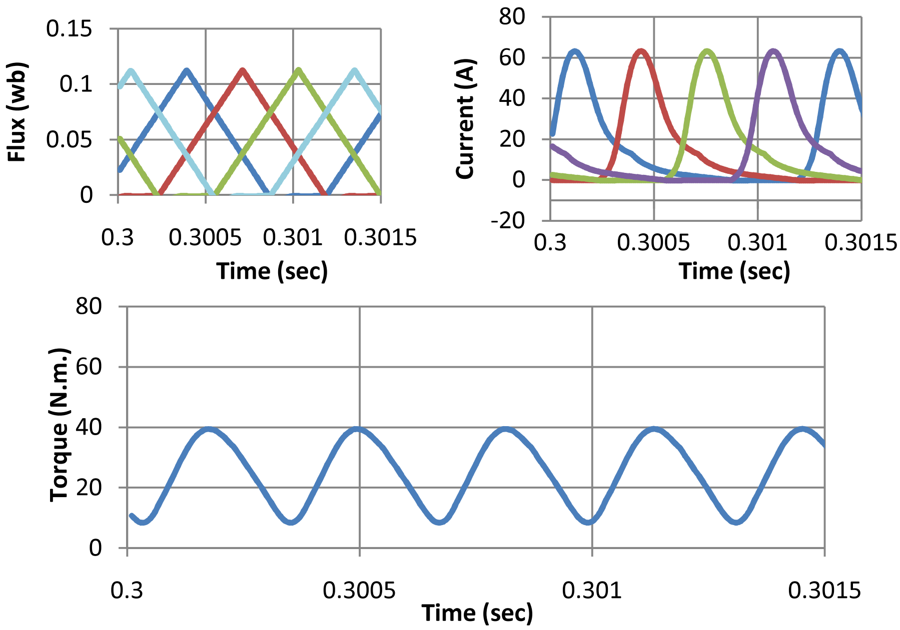

Fig.7. Multiphase excitation (and multi-level) of SRM. (a) flux (b) excitation current (c) torque.

5.3 Impact of Dwell Angle Duration

Fig. 8(a)–(c) shows simulated torque for a multiphase excitation with a customized shape of a square-wave which has some rise and fall time of the waveform making it non-ideal square wave. However, in this section, a study is carried out for isolating the effect of longer dwell angle without co-coordinating the turn-on and turn-off angle in such a way to reduce the torque ripple. Therefore, This shape of multiphase excitation does not show any significant improvement because of the heavy overlap and the two adjacent poles contribution is cancelling each other i.e. the when the current is increasing in one of the adjacent coil at the same time it is decreasing with the same slope in another adjacent coil. This proves that only the sharing the duration of conduction angle is not enough and passing the cancelling current in the two adjacent poles are also useless. As can be seen in 9 (c), this results in a reduction of torque ripple during commutation of phases, and a decrease of noise to prevent abrupt change of MMF due to he change in excitation current shape by varying the dwell angle parameters range between the excited phases of stator coils. Fig. 9(a), (b) and (c) shows fluxes, phase currents and generated torque with the square-shaped longer dwell angle.

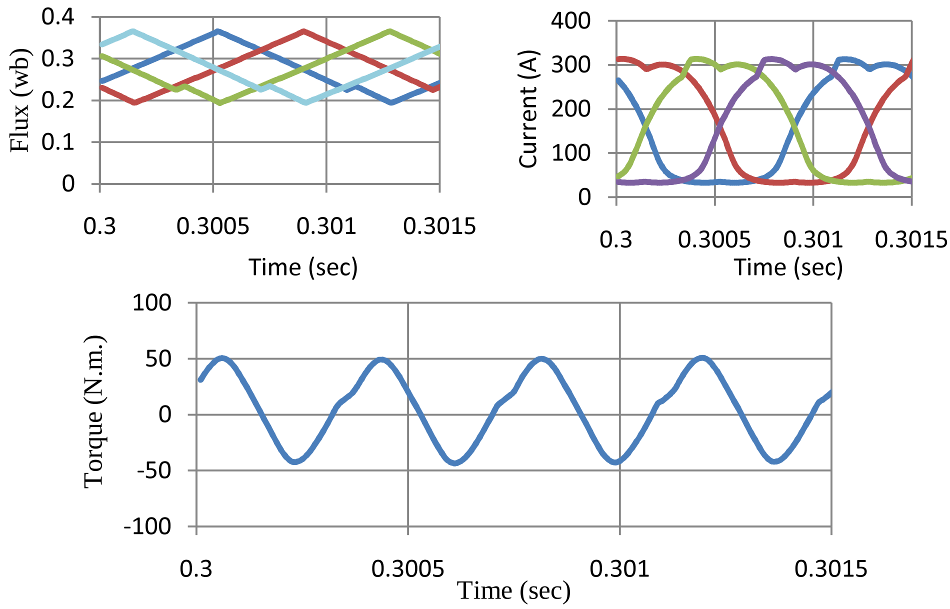

Fig.8. Analysis of multiphase excitation (multi-level) of SRM. (a) flux (b) excitation current (c) torque.

