ISSN (Online) 2395-2717
International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
Vol 2, Issue 8, August 2016

Performance Analysis of High Precision Position Controlled Switch Reluctance Motor Drive

P.Simhachalam
Assistant Professor,
Department of Electrical & Electronics Engineering,
Indo American Institutions and Technical Campus,

Abstract: **The aim of this paper is to investigate the problem of high-precision position control in Switched Reluctance Motor (SRM) drives. Proportional-differential (PD) controller and Advanced gain scheduling proportional-integral (PI) controllers are adopted for position and speed controls, respectively. The control scheme used for the SRM drive operates over a wide speed range and supports the four quadrant operation and also provides low torque ripple at an acceptable level. The proposed four quadrant control scheme is based on the average torque control method. Low torque ripple is achieved by controlling the turn-on and turn-off angles through simple formulas so as to minimize the pulsations of the torque at the commutation intervals. The fine tuned PI controller parameters are online determined according to the load torque and speed of the rotor. In order to provide precise position control, a gain scheduling technique is adopted in the speed control design. A low-pass filter is included in the position controller to improve the set-point tracking and to prevent the impulse of the control signal. The SRM drive is designed and implemented in MATLAB/Simulink environment at different rotor positions and several simulation results are presented to validate the feasibility of the proposed control scheme.**

***Index terms*—Current control, four quadrant operation, PI controller, position control, switched reluctance motor (SRM) drives, torque control, variable speed drives.**

I. INTRODUCTION

The switched reluctance motor has stator and rotor in salient nature in which the torque is produced by the tendency of the rotor to move to a position where the inductance of the excited winding is maximized. The induction motor is possibly the least expensive in both manufacture and maintenance, resulting in its common usage. The single phase induction motor is commonly employed in domestic applications. The major drawback is its poor efficiency and control. This is where the brush DC motor comes in. However it has the drawback of limited speed due to its brushes and high maintenance. In recent years, the DC brushless motor has been efficiently employed with electronic commutation. The motor is of suitable caliber, except for possible reduced reliability, high maintenance position sensors required to operate the motor and cost of magnets required as the main components of the motor. The SRM takes a merits such as simple structure, low cost, flexible control etc. so the SRM becomes the preferred machine. Switched Reluctance Motor Drive (SRD) is an advanced electromechanical device that conventional AC or DC drive system may have not. The SRM also have drawback of higher torque ripple compared with conventional machines that cause vibrations and acoustic noise. Due to these it has never been a popular choice in high-precision position actuators. The SRM has highly non linear magnetic characteristics, and therefore, it is difficult to design, simulate, and control them [1], [2].

In recent years, SRMs become a popular choice because of the complex design is shifting to the highly effective and easier to control environment. SRMs can operate as a motor or a generator by adjusting the turn-on and turn-off angles. At low speeds, the torque is limited by the current which is controlled by either voltage-PWM or current regulation. At high speeds the available voltage is insufficient to regulate the current due to high back emf, so the torque is controlled by single pulse mode.

The present literature targets the high performance position control applications for the SRM drives. In [3], a micro-step control strategy respected with a fuzzy logic based controller was proposed. However it does not give high-precise position and is limited to a predefined step angle. In [4], a position control system was presented but only response characteristics of the position controllers in slow ramp-shape command position was determined. Four-quadrant sensor less control over entire speed range is described in [5] and [6]. The development oflinear motion actuator systems for position control applications was presented in [7] and [8].A self tuning regulator for obtaining high-precision position control of a linear SRM drive was proposed in [9] and [10]. The control of SRMs requires proper synchronization of rotor position with the pulses of phase currents. The large stroke angle is a problem for high performance position control. However, it is solved by using the fine tuning regulation of the control parameters. Gain scheduling has the advantage that the parameters can be changed quickly, and thus, the system can follow rapid changes of the operating conditions [11].

A gain scheduling control system for dc motor drives was presented in [12], and an adaptive fuzzy gain scheduling control was presented in [13]. In [14] and [15] the problem of high precision position control is presented and it was developed based on the average torque control method. In [17], gin scheduling regulator for high precision application which are seldom used in actuators was presented.

The aim of this paper is to develop a high-precision position control system for high performance applications of SRM drive in four quadrants. The control system provides high dynamic performance and low torque ripple in steady state operation. The four-quadrant control scheme is based on the average torque control method.

The contribution of this paper is as follows: section II presents the principle of operation of SRM, and torque production. Section III presents the determination of firing angles for both PWM and single-pulse mode of operation for motoring operation as well as generating operation. Section IV presents about the gain scheduling regulators of PI controller for controlling the speed which are used in high precision applications. Section V presents the control strategy which is used in this paper. Section VI presents the implementation of control system and designed using the MATLAB software. Section VII presents the simulation results for small rotation, medium rotation, and large rotation angle step commands. The four quadrant speeds also presented and the performance also analyzed. Section VIII presents the conclusions for this paper.

II. OPERATING PRINCIPLES OF SRM

The SRM operates on the principles of inductance or reluctance variation of a stator phase as a function of the rotor pole position [1].If the phase is excited at the positive inductance slope of stator poles($dL/d\theta > 0$), positive torque is produced towards the direction of rotation and SRM operates as a motor. If the phase is excited at the negative inductance slope($dL/d\theta < 0$), negative torque is produced and trying to oppose rotation and SRM operates as a generator.

