Design and Simulation of a Pi Controlled Frontend and Power Converter for Switched Reluctance Motor

[1]X. Felix Joseph and [2]S. Pushpa Kumar

[1]Research Scholar, PRIST University, Noorul Islam University, Kumaracoil, India
[2]Principal, Heera College of Engg & Tecnology, Nedumagaud, India

Abstract: This paper presents the design and simulation of a soft switched boost converter which acts as a frontend converter for a switched reluctance motor with a closed loop controller. A soft switching scheme is proposed in the converter with minimum components, which reduces the switching loss and stress across the switch so that the harmonic generation is reduced in the output. The switch used in this converter switched ON at zero current and switched OFF at zero voltage. Most of the research was done on the power converter circuit of the srm to control the speed. But in the proposed system a soft switched boost converter is designed to regulate the input voltage to SRM for any line variations and a power converter is used to control the speed of SRM. The PI controller is used as closed loop controllers, which improves the speed control of the switched reluctance motor for any load and regulate the input voltage to SRM for any line variations. The duty cycle of the switch is controlled by PI controller using PWM technique. A 500W/50KHz PWM based soft switched boost converter is designed and simulated for 6/4 pole 3 phase SRM with variable loads. The results are simulated using MATLAB SIMULINK.The output of the soft switched dc dc converter gives a constant output voltage for any line variations, so that the input voltage to srm is constant. The output speed of the srm is controlled using PI controller and rotor current. The soft switched dc dc converter regulates the input supply and a power converter control the speed of Switched reluctance motor simultaneously.

Key words: Soft switched Boost converter · Zero voltage switching · Zero current switching · Switched Reluctance Motor · Power converter · PI controller

INTRODUCTION

Switched reluctance motor drives (SRD) are now become popular compared to conventional ac or dc motor drives due to their simple construction, robustness, high efficiency and high power density. However, in speed control this motor facing some problems due to its nonlinear characteristics. The function of flux linkage depending on phase current and rotor position represents the key characteristic of the switched reluctance motors (SRM) and it is difficult to describe such a relationship due to the effects of magnetic saturation and double saliency of the construction. In order to improve its performance some advanced control strategies have been proposed, such as current or flux linkage profile control. To achieve these strategies the motor phase current or phase flux linkage should be controlled precisely. All these require increasing the switching frequency of converter to upgrade stability and dynamic response

speed. On the other hand, the higher switching frequency may cause the higher switching losses, higher Electro-Magnetic Interference (EMI) and the lower overall efficiency.

The use of soft-switching techniques in converter can contribute to reduce them. A great deal researches and developments on SRM soft-switching converter have been reported. There are several converter methods available to regulate the power supply of SRM. The converters have different topologies [1]. These topologies are having number of switches according to the design [2, 3]. The SRM drives always have a phase winding in series with a switch. In case of a shoot-through fault, the inductance of the winding limits the rate of rise in current and provides time to initiate protective relaying to isolate the faults. The phases of the SRM are independent and, in case of one winding failure, uninterrupted operation of the motor drive operation is possible. Many researchers presented papers on speed

---

Corresponding Author: X. Felix Joseph, Research Scholar, PRIST University, Noorul Islam University, Kumaracoil, India.
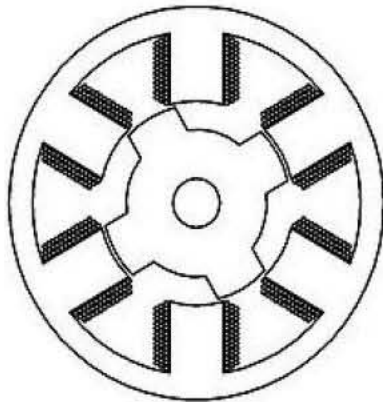
Fig. 1: SRM with 6/4 poles

control of SRM using converters [4]. In some papers soft switched based converters used to control the speed for SRM [6]. Some of the researchers presented neuro and fuzzy controller based converters [8, 9]. Some different converters were designed exclusively for SRM drives. A new converter for switched reluctance motor (SRM) drive is discussed in a paper [10], which uses one switch in each phase.

