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Performance evaluation of PI controlled Soft Switching Converter for Switched Reluctance Motor

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Abstract - The Switched Reluctance Motor (SRM) is known to be the low cost motor having the simplest construction with no brushes, commutators, windings or magnets on its rotor and have only concentrated winding on its stator. There are many converters available for the SRM like classic inverter, C dump inverter and Buck-Boost inverter. Speed response, torque ripple and cost are the constraints for designing the converter and controller for SRM. Most importantly the current overlapping is the main problem associated with the above converters. To overcome these difficulties a converter uses single switch for each phase along with the PI Controller is proposed. The fast phase current commutation capability of the proposed converter is evaluated by verifying the phase current overlapping with the MATLAB/Simulink. Also the speed response and torque ripples of the proposed PI controlled converter is simulated and compared with the conventional asymmetric converter.

Keywords- SRM, PI Control, Torque ripple, Commutation

Introduction

SRM is a single excited and double salient pole electric motor. It is electromagnetic and electro dynamic equipment. It has concentrated winding on its stator and no winding on its rotor. The rotor is made from lamination in order to minimize the eddy current losses. The rotor tries to get to a position of minimum reluctance by aligning itself with the stator magnetic field when the stator winding are excited.

Growing energy and environmental concerns have increased demand for variable-speed drives in low-cost, high performance and the high- volume applications. The interest over SRM is due to its advantages over the induction motor and the synchronous motor. It includes low cost, boosted performance, equal or better efficiency and the comparable reliability [1-5].A number of power electronic converter topologies have been developed over the years exclusively for use in conjunction with SRM drives. In principle, the quest has always been for a converter with a minimum number of switches [6].

New power electronic converter topology for SRM drives is entirely based on utilization of standard inverter legs has been presented [7]. One of its most important features is that both magnetizing and demagnetizing voltage may reach the DC-bus voltage level while being contemporarily applied during the conduction overlap in the SRM adjacent phases. At the same time, the voltage stress across the power switches equals the DC-bus voltage.

A simple, low-cost SRM drive is needed for efficient operation of hostile environment of the car. However, in such low-voltage applications, the voltage drop across the converter switches is a significant fraction of the available dc voltage, and the common SRM converter topologies are not suitable. A modified dump resistor converter topology for star – connected switched reluctance motor with a dual time constant freewheeling circuit has been designed to improve the drive performance and efficiency over a wide range of speeds [8]. To manage any input line variations of SRM, a soft switched boost converter is designed to regulate the input voltage and a power converter is used to control the speed of SRM [9]. 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.

SRM drive has the crucial problem of large torque ripples due to lack of continuity in the generated torque. But this can be mitigated to a great extent by phase current overlapping. Therefore, the converters used for SRM drive requires separate control for each phase so that the torque ripples can be reduced by phase current overlapping[10]. Another reason for torque ripples is that the stator current falls behind the reference current during the commutation of each SRM phase current because of back EMF. This means that during commutation, the phase current reaches zero after the reference current which causes negative torque and more ripples in the torque produced by the motor. Thus, the converter used in the SRM drive must have the quick commutation ability of phase currents, which will reduce torque ripples considerably. This is more important at higher speeds where commutation interval is very short. Therefore a new converter which performs the commutation process with high speed and provides excellent drive performance at higher speed is proposed.

The design of new converter, consisting of "half-bridge" IGBT modules and SCRs, for closed loop control of switched reluctance motor drives are proposed and Compared to the conventional asymmetric bridge converter[11], the proposed one using half-bridge switch modules is more compact and has higher utilization of power switches. A performance comparison of Proportional Integral (PI) Controller with Sliding Mode Controller is presented [12] for speed control of Switched Reluctance Motor. A new PI controlled soft switching converter for switched reluctance motor drive is proposed in this paper, which uses only one switch with coupled inductor for each phase winding. It performs the commutation process with high speed which provides excellent drive performance at higher speeds.

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. Figure 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. The rotor position influence the inductance variation of windings in the stator. For better understanding of the relationship between the phase inductance profile and the torque profile, a linear variation is considered. This can be obtained from the figure 2.