SRM dynamics and electromechanical torque expressions are expressed in time-domain equations, as follows. The voltage equation for each phase of SRM is given by

$$v_{ph} = R_{ph} i_{ph} + \frac{d\lambda_{ph}(i_{ph},\theta)}{dt} \quad (1)$$

And rate of change of the flux linkage, at constant speed, is

$$\frac{d\lambda_{ph}}{dt} = \frac{\partial\lambda_{ph}}{\partial i}\frac{di}{dt} + \frac{\partial\lambda_{ph}}{\partial\theta}\omega_r = L(i_{ph},\theta)\frac{di}{dt} + e_{ph} \quad (2)$$

where $L(i_{ph},\theta) = \partial\lambda/\partial i$ is the incremental inductance, e_{ph} is the back emf, v_{ph} is the applied voltage, i_{ph} is the phase current, R_{ph} is the winding resistance per phase, λ is the phase flux linkage, and θ is the mechanical angle [1].

The instantaneous electromagnetic torque produced by each of the phase is given from the partial derivative of the phase co-energy and is defined by

$$T_{ph}(i_{ph},\theta) = \left.\frac{\partial W_{cph}(i_{ph},\theta)}{\partial\theta}\right|_{i=\text{const}} \quad (3)$$

Where

$$W_{cph} = \left.\int_0^i \lambda_{ph}(\xi,\theta)d\xi\right|_{\theta=\text{const}} \quad (4)$$

The total instantaneous electromagnetic torque is given by the sum of the individual torques of each phase

$$T_e = \frac{1}{2}\sum_{ph=1}^{m} i_{ph}^2 \frac{dL_{ph}(\theta)}{d\theta} \quad (5)$$

Where$m$ is the number of SRM phases [2].

The SRM machine model consists of lookup tables, with the flux linkage $\lambda_{ph}(i_{ph},\theta)$ and the electromagnetic torque $T_e(i_{ph},\theta)$ expressed as functions of current level i_{ph} and the rotor positionθ.

ISSN (Online) 2395-2717
International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
Vol 2, Issue 8, August 2016

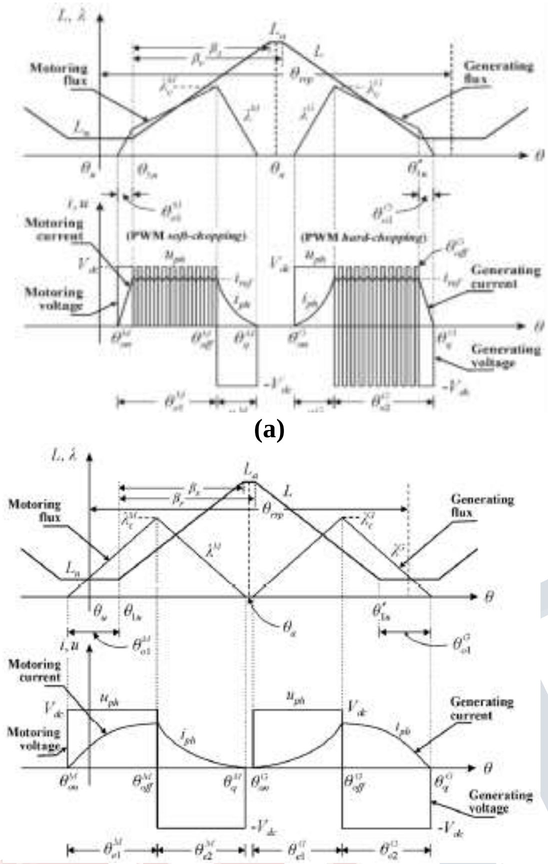


Fig. 1. Typical SRM drive waveforms in motoring and generating Operation: (a) PWM soft chopping current control and (b) singlepulse control

III. DEFININGTHETURN-ON AND TURN-OFF ANGLE CONDITIONS FOR SMOOTH TORQUEFOUR-QUADRANTPOSITIONING CONTROL

In the SRM, torque is generated by sequence pulses of phase current properly synchronized with rotor position. The torque pulsations in an SRM are due to the discrete nature of torque generation mechanism. Stator phases of the SRM are independently controlled. The total torque is the sum of torques generated by the individual phases. At the commutation intervals the torque ripples are more because the torque generated by the outgoing phase is added with the incoming phase at the commutation intervals. So, by controlling the turn on and turn off angles the torque ripples are minimized, so that the total current waveform will be smooth.

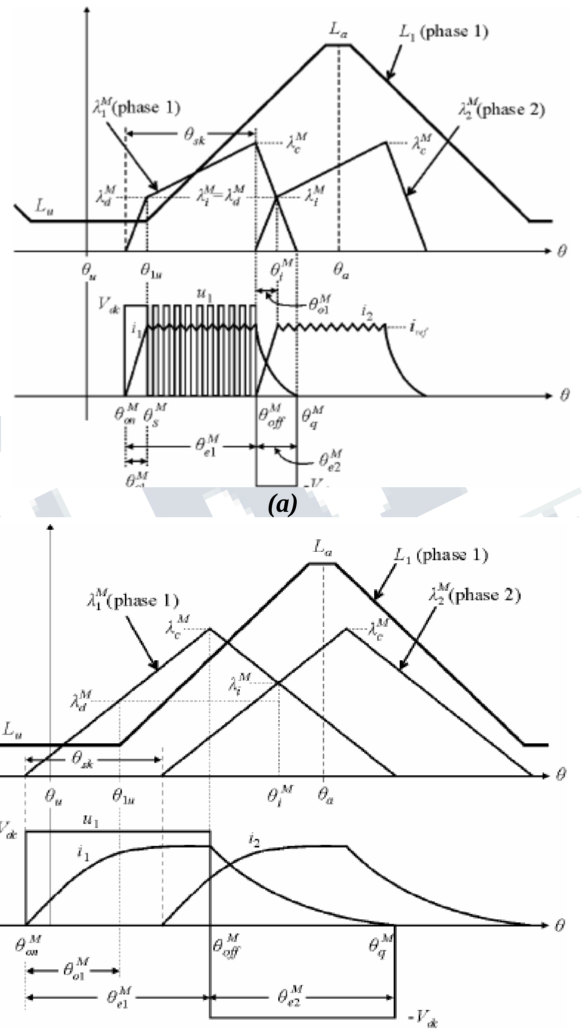


Fig. 2. Typical SRM waveforms in motoring operation considering the overlapping flux-linkage and current profiles of two neighboring phases: (a) PWM soft chopping control and (b) single pulse control.

