

Design and Simulation of a PI Controlled Soft Switched Front End Converter for Switched Reluctance Motor

X.Felix Joseph

Research Scholar, PRIST University,
Associate Professor, Noorul Islam University
Kumaracoil, India

Dr.S.Pushpa Kumar

Principal
Heera college of Engg. & Technology
Trivandrum, India.

ABSTRACT

This paper presents the design, and simulation of a soft switched boost 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. Lot of researches were 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.

Keywords

Soft switched Boost converter, Soft Switching, Zero voltage switching, Zero current switching, Switched Reluctance Motor.

1.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 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. 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 8/6 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.

This paper is organized as follows. The basic operation of SR motors is discussed in Section II. The proposed topology is introduced and its operation is described in Section III. Design examples for soft switched dc dc converter operation are taken

up in Section IV. Power converter circuit is explained in section V. Design of PI controller explained in Section VI and simulation results are presented in Section VII. Section VIII concludes the paper.

2. SWITCHED RELUCTANCE MOTOR

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.

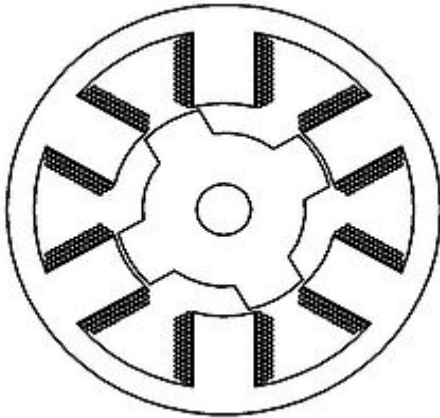


Fig 1. SRM with 6/4 poles

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.

2.1 Development Of Torque

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

$$T = [\partial W / \partial \theta] i = \text{Const} \dots (1.1)$$

$$\text{Since } W = \text{Co-energy} = \frac{1}{2} F \Phi = \frac{1}{2} N I \Phi \dots (1.2)$$

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

Neglecting saturation non-linearity

$$L = \text{Inductance} = N\Phi / I \dots (1.3)$$

$$T = \frac{1}{2} i^2 dL/d\theta \dots (1.4)$$

This equation shows that the developed torque independent of direction of current but only depends on magnitude of current & direction of $dL/d\theta$.

2.2 Generalized Equation of motor

$$V = r i + d\Psi / dt \dots (1.5)$$

$$\Psi = Li = N\phi \dots (1.6)$$

For $r = 0$

$$V = L di/dt + i (dL/d\theta) (d\theta/dt)$$

$$V = L di/dt + i \omega (dL/d\theta) \dots (1.7)$$

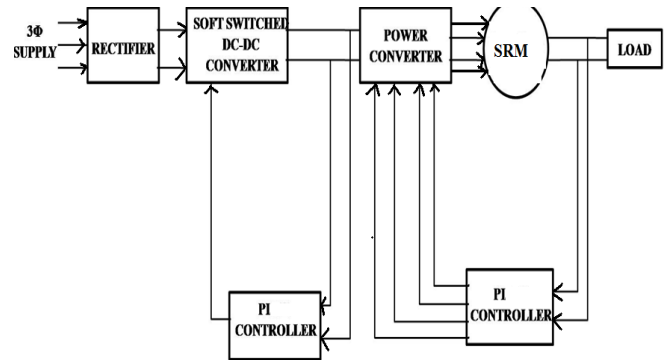


Fig.1. Block diagram of the proposed converters and controllers for 6/4 poles 3 phase srm

The block diagram in fig.1 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.

3. DESIGN AND ANALYSIS OF SOFTSWITCHED DC-DC BOOST CONVERTER

3.1 Configuration of the proposed converter

The configuration diagram of the proposed converter with soft switching scheme is shown in fig.1, the switch S_1 , L_1 , D_3 and C_2 are the main boost converter components, while R represents the resistive load on the converter. Inductor L_2 , L_3 , D_1 , D_2 and C_1 form the auxiliary circuit for accomplishing the soft switching of S_1 . Inductors L_2 and L_3 are much smaller than L_1 and C_1 is much smaller than C_2 . There are seven modes of operation.