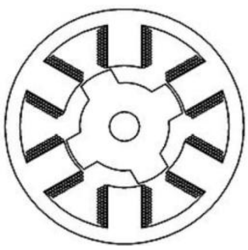


Fig.1.SRM with 6/4 poles

The figure 2. (a) shows ideal variation of inductance of typical one stator phase as a function of rotor position. The cross sectional view of SRM as shown in figure1., the movement of SRM rotor in clockwise direction at intermediate rotor position for motoring torque production, at aligned rotor position, at intermediate rotor position for generating torque production and unaligned rotor position.

At each of the rotor positions, range of inductance values are produced such as L_{int}(intermediate inductance),L_a(aligned inductance),and L_u(unaligned inductance),as shown in figure2.Then ,the corresponding torque profile at constant current as a function rotor position is shown in figure2.(b).

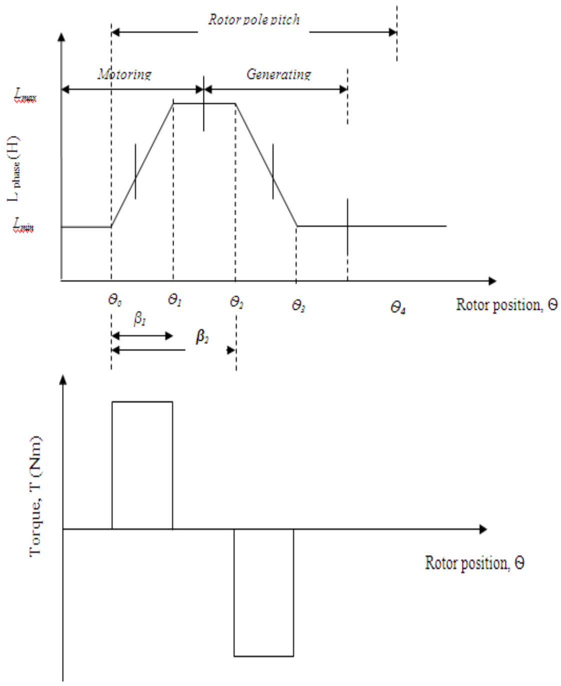


Fig.2.a) Ideal variation of inductance of one stator phase b) torque with constant current

Generalized Equation of Motor

The voltage equation is,

$$V = Ri + d\Psi / dt \quad (1)$$

Where $\psi = Li = N\varphi$ (2)

R = Winding resistance

L = Nonlinear equivalent inductance

For R = 0,

$$V = L\, di/dt + i\,(dL/dt)$$
$$= L\, di/dt + i\,(dL/d\theta)\,(d\theta/dt)$$
$$V = L\, di/dt + i\,\omega\,(dL/d\theta) \quad (3)$$

Development of Torque

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

$$T = [\partial W' / \partial \Theta]\, i = Const \quad (4)$$

Since,

$$W' = Co-energy = ½ F\, \Phi = ½ N I \Phi \quad (5)$$

This equation shows that input electrical power goes partly to increase the stored magnetic energy $(½ L * i^2)$ and partly to provide mechanical output power $\left(\frac{i^2}{2} * \frac{dL}{d\theta} * \omega\right)$, the latter being associated with the rotational emf in the stator circuit.

Neglecting saturation non-linearity,

$$L = Inductance = N\Phi / I$$

$$T = ½\, i^2\, dL/d\theta \quad (6)$$

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

$$T_e = \sum_{i=1}^{N} T_d \quad (7)$$

$$= T_L + B\omega + \frac{Jd\omega}{dt} \quad (8)$$

Where, T_e is the sum of the torque developed by all phases, N is the number of phases, and J and B represent the total moment of inertia and the total damping ratio.

Proposed Converter for SRM

A. Basic requirements of the converter

- Each phase of SRM should be able to conduct independent of the other phases.
- The converter should be able to demagnetize the phase before it steps into the generating region if the machine is acting as a motor and should excite the phase if it operates as a generator.
- The converter should be able to freewheel during the chopping period to reduce the switching frequency.
- The converter should be able to utilize the demagnetizing energy by either feeding it back to the source or by using it in the next phase.