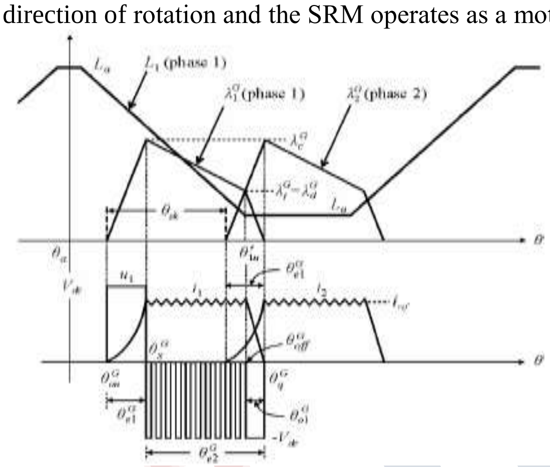
Depending on the magnitude of the speed, theSRM can operate in pulse width modulation (PWM) or single-pulse control mode. In order to provide smooth transition between the pulse width modulations (PWM) and single-pulse modes, the turn on and turn off angles are online determined. The

ISSN (Online) 2395-2717
International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
Vol 2, Issue 8, August 2016

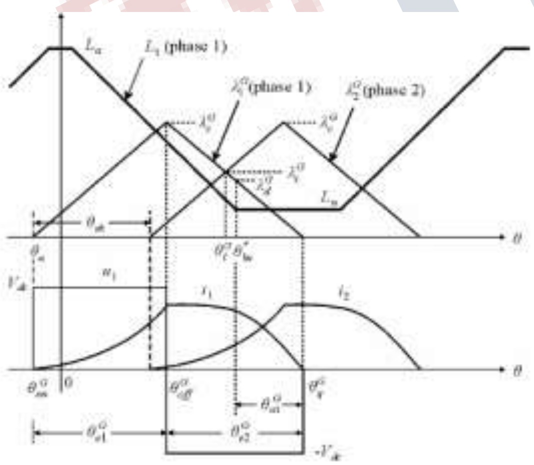
relationship between the idealized inductance profile and the motoring and braking flux linkage, voltage, and phase current waveforms of an SRM with PWM is shown in Fig. 1

A. Motoring Operation in PWM mode

The SRM motoring operation is "if the phase is excited before the rotor poles come to alignment with the stator poles$(dL/d\theta > 0)$, positive torque is produced in the same direction of rotation and the SRM operates as a motor".



(a)



(b)

Fig. 3. Typical SRM waveforms in generating operation considering The overlapping flux-linkage and current profiles of two neighboring Phases: (a) PWM soft chopping control and (b) single pulse control.

In PWM mode of current controlled motoring operation, the rotor speed is low, so the back-emf is lower than the source voltage so the current controlling is possible. Soft-chopping control is used in motoring operation, while hard-chopping control is used in generating operation to hold on the load torque and to provide stable operation at zero speed. The firing angles are online determined through simple formulas for providing smooth torque operation and high-precision position control.

In this mode, the turn-on angle is selected so that the phase current reaches its reference value i_{ref} on the angle θ_{1u}at which the stator and rotor poles start to overlap and the inductance starts rising.

From the Fig. 2(a)by neglecting the winding resistant R and fringing effect, the turn-on angle is determined by

$$\theta_{\text{on}}^{M} = \theta_{1u} - \theta_{o1}^{M} = \theta_{1u} - \frac{L_u i_{\text{ref}} \omega_r}{V_{\text{dc}}} (6)$$

The flux-linkage and current profiles of two neighboring phases in PWM motoring operation is illustrated in Fig. 2(a).

The torque pulsations are minimized which are stronger at commutation intervals is achieved if smooth current transfer between adjacent phases is accomplished so that the sum of all phase currents provides a smooth current waveform. The firing angles are controlled to get the smooth current transfer between adjacent phases so that the θ_{o1}^{M} interval is equal to the half of the defluxing period θ_{e2}^{M}

$$\theta_{o1} = \frac{\theta_{e2}}{2} (7)$$

And, consequently,

$$\lambda_d = \frac{\lambda_c}{2} (8)$$

Substituting (7) in (6), the turn-on angle condition for smooth current transfer is written as follows:

$$\theta_{\text{on}}^{M} = \theta_{1u} - \frac{\theta_{e2}^{M}}{2} (9)$$

The turn-on angle of the incoming phase 2 should co-inside with the turn-off angle of the outgoing phase 1 and then the dwell period is equal to the stroke angle$(\theta_{e1}^{M} = \theta_{sk})$. Thus, the turn-off angle in PWM motoring mode is determined by

$$\theta_{\text{off}}^{M} = \theta_{\text{on}}^{M} + \theta_{sk} (10)$$

B. Motoring Operation in Single-pulse Mode

At high speeds, the motor back-emf is larger than the available dc-link voltage and there is no control over the phase current. So the SRM turns to single pulse mode. Fig. 2(b) illustrates the waveforms in single-pulse mode. In this mode the torque is controlled by adjusting the firing angles of a single current pulse for providing smooth torque operation and high-performance position control.When $\theta_e = \theta_{sk}$, the SRM mode changes from PWM to single pulse and vice-versa. For single-pulse control the turn-on angle is determined by

$$\theta_{\text{on}}^{M} = \theta_{1u} - \frac{\theta_{e2}^{M}}{2} \quad (11)$$

Taking into account that, in single-pulse mode, the dwell period is almost equal to the de-fluxing period($\theta_{e1}^{M} \approx \theta_{e2}^{M}$), then the turn-off angle is determined by

$$\theta_{\text{off}}^{M} = \theta_{\text{on}}^{M} + \theta_{e2}^{M} \quad (12)$$