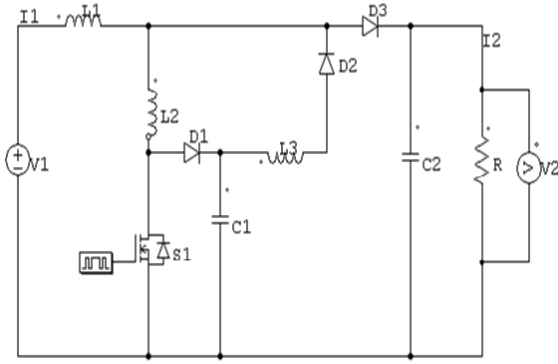


Fig.2 Design and Analysis of the Proposed Converter

A. Operational analysis of the proposed converter

MODE 1: This mode begins with the turn on of S_1 , at zero current at t_0 . The expressions are,

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

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

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

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

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,

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

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

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

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

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.

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

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

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,

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

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

$$I_{L_3}(t) = \frac{L_2}{(L_2 + L_3)} [-V_2 C_1 \omega_3 \sin \omega_3 t + I_2 (1 - \cos \omega_3 t)] \quad (12)$$

$$\text{Where } \omega_3 = \frac{1}{\sqrt{\frac{L_2 L_3}{L_2 + L_3} C_1}}$$

This mode ends when i_{L_2} reaches zero at t_6 .

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,

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

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

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

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

$$B = V_2 - V_s$$

4. POWER CONVERTER

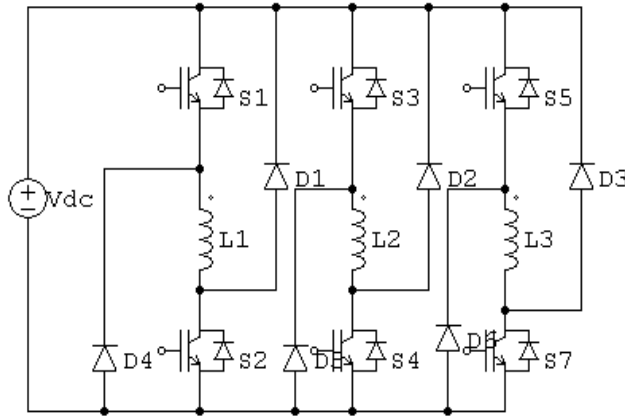


Fig.3. Unipolar converter with two switches per phase

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.

5. 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 (i.e., PI) employed with a feedback loop can take the place of manual adjustment in your DC-DC converter and act much more quickly than is possible “by hand.” Consider the DC-DC converter as “a process,” The DC-DC converter includes the converter itself, plus the DC power supply. In the open loop

mode, as you used previously. 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 αV_{out} equals V_{set} , 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,” .

5.1 Mathematical Model Of PI Controller

The controller output is given by

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

Where,

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

$$\Delta = SP - PV. \quad (5.2)$$

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

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

Where

$$G = K_P = \text{proportional gain}$$

$$G / \tau = K_I = \text{integral gain}$$

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

B. Design of PI control 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 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.

Fig. 2.shows the closed loop of the soft switched dc-dc boost converter with PI controller. 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

$$\frac{V_o(s)}{D(s)} = \frac{V_s}{(1-D)^2} \frac{\left(1 - s \frac{L}{R(1-D)^2}\right)}{1 + s \frac{L}{R(1-D)^2} + s^2 \frac{LC}{(1-D)^3}}$$

6. 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 simulated results show the regulated output voltage and constant speed in srm.Fig3.shows the input three phase ac supply fed to the rectifier.