A new converter for switched reluctance motor (SRM) drive is discussed in a paper [10], which uses one switch in each phase. The proposed converter is suitable for high speed drive application which is mainly due to the fast phase current commutation capability of this converter and due to generation of negative torque consequently generation of large ripple torque in SRM drives are resolved. A paper described a soft switching converter [11] for switched reluctance motor to improve the performance of the drive. In a paper [12] a novel soft-switching converter for SRM is presented, which possesses advantages of Resonant Switch converter (RS), resonant dc Link converter (RDCL) and PWM. All these methods have some disadvantages in the switching operation without soft switching or speed control are not precise and they do not consider the load and line variations.

In this paper we designed a soft switched boost converter in the dc link of the 6/4 structure SRM to regulate the input supply and a power converter is designed to control the speed, for load changes and supply disturbances using two closed loop PI controllers. In these converters with closed loop control we achieve a constant speed and voltage for any load and line variations.

Switched Reluctance Motor: The switched reluctance motor (SRM) drives for industrial applications are of recent origin. Key to an understanding of any machine is its torque expression, which is derived from first principles. The implications of machine operation and its salient features are inferred from the torque expression. The torque expression requires a relationship between machine flux linkages or inductance and the rotor position. The reluctance motor is a type of synchronous machine. It has wound field coils of a DC motor for its stator windings and has no coils or magnets on its rotor. Fig. 1 shows its typical structure of 6/4. It can be seen that the stator and rotor have salient poles; hence, the machine is a doubly salient machine. The rotor is aligned whenever the diametrically opposite stator poles are excited. In a magnetic circuit, the rotating part prefers to come to the minimum reluctance position at the instance of excitation. While two rotor poles are aligned to the two stator poles, another set of rotor poles is out of alignment with respect to a different set of stator poles. Then, this set of stator poles is excited to bring the rotor poles into alignment.

Development of Torque: The most general expression for the torque produced by one phase at any rotor position is,

$$\text{Torque } T = [\partial W`/\partial\theta]\, i = \text{Constant} \qquad (1)$$

$$\text{Since } W` = \text{Co-energy} = \tfrac{1}{2} F\,\Phi = \tfrac{1}{2} N\,I\Phi \qquad (2)$$

This equation shows that input electrical power goes partly to increase the stored magnetic Energy ($\tfrac{1}{2}L*i_2$) and partly to provide mechanical output power ($i^2/2$ x $dL/d\theta$ x ω), the latter being associated with the rotational e.m.f. in the stator circuit.

Neglecting saturation non-linearity

$$L = Induc\tan ce = N\frac{\varnothing}{I} \qquad (3)$$

$$T = \frac{1}{2}i^2 \qquad (4)$$

This equation shows that the developed torque independent of direction of current but only depends on magnitude of current & direction of $dL/d\theta$.
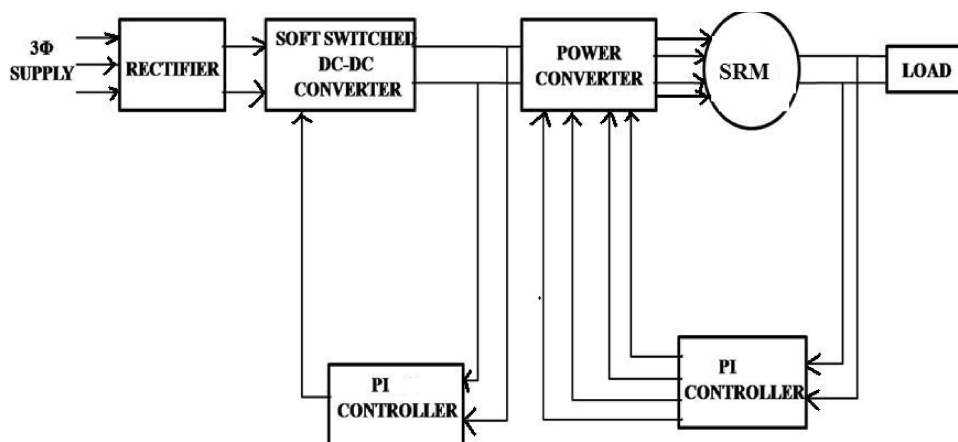
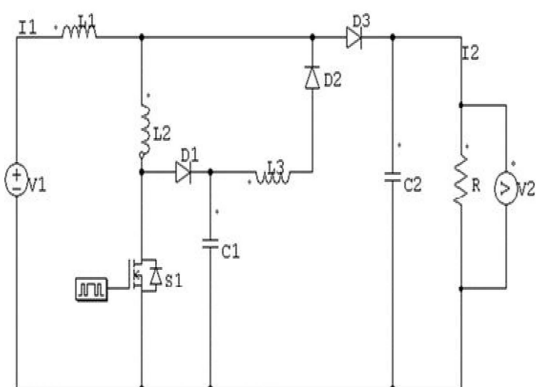Fig. 2: Blockdiagram of the proposed converters and controllers for 6/4 poles 3 phase srm