C. Generating Operation in PWM mode

If the phase is excited after the aligned position($dL/d\theta < 0$), negative torque is produced and trying to oppose the rotation and SRM operates as a generator. Fig. 3 (a) shows the flux-linkage and current waveforms of two adjacent phases in PWM generating operation. During the intervalθ_{o1}^{G}, the stored field energy in the windings of SRM is returned to the dc-link without extracting mechanical energy from the prime mover. Therefore the turn-off angle for smooth hard-chopping PWM generating operation is selected at the rotor position that stator pole and rotor pole corners complete overlap

$$\theta_{\text{off}}^{G} = \theta_{1u}^{'} \quad (13)$$

As in motoring operation, torque ripple is minimized by providing smooth current transfer between adjacent phases.

Therefore, the θ_{o1}^{G} interval should be equal to the half of the dwell period θ_{e1}^{G}

$$\theta_{o1}^{G} = \frac{\theta_{e1}^{G}}{2} \quad (14)$$

For providing smooth torque in hard chopping mode the turn-on angle condition is given by

$$\theta_{\text{on}}^{G} = \theta_{1u}^{'} - \left(\theta_{sk} + \frac{\theta_{e1}^{G}}{2}\right) \quad (15)$$

D. Generating Operation in Single-pulse Mode

As in motoring operation, condition (14) of PWM control holds for single pulse too. From Fig. 3(b) taking into account that the dwell period is almost equal to de-fluxing period ($\theta_{e1}^{G} \approx \theta_{e2}^{G}$) as like motoring, it is concluded that the turn-on and

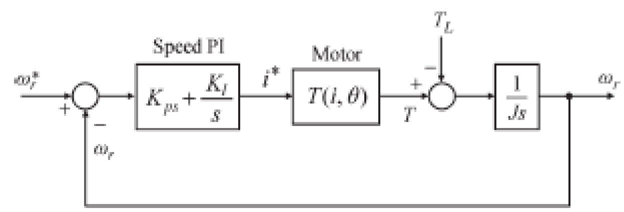


Fig. 4. Speed control closed-loop of SRM.

Turn-off angle conditions are determined by

$$\theta_{\text{on}}^{G} = \theta_{1u}^{'} - \frac{3}{2}\theta_{e1}^{G} \quad (16)$$

$$\theta_{\text{off}}^{G} = \theta_{\text{on}}^{G} + \theta_{e1}^{G} = \theta_{1u}^{'} - \frac{\theta_{e1}^{G}}{2} \quad (17)$$

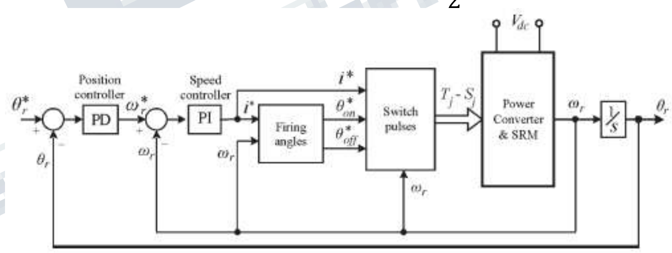


Fig. 5. General block diagram of the SRM speed and position closed-loop control system

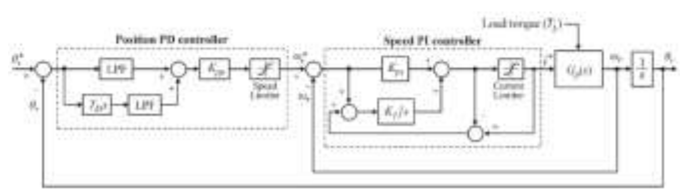


Fig. 6. Model configuration of the advanced speed and position controllers

ISSN (Online) 2395-2717
International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
Vol 2, Issue 8, August 2016

IV. GAIN SCHEDULING REGULATOR FOR SPEED CONTROL

The speed controller is designed with gain scheduling technique for providing high dynamic performance and precise position control. Fig.4shows the simplified SRM control system with speed closed loop system. The standard form of the speed PI controller is given by

$$G_{\rm PI}(s) = K_{ps} + \frac{K_I}{s} \quad (18)$$

The non-linear model of the SRM electromagnetic torque is expressed a function of the phase current and rotor position that is given by the static torque lookup table i.e.,T(i,θ).

The torque production of the SRM is nonlinear and therefore it should be linearized for determining the PI controller parameters. This can be accomplished by small-signal behavior of the system for small displacement of its variables. For this purpose, the phase current i^* is expressed by the following form

$$i^* \cong i_0 + \Delta i^* (19)$$

The SRM torque for small displacement of phase current Δi^* is expressed as

$$T \cong T_0 + \Delta T \quad (20)$$

Where$T_0$the steady-state is value and ΔT is the small displacement of torque. The transfer function of the speed closed loop with respect to small displacement of speed command is given as follows

$$G_s(s) = \frac{\Delta\omega_r(s)}{\Delta\omega_r^*(s)} = K_1 \frac{s + K_I/K_{ps}}{s^2 + K_1 s + K_2} (21)$$

where

$$K_1 = K_{ps}\frac{T(i,\theta)}{J} (22)$$

$$K_2 = K_I \frac{T(i,\theta)}{J} (23)$$

To determine $K_{ps}$and $K_I$in order to meet the control objectives, a simple and straightforward design procedure is followed. One of the most common control objectives is the frequency bandwidth $\omega_n$and the damping coefficient $\zeta_c$of the speed control loop. The transfer function is given by

$$G_s(s) = \frac{\omega_r(s)}{\omega_r^*(s)} = \left(\frac{\omega_n^2}{\delta}\right)\frac{s+\delta}{s^2 + 2\zeta_c\omega_n(s) + \omega_n^2} (24)$$