B. Types of converters

In classic converter the conduction mode is usually initiated before the start of the rotor such that phase current reaches the reference value before the phase inductance begins to increase.

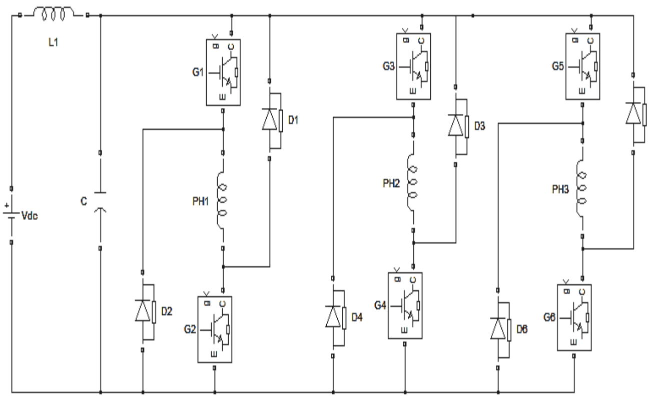


Fig.3. Classic converter

This helps to reduce the torque ripple. But the disadvantage of this system is the more number of switches used and are applicable for low voltage applications [10]. R-dump converter is the single switch used in each phase which makes it smaller and lower cost. The disadvantage is the lower efficiency due to the wastage of phase inductor energy in the resistance. C-dump converter uses the phase inductance energy in a capacitor (Cn) rather than dissipating it through a resistance. Also, the reverse voltage used for the phase current commutation is very much limited.

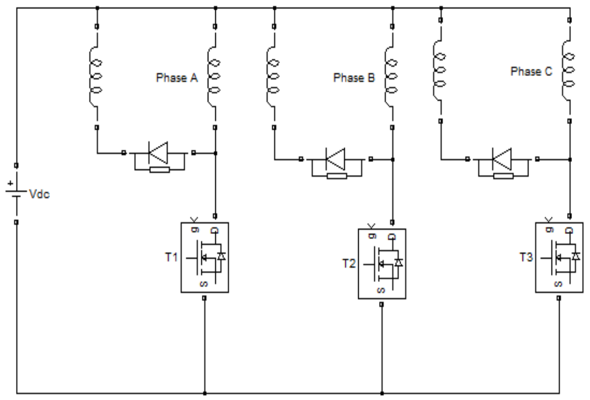
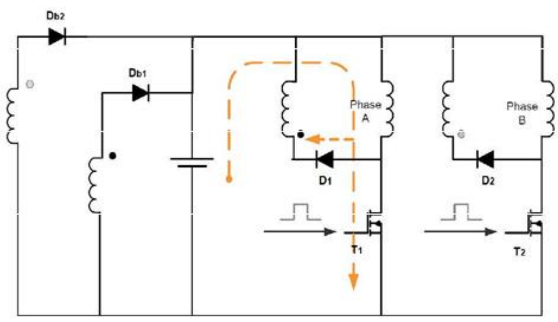


Fig.4. Proposed SRM converter

All the power converter topologies offers to minimize commutation interval in order to mitigate the torque ripple problem and improve the performance at higher speeds. But, all these converters have the problem of either increased number of components or the commutation process is not fast enough. A new converter is proposed in this work, which uses only one switch for each phase in its structure. The proposed drive topology operation is simple with minimum number of switches so that making the phase current commutation more easily and quickly. In addition to its simpler construction, it has higher efficiency and current commutation speed than any other converters.

C. Modes of Operation of Proposed converter



1. Magnetization Mode

Fig.5. Magnetizing mode

In this mode, the switch T_1 turns on in order to magnetize Phase A and the energy is transferred from source to the phase winding and the current in the phase conductance increases. When the magnetizing inductances of coupled inductors are reset, diode D_1

turns off. The reset of coupled inductors magnetizing inductance is similar for other phases.