Fig. 3: Design and Analysis of the Proposed Converter

Generalized Equation of Motor:

$$V = r\,i + d\Psi\,/\,dt \tag{5}$$

$$V = L\,di/dt + I(dL\,/\,d\theta) \tag{6}$$

$$V = L\,di/dt + i\,\omega(dL\,/\,d\theta) \tag{7}$$

The block diagram in Fig. 2 shows the proposed controller with two converters. The rectifier converts ac to dc and dc fed to the soft switched dc dc converter, which regulates the voltage to the power converter with the help of the closed loop PI controller. The switch used in this converter switched ON at zero current and switched OFF at zero voltage. The regulated output for any line variations from the converter is given to the power converter. The power converter has four switches and all are used to control the speed of srm. The closed loop PI controller triggered the gate signals of these switches by the variable speed signals taken from the motor. The rotor position is sensed by sensor less control method. According to the rotor position and variable speed, PI controller sends triggering signal to the gate. This closed loop controller maintains the speed constant, which is set as reference. Thus the controllers used in these converters regulate the input supply and control the speed for any load and line variations.

Design and Analysis of Soft Switched Dc-dc Boost Converter: The configuration diagram of the proposed converter with soft switching scheme is shown in Fig.3, the switch S1, L1, D3 and C2 are the main boost converter components, while R represents the resistive load on the converter. Inductor L2, L3, D1, D2 and C1 form the auxiliary circuit for accomplishing the soft switching of S1. Inductors L2 and L3 are much smaller than L1 and C1 is much smaller than C2. There are seven modes of operation.

Operational Analysis of Theproposed Converter
Mode 1: This mode begins with the turn on of S_1, at zero current at t_0. The expressions are,

$$i_{L_2}(t) = \frac{V_1}{L_2}t \tag{1}$$

$$v_{C_1}(t) = [V_1 - V_{C_1}(t_0)][1 - \cos\omega_1 t] + V_{C_1}(t_0) \tag{2}$$

$$i_{L_3}(t) = [V_{C_1}(t_0) - V_1]\frac{\sin\omega_1 t}{\omega_1 L_3} \tag{3}$$

Where $\omega_1 = \frac{1}{\sqrt{L_3 C_1}}$

When D_3 stops conducting and this mode comes to an end.

MODE 2: The initial conditions on L_3, L_2 and C_1 are , $i_{L_3}(t_1)$, $i_{L_2}(t_1) + I_1$ and V_{C_1} respectively, attained at the end of Mode 1.The expressions are,

$$V_{C_1}(t) = -V_{C_1}(t_1)[1 - \cos \omega_2 t] + \frac{i_{L_3}(t_1)}{\omega_2 C_1} \sin \omega_2 t - V_{C_1}(t_0) \quad (4)$$

$$i_{L_3}(t) = \frac{V_{C_1}(t_1)}{\omega_2 (L_2 + L_3)} \sin \omega_2 t + i_{L_3}(t_1) \cos \omega_2 t \quad (5)$$

$$i_{L_2}(t) = \frac{V_{C_1}(t_1)}{\omega_2 (L_2 + L_3)} \sin \omega_2 t + i_{L_3}(t_1) \cos \omega_2 t + I_1 \quad (6)$$

Where $\omega_2 = \frac{1}{\sqrt{(L_2 + L_3)C_1}}$

This mode comes to an end when V_{C_1} reaches zero at t_2.