From (21) and (24) and for the given values of $\omega_n$and$\zeta_c = 1/\sqrt{2}$, the speed PI controller gains are determined by

$$K_I = \frac{J\omega_n^2}{T(i,\theta)} (25)$$

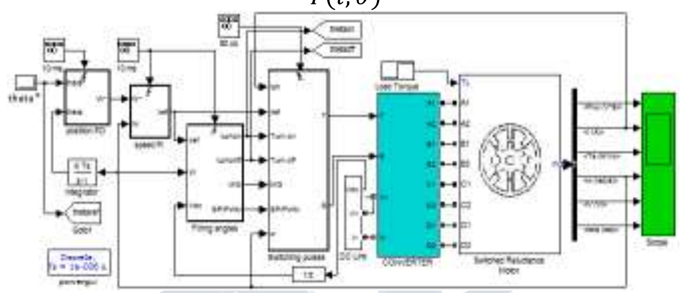


Fig. 7. Simulink diagram of the SRM drive with advanced speed PI and position PD controllers

$$K_{ps} = \frac{\sqrt{2}\,K_I}{\omega_n} \quad (26)$$

From the above equations it is concluded that the speed PI controller gains ($K_I$andK_{ps}) depend on the frequency bandwidth ω_n and the load torque$T(i,\theta)$.

Therefore K_I and K_{ps} are adopted according to$T(i,\theta)$. Instead of keeping them constant, the characteristics of the speed control loop will be identical at all rotor positions. This means that the speed PI parameters are adjusted according to the speed and load torque conditions in order to meet the control objectives and to provide high performance of the drive. $T(i,\theta)$Can be given to the controller through a lookup table. This can be obtained with a combination of offline experiments and pre-calculated data obtained from the numerical analysis of the SRM system.

V. CONTROL STRATEGY

For deriving a low-complexity model of the SRM that is suitable for speed and position control, the machine dynamics are classified into groups with regards to their time constants. Therefore, a cascade control approach with two closed-loop controllers is used. Fig. 5 shows the general block diagram of the developed SRM speed and position control system. For speed control, a proportional-integral (PI) controller has been adopted to provide quick transient response and to ensure zero steady-state error. The standard form of the speed PI controller is given by

IFERP
ISSN (Online) 2395-2717
International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
Vol 2, Issue 8, August 2016

$$G_{PI}(s) = K_{ps}\left(1 + \frac{1}{T_I s}\right) (27)$$

An anti-windup protection is used in order to avoid low-frequency oscillations that may lead to instability. This can be realized by applying inner feedback to the integral action of the speed PI controller.

For position control, a proportional-differential (PD) controller has been used to compensate the delay effect of the integration applied in the speed control loop and to eliminate the overshoot in the position response. The standard form of the position PD controller is given by

$$G_{PD}(s) = K_{pp}(1 + T_D s) (28)$$

The derivative term of the position control results a high control signal when a step change of the reference signal or disturbance occurs. To prevent this impulse of the signal a low pass is cascaded with differentiator is used. Therefore the position controller becomes

$$G_{PD}(s) = K_{pp}\frac{T_D s}{1 + (T_D/\beta)s} (29)$$

Whereβ is a constant. A low pass filter is also included in the proportional term to prevent the set-point tracking performance. This filter improves the regulation performance at steady state.

VI. DESIGN AND IMPLEMENTATION OF THE CONTROL SYSTEM

The feedback system with the speed and position controllers is shown in Fig. 6. The transfer function $G_p(s)$ represents the SRM and the power converter with the current and single-pulse control. Fig. 7shows the Simulink diagram of the SRM drive that is used in simulations. Fig. shows the Simulink diagrams of the advanced speed and position controllers of the proposed SRM drive, respectively. The command turn-on and turn-off angles, i.e., θ^*_{on} andθ^*_{off}, respectively are determined by the block "Firing angles" through the equations presented in Section III. The block "Switching pulses" generates the control pulses for the SRM power converter switches. The reference phase current i^* is determined through the speed error $(\omega^*_r - \omega_r)$ by the block "adaptive speed PI". The gains of the PI controller are online adopted and determined in order to get the high dynamic performance and for precise position control. The function $T(i,\theta)$ that considers the variation of phase inductance with respect to rotor angle is modeled by a look-up table