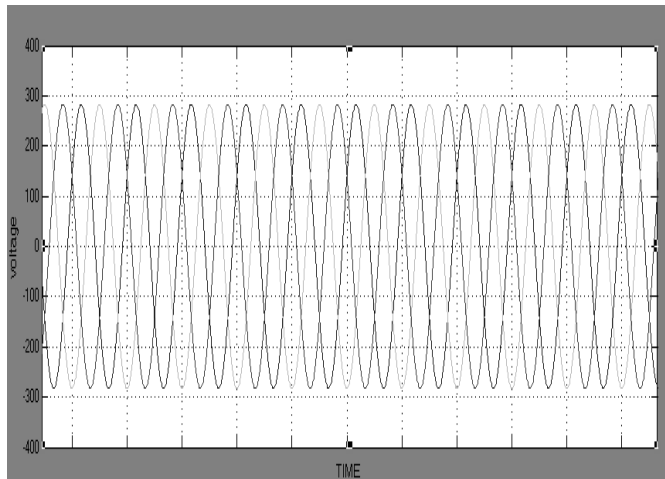


Fig.3.Input voltage

Fig.4.Shows the regulated output voltage from the softswitched 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.

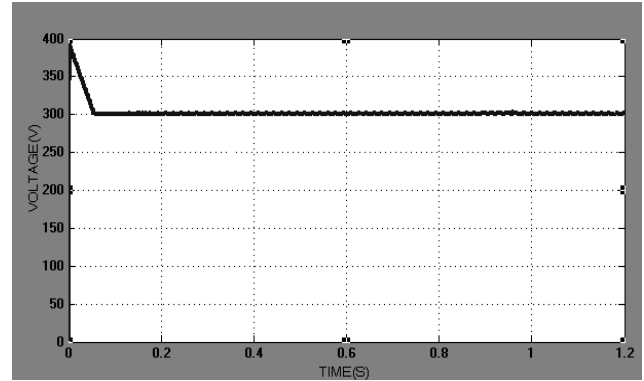


Fig.4.Regulated output voltage from the proposed Converter

In the speed control method of srm most of the control is done by current, which is called as current controller. The fig.5 shows the rotor current, which is feedback to the converter by comparing with the reference current and variable speed.

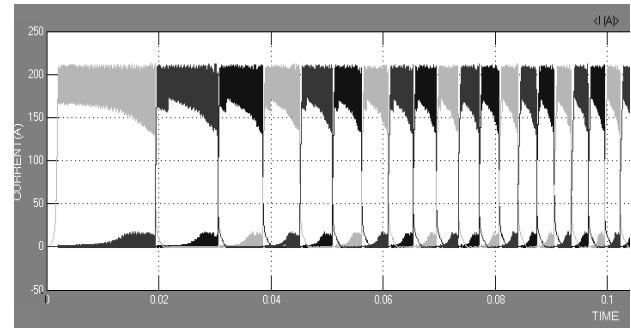


Fig.5 Output current in the SRM

Fig.6 shows the constant speed 3000rpm is maintained in the srm for any load variations.

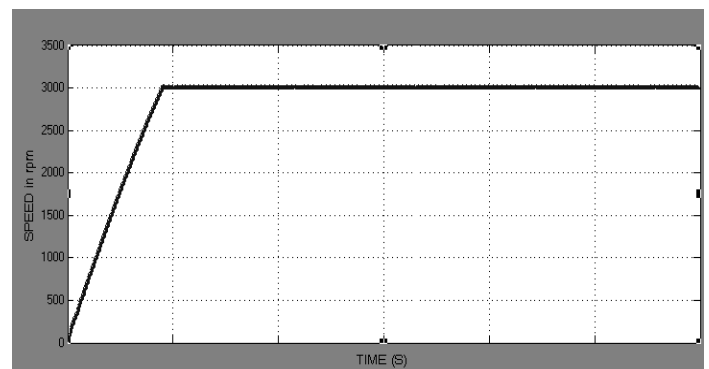


Fig.6.Speed in the SRM

7. 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 for any load variations.

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