Mode 3: The initial conditions on i_{L_2}, i_{L_3} and V_{C_1} for this mode $i_{L_2}(t_2), i_{L_3}(t_2)$ are zero. The expression for i_{L_3} is,

$$i_{L_3}(t) = -\frac{V_S L_2}{L_1 L_2 + L_2 L_3 + L_3 L_1} t + I_{L_3}(t_2) \quad (7)$$

This mode comes to an end at t_3 when i_{L_3} reaches zero at t_3.

Mode 4: In this mode current buildup in L_1 and L_2 and $V_{out}(t)$ are governed by the equations as follows.

$$i_{L_1}(t) = i_{L_2}(t) = \frac{V_S}{L_1 + L_2} t + I_1 \quad (8)$$

$$V_{out}(t) = V_1 e^{\frac{1}{RC_2}} \quad (9)$$

This mode comes to an end when S_1 is turned off at zero voltage at t_4.

Mode 5: This mode begins with the turn off of S_1 at zero voltage at t_4.The expressions are,

$$V_{C_1}(t) = V_2(1 - \cos \omega_3 t) + \frac{I_2}{\omega_2 C_1} \sin \omega_3 t \quad (10)$$

$$I_{L_2}(t) = \frac{L_2}{(L_2 + L_3)} [V_2 C_1 \sin \omega_3 t - I_2(1 - \cos \omega_3 t)] + I_2 \quad (11)$$

$$I_{L_3}(t) = \frac{L_2}{(L_2 + L_3)} [-V_2 C_1 \omega_3 \sin \omega_3 t + I_2(1 - \cos \omega_3 t)]$$

Mode 6: In this mode i_{L_3} reduces to zero. This mode comes to an end at t_6 when i_{L_3} becomes zero. The expression for i_{L_3} and V_{C_1} for these mode is.

$$i_{L_3} = \frac{V_{C_1}(t_5) - V_2}{L_3 \omega_1} \sin \omega_1 t + i_{L_3}(t_5) \cos \omega_1 t \quad (13)$$

$$V_{C_1}(t) = [V_{C_1}(t_5) - V_2][\cos \omega_1 t - 1] \frac{i_{L_3}(t_5)}{\omega_1 C_1} \sin \omega_1 t \quad (14)$$

Mode 7: In this mode i_{L_2}, i_{L_3} are zero. This mode comes to an end at t_7 when S_1 is turned on at zero current. This is the normal mode of the boost converter. The expressions are,

$$V_{out}(t) = e^{-\alpha t}[A \sin \omega_4 t + B \sin \omega_4 t] + V_S \quad (15)$$

$$i_{L_1}(t) = \frac{V_{out}(t)}{R} + e^{-\alpha t}[(-BC_2 + AC_2 \omega_4 t) \cos \omega_4 t - (AC_2 + BC_2 \omega_4) \sin \omega_4 t] \quad (16)$$

Where $\alpha = \frac{1}{2RC_2}$, $\omega_4 = \frac{1}{\sqrt{L_1 C_2}}$

$$A = \frac{I_2}{\omega_4 C_2} - \frac{V_2}{R \omega_4 C_2} + \frac{\alpha(V_2 - V_5)}{\omega_4}$$

$$B = V_2 - V_S$$

Power Converter: Fig. 3 shows the unipolar converter with two switches per phase which is a power converter for srm. The regulated output from the soft switched converter is fed to the power converter. The gate signals to the switches controls the speed of srm, getting the pwm signal from the PI controller.