2. Demagnetizing Mode

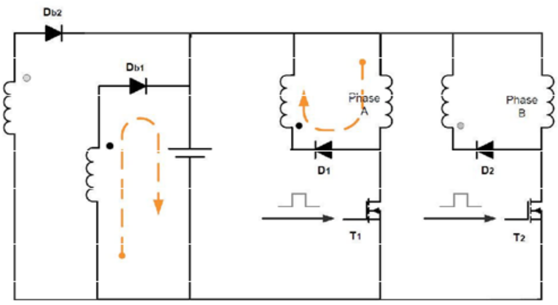


Fig.6. Demagnetizing mode

When the phase current reaches the reference, T_1 is turned off and the demagnetization process starts. Due to reversal of the voltage across phase winding D_1 and Db_1 is turned on. This creates a negative voltage across the phase winding in proportion to the coupling ratio which always accelerates the current commutation.

3. Overlapping mode

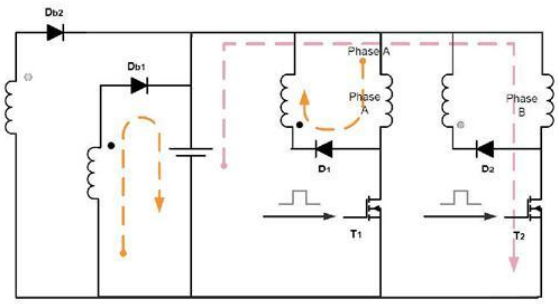


Fig.7. Overlapping mode

The magnetization and demagnetization of Phase A and Phase B are taking place alternatively. Also the converter has the ability to separately control the phase currents. For the proper design of this converter, the coupled inductors ratio has to be determined considering the performance speed of the drive. If the phase current doesn't reach zero fast enough during the commutation, the phase current continues to exist in the negative torque production area and will cause in the production of large ripples in the motor [9].

D. Control Strategies

Different control strategies such as

- Voltage control,
- Hysteresis control
- Proportional plus Integral Control
- Proportional plus Integral plus Derivative Control

For linear as well as nonlinear modeling has been applied to get simulation results. Controller is a device which when introduced in the feedback or forward path of a system controls the steady-state and transient response according to the requirement. 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.

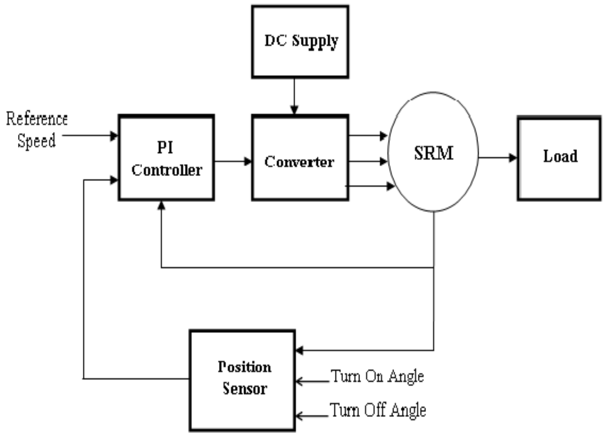


Fig.8.Block diagram of speed control SRM

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 α V 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,"

The controller output is given by following equations,

$$Kp\Delta + Ki\int \Delta dt \qquad (9)$$

Where, Δ is the error (or) deviation of actual measured value (MV) from the Set-Point (SP)

$$= SP - MV$$

A PI controller can be modeled easily in software such as Simulink

$$C = \frac{G(1+T_S)}{T_S} \qquad (10)$$

Where,

G = K_p = proportional gain
G/τ = K_i = integral gain

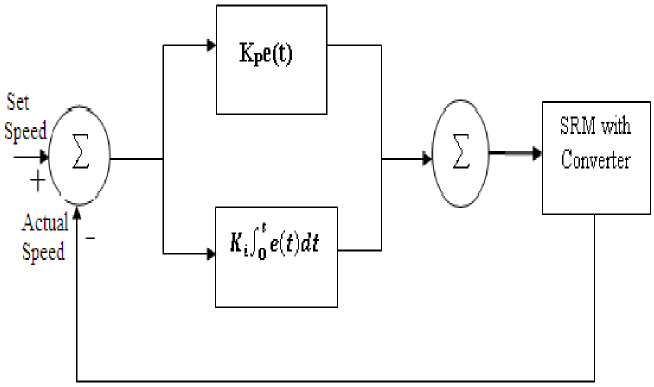


Fig.9. Block Diagram of PI Controller

Here K_p and K_i are the proportional and integral gains known as controller parameters. Thus the effect of PI controller on the system is that it increases the order of the system by one, which reduces the steady state error. In order to maintain the stability of the system K_i should be designed properly.