5.3 Impact of Longer Tailing Angle (Turn-off angle)

As shown in Fig. 9, the proposed excitation method prevents the rapid change of flux at commutation region. The proposed excitation method is operated by long dwell angle to excite two phases. Because the switch-off angle is located in the high inductance region for long dwell angle, tail angle is increased. When the “tail current” overlaps with the decrease of inductance, the negative torque produced and overall torque decreases. Therefore the control of dwell angle for avoiding the negative torque production is important with respect to the system performance of acceleration. Therefore, to avoid this decrease in torque the turn-on angle is also extended and the excitation in the third phase is started quite ahead of time. Due to magnetic coupling between phases, all possible products of phase currents are involved in the production of force. Therefore, constrained optimization is used to determine phase currents that produce a desired force with minimum power dissipation.

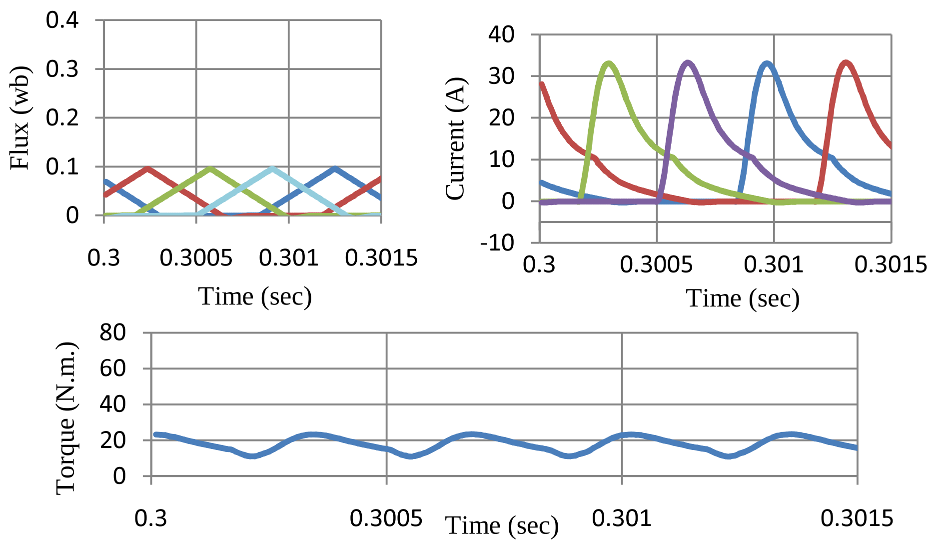

Fig.9. Excitation (multi-level) with sharp turn-on and increased tail. (a) Flux (b) Excitation Current (c) Torque.

5.4 Impact of Angle Advancement (Turn-on angle)

If the switch-on angle varies, the shape of the current waveform at the beginning point of the torque generation ran are changed, and these are nearly proportional to the advance angle when the winding resistance is neglected. And the phase current waveforms show that the generated torque is not constant and the torque pulsation is severe during the torque generation range because the variation rate of current is positive or negative. Therefore this advance angle selection can be used to balance out the decrease in the torque due to the longer tail angle. Since a gradually varying excitation current waveform during the torque generation range, shows that a uniform torque is generated and the torque pulsation is not severe if the variation rate of inductance is uniform. So that current becomes the standard current in order to drive motor effectively. This will be the situation when the effect of the advance angle of the next phase will cancel out the effects of the tail angle of the previous phase. A longer advanced commutation without elongated tail current actually changes the direction of torque and motor might go into regenerative mode. Fig 10 shows the analysis.