Design Of PI Controller: A PI Controller (proportional-integral controller) is a feedback controller which drives the plant to be controlled with a weighted sum of the error (difference between the output and desired set-point) and the integral of that value. PI controller is mainly used to improve the performance of the system under disturbances. The dynamic performance of the PI controller can be improved by giving feedback to the converter to overcome the disturbances. A proportional-integral controller employed with a feedback loop can take

the place of manual adjustment in DC-DC converter and act much more quickly than is possible. Consider the DC-DC converter as "a process," The DC-DC converter includes the converter itself, plus the DC power supply. To automate the control process, the "feedback loop" is closed, producing an error signal (+ or –). The PI controller acts upon the error with parallel proportional and integral responses in an attempt to drive the error to zero. When áVout equals Vset, then the error is zero. It can be used with the op-amp implementation of the controller. A proportional-integral controller (i.e., PI) employed with a feedback loop can take the place of manual adjustment in DC-DC converter and act much more quickly than is possible "by hand." Consider the DC-DC converter as "a process," The controller output is given by

$$K_P\Delta + K_I \int \Delta dt \qquad (5.1)$$

Where,

Δ is the error or deviation of actual measured value (**PV**) from the set-point (**SP**).

$$\Delta = \textbf{SP - PV}. \qquad (5.2)$$

A PI controller can be modeled easily in software such as Simulink using a "flow chart" box involving Laplace operators:

$$C = \frac{G(1+\tau s)}{\tau s} \qquad (5.3)$$

Where

$G = K_P$ = proportional gain
$G / \tau = K_I$ = integral gain

Setting a value for G is often a tradeoff between decreasing overshoot and increasing settling time.

Design of PI Controller for a Boost Converter: PI control is a traditional linear control method used in industrial applications [15]. The linear PI controller controllers are usually designed for dc-dc converters using standard frequency response techniques and based on the small signal model of the converter [16]. A Bode plot is used in the design to obtain the desired loop gain, crossover frequency and phase margin. The stability of the system is guaranteed by an adequate phase margin. However, linear PID and PI controllers can only be designed for one nominal operating point. A boost converter's small
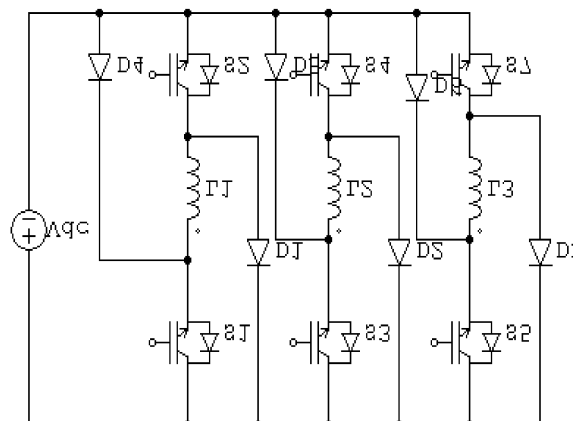

Fig. 4: Unipolar converter with two switches per phase
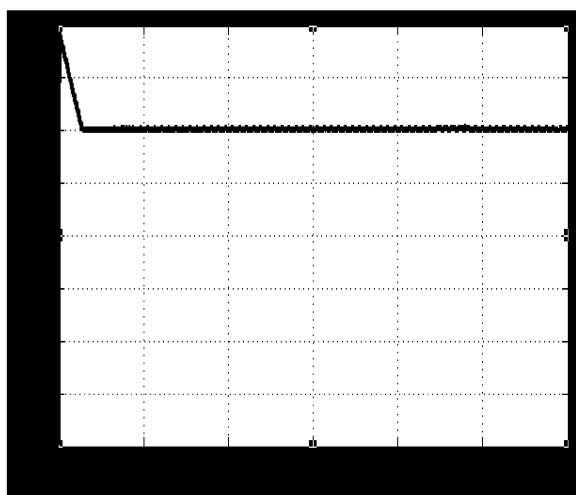