Results and Discussion

In this section, the soft switching converter has been simulated using the following motor parameters shown.

TABLE I
Machine Parameters of 6/4 SRM

Parameter	Value
Number of stator poles	6
Number of rotor poles	4
Supply Voltage	200V
Stator resistance	0.05Ω
Inertia	$0.05kgm^2$
Maximum Speed	4000 rpm

The simulation results of SRM drive using the proposed converter is compared with asymmetric and C-dump converter. The maximum SRM drive speed depends on the type of converter used and is illustrated by the following equation.

$$T_f = \tau_a \ln\left[1 + \frac{R_s I_p}{V_c}\right] \qquad (11)$$

where T_f is the time needed for the current to reach from reference value to zero, τ_a is the electrical time constant of machine phases, Rs is the resistance of each phase winding, V_c is the reverse voltage applied to the phase inductance during commutation. In the proposed converter, the commutation is carried out faster by increasing V_c this can be achieved by increasing the coupled inductors L_1 and L_2 turns ratio. Turns ratio of 0.9 has been used in the proposed converter to minimize the phase current overlapping. And the phase current waveform of the asymmetric converter is shown in fig.10.a. here the current overlapping between phase A and B is higher than the proposed converter. Hence to improve the commutation capability of asymmetric converter needs snubber circuits which increase the cost of converter circuit.