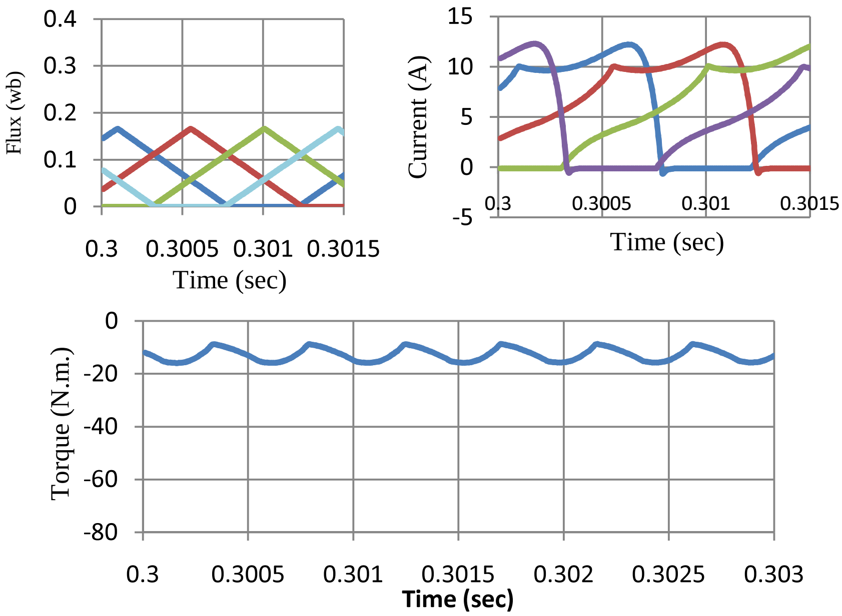

Fig.10. Excitation (multi-level) with sharp turn-off and longer advance angle. (a) Flux (b) Excitation Current (c) Torque.

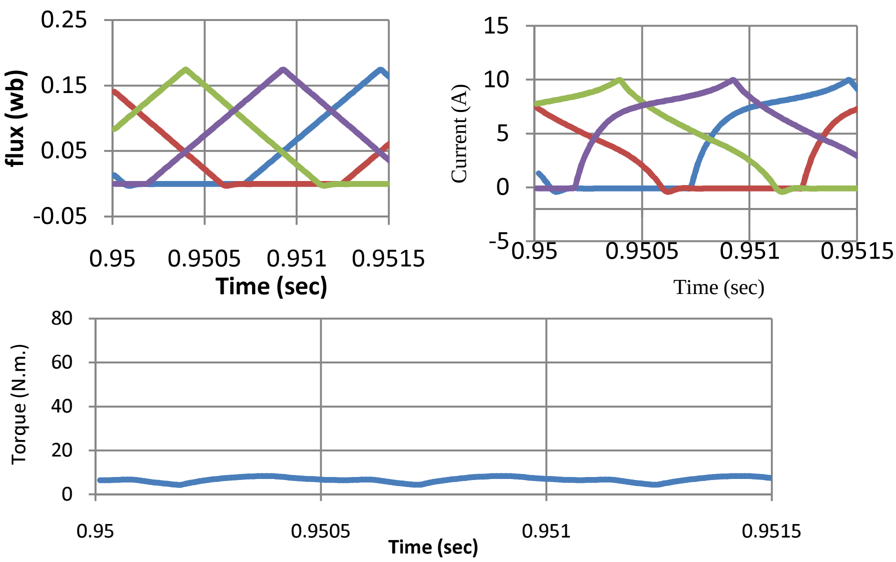

Fig.11. Customized multiphase excitation (multi-level) with sharp turn-on and increased tail. (a) Flux (b) Excitation Current (c) Torque.

5.5 Strategy for Optimization of Parameters

Fig. 11 shows that how a balanced and closer to sinusoidal multiphase excitation of phase currents is favorable to the generation of positive torque. But, if the phase current exists beyond the maximum value of the angle, a negative torque is generated and is the origin of the reduction of the mechanical output power and torque pulsation. Therefore, regardless of load torque and driving speed, if the switch-on angle is to be determined to the shape phase current is to be smooth and the turn-off angle is adjusted not to generated negative torque, the reluctance torque would be utilized effectively and the smooth torque which has minimum pulsation would be obtained.

6. CONCLUSIONS

The electromagnetic structure of an ac motor has been designed to be suitable for operation with a sinusoidal wave source. However, an SRM has an electromagnetic structure suitable to be operated with current pulse. The inherent torque ripple and noise derives from the torque production mechanism of the SRM. In this paper, the precise dwell angle control method is proposed for multi-level and multiphase excitation method to reduce torque ripple and vibrations in SRM. The impact of dwell angle parameters is analyzed in detail in order to get optimized values. The ripple, vibration and acoustic noise are reduced because the scheme reduces abrupt changes of excitation level by distributed and balanced excitation.

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BIOGRAPHY OF AUTHOR

Syeda Fatima Ghousia received her Bachelor degree in Electronics Engineering from Dawood College of Engineering and Technology, NED University, Karachi, Pakistan. She received her Master of Engineering degree in Electrical Power Engineering from University of Alberta, Edmonton, Canada. She is currently working toward the PhD degree at the Department of Electrical and Computer Engineering, University of Windsor, Ontario, Canada. Her research interests includes design and control of Switched Reluctance Motors and drives in Electric Vehicle and Wind Energy applications, Matrix Converter topologies and applications in renewable energy generation applications.