Fig. 5: Input voltage

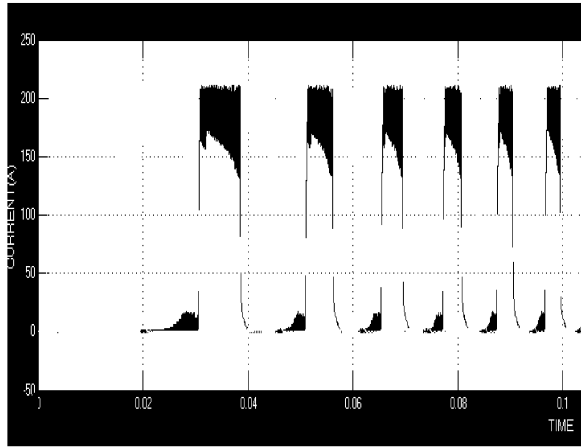Fig. 6: Regulated output voltage from the proposed Converter
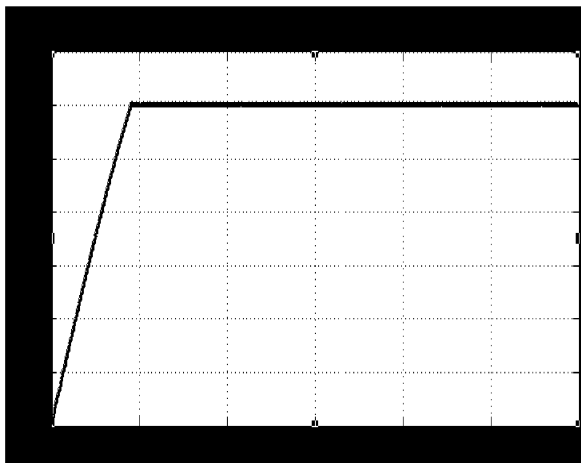
Fig. 7: Output current in the SRM

Fig. 8: Speed in the SRM

$$\frac{Vo(s)}{D(s)} = \frac{Vs}{(1-D)^2} \frac{\left(1-5\dfrac{L}{R(1-D)^2}\right)}{1+s\dfrac{L}{R(1-D)^2}+s^2\dfrac{LC}{(1-D)^2}}$$

Simulation Results: The proposed soft switched converter is designed and simulated using matlab /simulink. Two PI controllers are designed and simulated to regulate the input voltage fed to srm and control the speed of srm. The outputs are clearly shown that the soft switched converter with PI controller regulates the input supply to 300V as constant and the power converter with PI controller maintains a constant speed 3000 rpm in a 3phase 6/4 poles SRM. The outputs are constant for any load and line variations.

Fig. 5. shows the input three phase ac supply fed to the rectifier.

Fig. 6. Shows the regulated output voltage from the softswtched dc dc converter.The converter is controlled by a PI controller.It is clearly seen that the output voltage is constant for any line variations.

In the speed control method of srm most of the control is done by current, which is called as current controller. The fig.7 shows the rotor current, which is feedback to the converter by comparing with the reference current and variable speed from the SRM.

Fig. 8 shows the constant speed 3000rpm is maintained in the srm for any load variations.

CONCLUSION

Thus a soft switching scheme is designed and simulated for SRM to regulate the input voltage to srm and control the speed of srm with a feedback controller. Two PI controllers are used as feedback control. We have simulated the soft switching technique and achieved the low stress and less switching loss in the converter. The linear PI controllers were designed based on frequency response of the boost converter using frequency response technique. The simulated results shows that the only switch used in this converter is switched ON at zero current and switched OFF at zero voltage. The output voltage is boosted and it is constant at steady state. It reaches the steady state value within several micro seconds for any line variations. It also maintains a constant speed foe any load variations.

signal model changes when the operating point varies. The poles and a right-half plane zero, as well as the magnitude of the frequency response, are all dependent on the duty cycle. Therefore, it is difficult for the PID controller to respond well to changes in operating point. The PI controller is designed for the boost converter for operation during a start up transient and steady state respectively. The load current of the proposed converter is given to the PI controller. The time constant of the controller is designed according to the small signal transfer function of the boost converter which is given below. Then the output of the PI controller changes the pulse width of the square wave which changes the firing angle of the MOSFET switch, so the output of the converter is controlled for different load disturbances.

The small signal model of the boost converter is designed based on the average state space averaging techniques, the small signal transfer function of a boost converter is

REFERENCES

1. Geun-Hie Rim, Won-Ho Kim and Jung-Goo Cho, 1996. ZVT Single Pulse Current Converter for Switched Reluctance Motor Drives. 11th annual applied power electronics conference and exposition, 2: 949-955.

2. Ching, T.W., K.T. Chau and C.C. Chan, 1998. A Novel Zero-Voltage Soft-Switching Converter For Switched Reluctance Motor Drives. 24th IEEE annual conference on i.ndustrial Electronics Society, 2: 899-904.