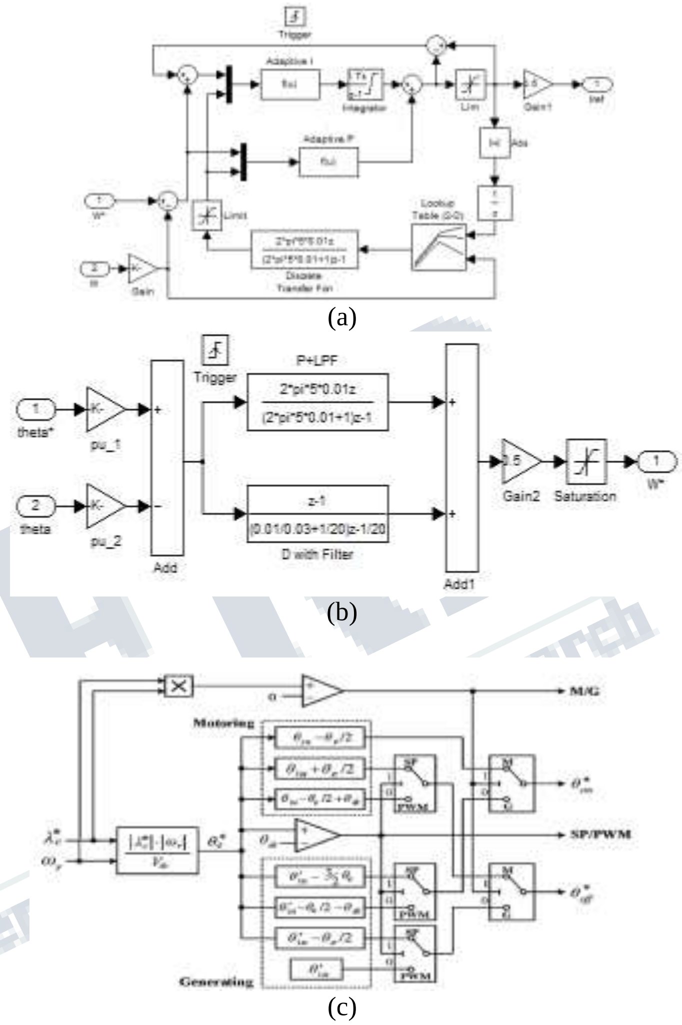


Fig. 8. Detailed diagrams of the blocks shown in Fig. 7. (a) "Speed PI." (b) "Position PD." (c) Firing angle

Table I Four-Phase 1-Hp 8/6 SRM

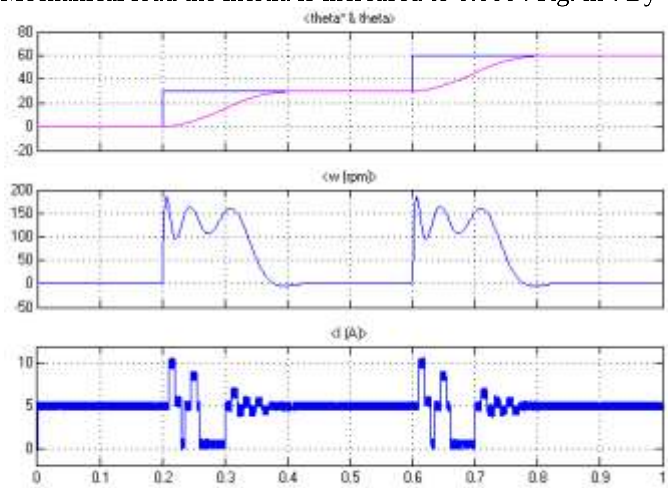
output power 1-hp at 4,000 rpm (motoring operation)	
Inertia 0.0004 Kg-m	
$m = 4$	$N_s/N_r = 8/6$
$\theta_{rrp} = 2\pi/N_r = 60°$	$R_{ph} = 1.3\Omega$
$L_a = 52.7$ mH	$L_u = 9.1$ mH

ISSN (Online) 2395-2717
International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
Vol 2, Issue 8, August 2016

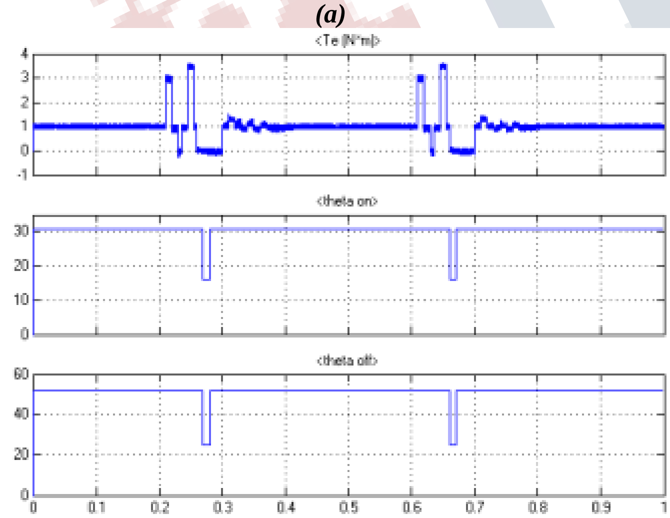
VII. SIMULATION RESULTS

A four-phase 1-hp 8/6 SRM drive is used to simulate the developed position control system in the MATLAB/Simulink.

The parameters of the motor are reported in Table I. The responses of the SRM drive to small, medium, and large rotation angle step commands are reported in Figs. 9-11, respectively. The mechanical load torque is 1N.m. Due to the Mechanical load the inertia is increased to 0.0004 Kg. m^2. By

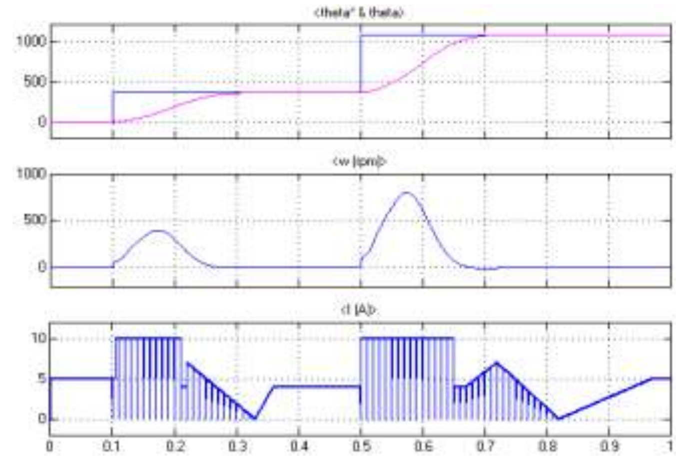


(a)

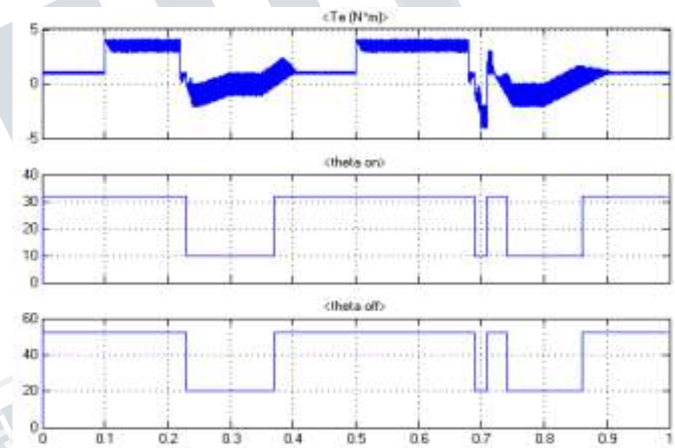


(b)