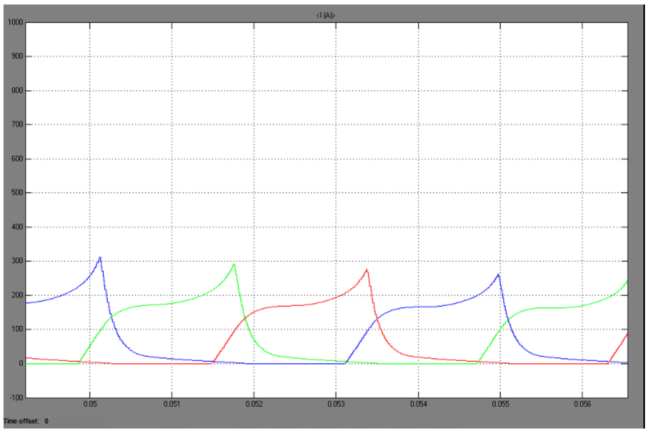


Fig.10. a) Phase current waveforms SRM driven by asymmetric converter at 4000rpm

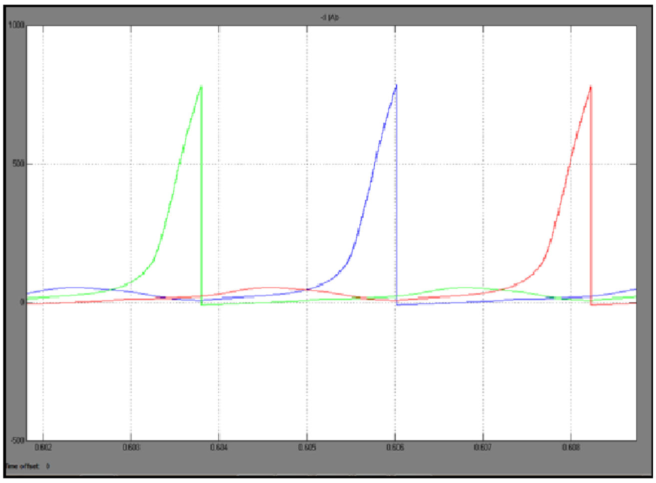
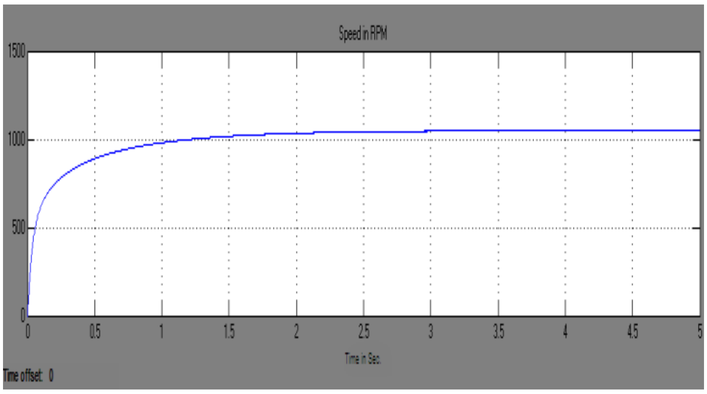
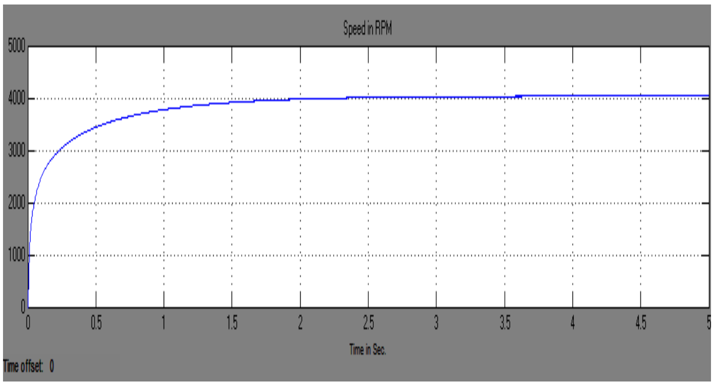


Fig.10. b) Phase current waveforms SRM driven by proposed converter at 4000rpm

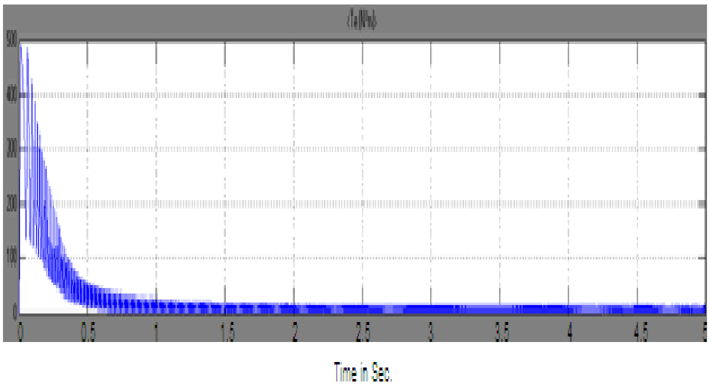
Fig.11 shows the performance characteristics of SRM drive with conventional asymmetric converter; here torque ripple is produced due to presence of negative torque and the speed response of drive for classic converter has the settling time of 2.9s and 3.6s respectively.



(a)



(b)

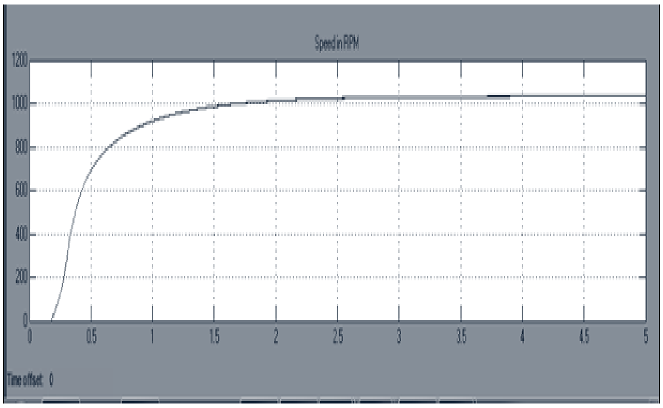


(c)