3. Hiller, M. and R. Marquardt, 2003. A New Converter Concept for Switched Reluctance Motor Drives With Multiple Energy Sources. The 5th international conference on power electronics and drive systems, 2: 1235-1240.

4. Bazzaz, Ebrahim Afjei, P. and Hamid A. Toliyat, 2005. A Hybrid Converter for High Speed Operation of Switched Reluctance Motor Drives. IEEE international conference on electric machines and Drives, pp: 71-71.

5. Yuen-Chung Kim, Yong-Ho Yoon, Byoung-Kuk Lee, Hack-Seong Kim and Chung-Yuen Won, "Control Algorithm for Four-Switch Converter of Three-Phase Switched Reluctance Motor". 37th IEEE power electronics specialists conference, pp: 1-5, 2006.

6. Aijuan Song and Yali Cao Deying Gu, 2010. Study of Based Fuzzy-PID Control for Switched Reluctance Motor", International Conference On Computer Design And Appliations (ICCDA 2010) V3-558 978-1-4244-7164-51.

7. Zheng lian-ming, Zhao Sheng-dun and Wei Shu-guo, 2009. Adaptive Fuzzy PID Control for Switched Reluctance Motor Direct Drive Servo Hydraulic Press, International Conference on Measuring Technology and Mechatronics Automation, pp: 771 - 774.

8. Han Li and Liu Yue, 2009. Speed Control of Switched Reluctance Motor by FVSC System Intelligent Systems, 2009. GCIS '09. WRI Global Congress on Volume: I Digital Object Identifier: 1O.1109/GCIS.2009.234 Publication Year.

9. WANG Mianhua, 2009. The Fuzzy-PI Control of Switched Reluctance Motor Based on DTC, International Conference on Measuring Technology and Mechatronics Automation, 978-0-7695-3583-8.

10. Dos Reis, L.L.N., F. Sobreira, A.R.R. Coelhoa, O.M. Almeida, J.C.T. Campos and S. Daher, 2009. Identification and Adaptive Speed Control for Switched Reluctance Motor using DSP, 978-1-4244-3370-4.

11. Zhou Guanxu, 2009. Adaptive PID control for hydraulic pump system based on fuzzy logic", Power Electronics and Motion Control Conference, 2009. IPEMC '09. IEEE 6th International Digital Object Identifier: 10.1 I 09IIPEMC.2009.5 I 57738.

12. Dos Reis L.L.N. *et al.*, 2008. Modeling And Control Of Switched Reluctance Motor Drives Based On Set point Relay, Revista Eletronica de Potencia, 13: 163-170.

13. Xiu lie and Xia Changliang, 2007. Fuzzy Logic Based Adaptive PID Control of Switched Reluctance Motor Drive Control, Conference CCC 2007. Chinese Digital Object Identifier:. 11 09/CHICC.2006.4347328. Publication Year.

14. Tungpimolrut, K. *et al.*, 2007. A Simplified Variable Speed Switched Reluctance Motor Drive without Using Encoder, Proc. of Int. Conf. on Electrical Machines and Systems, 2007, Seoul, Korea, pp: 1676- 1679.

15. Komatsuzaki, A. *et al.*, 2007. A Position Sensorless Speed Control for Switched Reluctance Motor at Low Speeds, Power Eng. Soc. Gen. Meeting, pp: 1-7.

16. Kumar, R., RA. Gupta, S. Goyal and S.K. Bishnoi, 2006. Fuzzy Tuned PID Controller Based PFC Converter-Inverter Fed SRM Drive, industrial Technology, 2006. ICIT 2006. IEEE International Conference on Digital Object Identifier: 1109IICIT.2006.372632 Publication Year: 2006.

17. Weiguo Liu, 2006. Application of Fuzzy Control in Switched Reluctance Motor Speed Regulating System Computational Intelligence for Modelling, Control and Automation, 2006 and International Conference on Intelligent Agents, Web Technologies and Internet Commerce, International Conference on Digital Object Identifier: 10.11 09/CIMCA.2006.

18. ZHAN Qiong-hua and YIN Chun-hui, 2006. The application and optimization of fuzzy controller used in SRD", Micromotors, Xi An, 4: 4-7.