Fig. 9. The responses of the SRM drive, with the gain-scheduling regulator, to a small rotation angle step command [0° →30° →60°]



(a)

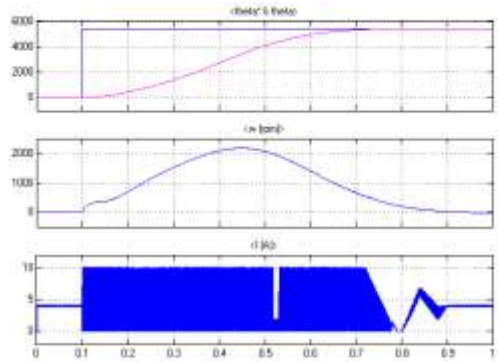


(b)

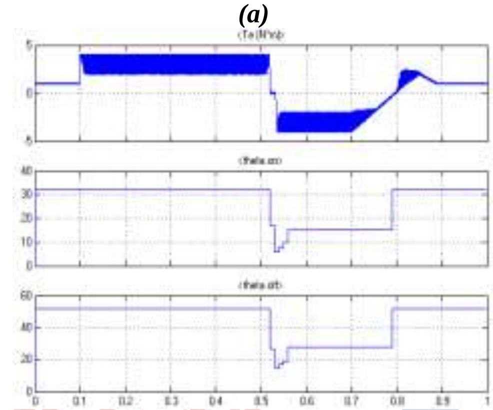
Fig. 10. The responses of the SRM drive, with the gain-scheduling regulator, to a medium rotation angle step command [0° →360° (1 revolution) →1080° (3 revolutions)]

Observing the Figs.9 and 10, the rotor speed is below the base speed at small and medium rotation angle step commands and therefore the SRM operates in the PWM control mode.

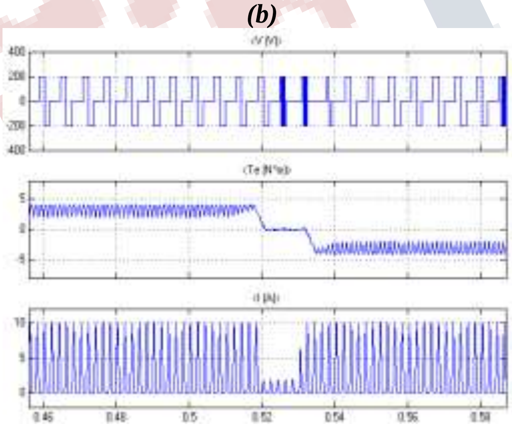
IFERP
connecting engineers... developing research
ISSN (Online) 2395-2717
International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
Vol 2, Issue 8, August 2016



(a)

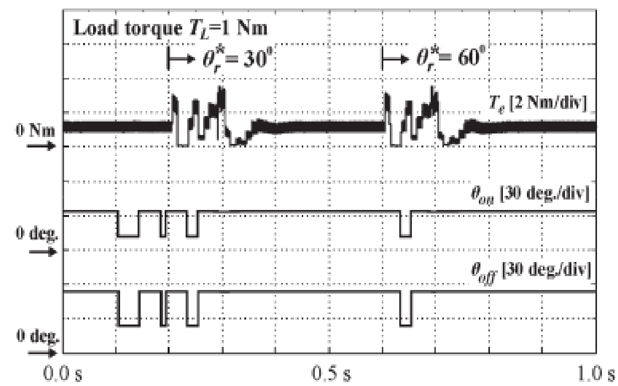


(b)

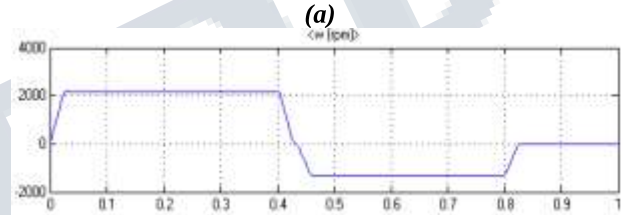


(c)

Fig. 11. The responses of the SRM drive, with the gain-scheduling regulator, to a large rotation angle step command [0° →5400°(15 revolutions)]

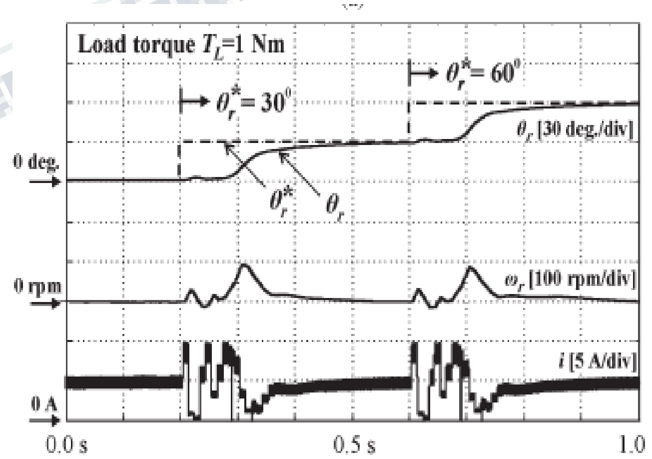


(a)



(b)

Fig. 12. Magnified part of the SRM drive dynamic response shown in Fig. 11, when it turns from motoring to braking operation



(a)

Fig. 12. Magnified part of the SRM drive dynamic response shown in Fig. 11, when it turns from motoring to braking operation

ISSN (Online) 2395-2717
International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
Vol 2, Issue 8, August 2016

In the case of large rotation angle, at the beginning the SRM operates in PWM mode and, the mode changes smoothly to single pulse mode when the speed is increased above the base speed. The SRM operation mode is also changed from single-pulse to PWM mode when $\theta_e = \theta_{sk}$.