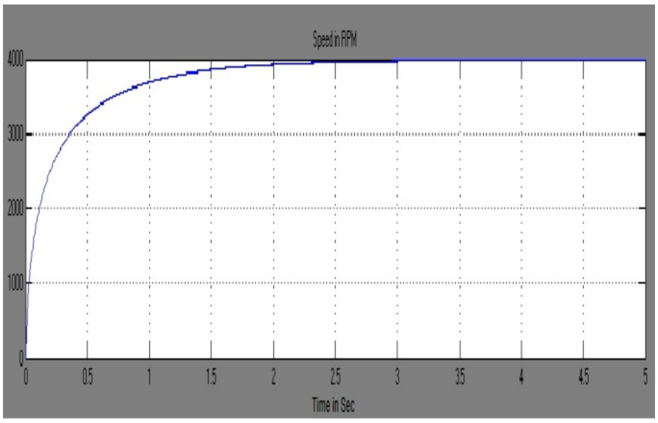
Fig.11. Measured dynamic responses with the asymmetric converter under T_L=0 for (a) speed at 1000rpm (b) speed at 4000rpm (c) torque ripple

From the above simulation result it is very well clear that there occurs a chance of electromagnetic ripple which is due to the production of negative torques. Since it is a main concern related with the SRM, here comes the demand of the new proposed converter with Proportional and Integral controller for getting better speed response. The PI controller is tuned with the gain value of K_p= 0.5 and K_i=0.0001 and the speed response of PI controlled soft switching converter is shown in fig.12.

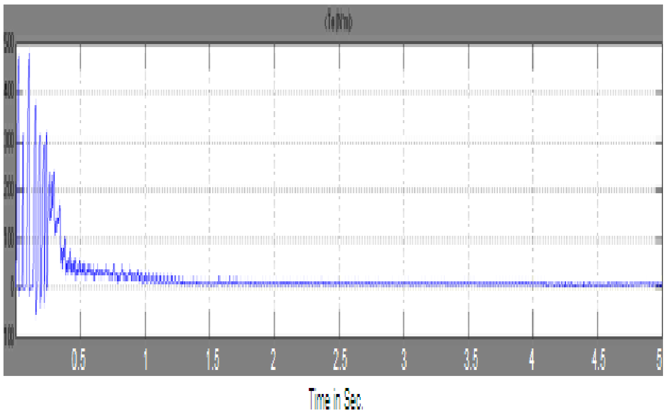
The above simulation output shows that the proposed converter with PI Controller has the settling time of 2.6sec and 3sec under no load condition which is smaller than the value of classic converter.



(a)



(b)



(c)

Fig.12. Measured dynamic responses with the Proposed converter under T_L=0 for (a) speed at 1000rpm (b) speed at 4000rpm (c) torque ripple

The integral value minimizes the overshoot and because of faster commutation the production of negative torque is controlled easily which in turn minimize the torque ripple for the proposed converter. The performance comparisons of proposed converter with the classic converter are shown in tables II and III.

TABLE II
Performance analysis for speed response of SRM with load torque, T_L=0

Reference Speed (in rpm)	Classical Converter		Proposed Converter	
	t_r(s)	t_s(s)	t_r(s)	t_s(s)
1000	0.7	2.9	0.9	2.6
4000	0.68	3.6	0.84	3.0

TABLE III
Performance analysis for speed response of SRM with load torque, T_L=1N-m

Reference Speed (in rpm)	Classical Converter		Proposed Converter	
	t_r(s)	t_s(s)	t_r(s)	t_s(s)
1000	0.75	3.3	0.95	3.0
4000	0.75	3.5	0.9	3.1

Table II and III provides the quantitative performance analyses of the proposed converter with PI Controller for different speed under no load and load respectively and compare them with that of Classical converter. It shows the rise time, the settling time of the drive that are used to evaluate the controller performances and all of them were calculated over the time interval of [0, 5] s. Also it resolves the production of negative torque due to faster commutation and this converter gains a very good speed even before settling.

Conclusion

In this paper a soft switching SRM converter with the PI controller scheme is analyzed and is compared with the existing asymmetric converter. The proposed converter uses a single switch with coupled inductors for each phase this will reduce the cost of converter. The negative torque production is minimized because of faster commutation capability of converter this is achieved by the use of coupled inductors is used in the converter which minimize the phase current overlapping. Also it is clear that the proposed converter with PI controller has low electromagnetic torque ripple and better dynamic speed response than the classic converter. Simulation results also provided to justify the same.

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