The benefits of proposed gain scheduling regulator in settling time and set point tracking position performance are improved by comparing Fig 9 with Fig 13 which shows the performance of same SRM drive with conventional PI and PD controllers. It can be observed that, in all cases (small, medium, and large rotation angle step commands) the controllers react very fast and the desired position is obtained without overshoot. When the operation changes from motoring and braking mode, the values of the turn-on and turn-off angles are also changed significantly.

It should be noticed that, that for the small rotation angle, the conduction of only three successive phases is needed. It justifies the difficulty in the controller design for achieving robust position tracking performance. During the steady state operation of the precision position control, only one of the SRM phases is conducting so that load torque is held on at zero speed.

VIII. CONCLUSION

In this paper, advanced Proportional-integral (PI), and Proportional Differential (PD) controllers for SRM are presented. The four quadrant speeds also presented in this paper which shows effectiveness of the proposed controller. The position PD controller is fine tuned to improve the set point tracking performance of the SRM drive. In PD controller the proportional term is combined with low-pass filter to suppress the impulse response presented in the integral term of PI controller. The parameters of the speed Proportional-integral (PI) controller is online determined according to the mechanical load torque, speed of the rotor, and operating mode of the SRM drive. The four-quadrant control method is based on the average torque control method, and it is capable for maintaining the torque ripple at an acceptable level over the entire speed range. Thus, it provides quick transient response for all rotation angle step commands and high-performance position control of the SRM drive. The proposed controller is easily implemented and does not require the knowledge of the SRM magnetization curves. Several simulation results are presented and examined to validate the feasibility of the proposed control scheme.

REFERENCES

[1] R. Krishnan *Switched Reluctance Motor Drives*. Boca Raton, FL: CRC Press, 2001.

[2] T.J.E. Miller, Electronic control of Switched Reluctance Machines, OXFORD, U.K., Newnes, 2001.

[3] G. Song, H. Sun, L.Huang, and J. Chu,” Micro-step position control of switched reluctance motors,” in *Proc. Conf. PEDS*, Nov. 2003, vol. 2, pp. 944–947.

[4] M.H. Kim, W. S. Baik, D.H. Kim, and K. H. Choi, “A high performance position control system of switched reluctance motor,” in *Proc. PCC*, Nagoya, Japan, Apr. 2007, pp. 249–252.

[5] S. Hossain, I. Husain, H. Klode, A. Omekanda, and S. Gopalakrishnan, “Four quadrant and zero speed sensorless control of a switched reluctance motor,” *IEEE Trans. Ind. Appl.*, vol. 39, no. 5, pp. 1343–1349, Sep./Oct. 2003.

[6] B. Fahimi, A. Emadi, and R. B. Sepe, Jr., “Four-quadrant position sensorless control in SRM drives over the entire speed range,” *IEEE Trans. Power Electron.*, vol. 20, no. 1, pp. 154–163, Jan. 2005.

[7] W. C. Gan, N. C. Cheung, and L. Qiu, “Position control of linear switched reluctance motors for high-precision applications,” *IEEE Trans. Ind. Appl.*, vol. 39, no. 5, pp. 1350–1362, Sep./Oct. 2003.

[8] L. Yuan-Jiang, G. P. Widdowson, S. Y. Ho, G. W. Chuen, and P. Borsje, “Design and analysis of linear switched reluctance motor for high precision control,” in Proc. IEMDC, May 2007, vol. 1, pp. 55–58.

[9] P. Tandon, A. V. Rajarathnam, and M. Ehsani, “Self-tuning control of a switched-reluctance motor drivewith shaft position sensor,” IEEE Trans. Ind. Appl., vol. 33, no. 4, pp. 1002–1010, Jul./Aug. 1997.

[10] K. Russa, I. Husain, and M. E. Elbuluk, “A self-tuning controller for switched reluctance motors,” IEEE Trans. Power Electron., vol. 15, no. 3, pp. 545–552, May 2000.

[11] K. J. Åström and B. Wittenmark, Computer Controlled Systems, 3rd ed. Englewood Cliffs, NJ: Prentice-Hall, 1996.

[12] M. R. Mataušek, B. I. Jefteniæ, D. M. Miljkoviæ, and M. Z. Bebiæ, "Gain scheduling control of DC motor drive with field weakening," IEEE Trans. Ind. Electron., vol. 43, no. 1, pp. 153–162, Feb. 1996.

[13] J. Talaq and F. Al-Basri, "Adaptive fuzzy gain scheduling for load frequency control," IEEE Trans. Power Syst., vol. 14, no. 1, pp. 145–150, Feb. 1999.

[14] H. Hannoun, M. Hilairet, and C. Marchand, "Gain-scheduling PI current controller for a switched reluctance motor," in Proc. Conf. ISIE, Jun. 2007, pp. 1177–1182.

[15] C. Mademlis and I. Kioskeridis, "Four-quadrant smooth torque controlled Switched Reluctance Machine drives," in Proc. IEEE PESC, Rhodes, Greece, Jun. 2008, pp. 1216–1222.

[16] K. H. Ang, G. Chong, and Y. Li, "PID control system analysis, design and technology," IEEE Trans. Control Syst. Technol., vol. 13, no. 4, pp. 559– 576, Jul. 2005.

[17] C. Mademlis and I. Kioskeridis, "Gain scheduling regulator for high-performance position control of switched reluctance motor drives" IEEE Transactions on Industrial Electronics, vol. 57, no. 9, pp. 2922–2931, Sept. 2010.