Design and Simulation of PFC Converter for Brushless SRM Drive

M. Rama Subbamma[1], V. Madhusudhan[2], K.S.R Anjaneyulu[3]
[1]Department of Electrical and Electronics Engineering, G. H. Patel College of Engineering and Technology, Kadapa, India
[2]Kandula Obul Reddy Memorial College of Engineering (K.O.R.M.C.E), Kadapa, India
[1,3]EEE Dept., Jawaharlal Nehru Technological University (JNTUA), Anantapuram, India

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ABSTRACT

In most of the industrial applications, Switched Reluctance Motor (SRM) is mainly employed due to the reasons like having low maintenance and high efficiency. SRM consists of windings only on its stator, but would not have any windings on rotor thus having very simple construction. The available supply is AC. But AC cannot be directly supplied to SRM when used for air-conditioner application which is employed in this paper. Also power factor in the system needs to be corrected when using a SRM drive. Thus AC supply is fed to power factor correction (PFC) converter which is Buck-Boost converter here in this paper. The output of the PFC converter is fed to SRM through a simple asymmetrical converter. This PFC circuit consists of a simple diode bridge rectifier with Buck-Boost DC-DC converter. A suiTable control circuit was proposed to control the input power factor under various loading conditions. This paper gives analysis of SRM drive for air-conditioner application with Buck-Boost converter based PFC circuit. A matlab/simulink based model is developed and simulation results are presented. Simulation is carried out for different speed response.

Corresponding Author:

M. Rama Subbamma,
Department of Electrical and Electronics Engineering,
GCET, Kadapa., A.P., (Affiliated to JNTUA), India.
Email: ramasekharslv@gmail.com

1. INTRODUCTION

Switched reluctance motor drives are introducing in the electrical engineering in the year 1830's [1]. The advantages of SRM are high efficiency and low maintenance. SRM which is very simple constructional wise gained its applications in many industries and SRM attracted the interest of engineers due to advancement in electronic manufacturing [2, 3]. Torque equation of a particular motor decides its applications and this torque is of two types electromagnetic and reluctance torque. Induction motor is an example of machine running with electromagnetic torque. But high maintenance and low efficiency makes induction motor not suiTable for all kinds of applications.

This problem can be addressed by using a Reluctance motor which operates on basic principle of alignment of rotor to low reluctance path produced when the pair of poles in the stator is excited. But having high torque ripples [4] with magnetically non-linear is disadvantage. Since rotor does not contain any windings, rotor of SRM can be run at high speeds.

For the operation of SRM, at a time pair of poles on the stator should be excited. This produces the flux, rotor try to align in the direction of the stator flux, by switching the phase at a time we can achieve the continuous rotation. For this switching operation of phases of SRM, many converters are available. In this paper we have considered air-conditioner application, so we are choosing simple asymmetrical converter for SRM drive. Since the excitation is DC and supply is AC needed a AC to DC converter [5-8]. A simple

AC-DC diode bridge rectifier is used in this paper. But production of power quality problems [9] due to diode bridge rectifier needs power factor correction converter which is Buck-Boost converter in this paper. The converter which is able to deliver output voltages at both higher as well as lower than (and even equal to) the input voltage is referred to as a Buck-Boost (or step-up/step-down) power converter [10]. The input current for a Buck-Boost power stage is discontinuous or pulsating due to the power switch current that pulses from zero to I_L every switching cycle [11]. The switched reluctance machine model is highly nonlinear and the process outlined in [12] has been used to aid in design. Buck-Boost converter for PFC [13] was used as a power factor corrector here. In this paper, results for SRM drive system used with both diode bridge converter and with Buck-Boost converter are compared. SRM with different conditions like SRM at starting conditions, constant DC link voltage, step change in DC link voltage and SRM with step variation in AC voltage are discussed in this paper with Matlab/Simulink models and results.

2. OPERATION OF SRM

Like all other electrical machines, SRM also consists of a stator and a rotor. Stator of SRM consists of windings but rotor will not have any windings on it. Rotor of SRM consists of just steel laminations like salient poles. Stator poles are also salient type and thus SRM can be called as doubly salient type machine. SRM works on basic principle of operation when a pair of stator poles is excited the rotor tends to align in the direction of low reluctance path provided by stator poles. Thus by sequential switching of stator poles, rotor tends to rotate producing torque. This produced torque is called reluctance torque since the rotation is produced due to reluctance.

The rotation of rotor depends on the switching sequence of excitation to the stator poles. To reduce the complexity of magnetic locking the number of rotor poles should be different to that of stator. A simple 6/4 SRM is shown in Figure 1. SRM in its operation consists of two rotor positions aligned position and unaligned position of rotor.

When the stator pair of poles are excited, produces flux and rotor tends to align to low reluctance path called aligned position of rotor. Unaligned position is the position of rotor when the rotor pole axis is not same as stator pole axis. Aligned and unaligned positions of rotor are shown in Figure 2 and Figure 3 respectively.

Figure 1. Basic diagram of SRM with 6/4 pole

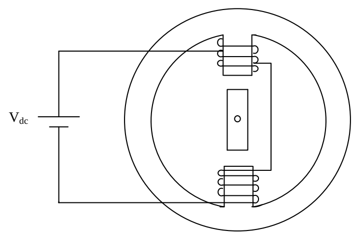

Figure 2. Basic Aligned rotor position

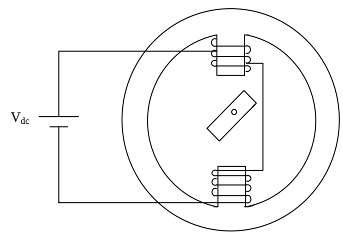

Figure 3. Basic Unaligned rotor position

3. SRM CONVERTER

To drive SRM, a converter is needed and in this paper a simple asymmetrical converter shown in Figure 4 is employed. This asymmetrical converter continuously switches the phases of stator and thus the rotor continuously rotates. Figure 4 shows the basic circuit of asymmetrical converter to drive SRM. By properly switching the switches in converter, the phase of SRM will be excited and hence rotor rotates. Controlling the switching operation controls the SRM. Switching on switches S1 and S2 energizes phase-A of SRM and similarly by proper switching switches S3, S4 and S5, S6 energizes phases B and C respectively. For current control mode, lower switch in leg will be turned ON continuously switching upper switch through the operation of one phase. Thus a 3-phase 6/4 pole SRM operates.

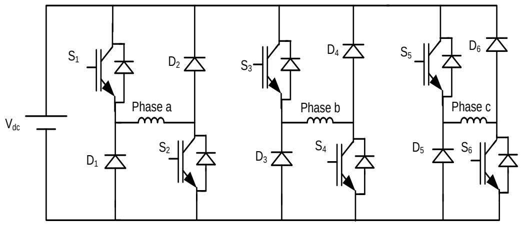

Figure 4. Asymmetrical converter of 6/4 pole SRM Drive

4. DIODE BRIDGE RECTIFIER FED SRM DRIVE

A simple block diagram of SRM drive is shown in Figure 5. The input AC supply is fed to diode bridge rectifier which converts AC-DC. A capacitor is connected at the output of rectifier to maintain constant DC voltage at the input of asymmetrical converter. The diode bridge rectifier induces harmonics in the system at the source side giving less efficiency, so needs to be controlled. Buck-Boost converter for power factor correction shown in Figure 6 is used for mitigating power quality. Buck-Boost converter consists of two number of MOSFET switches and with control strategy for PFC gives high efficiency.

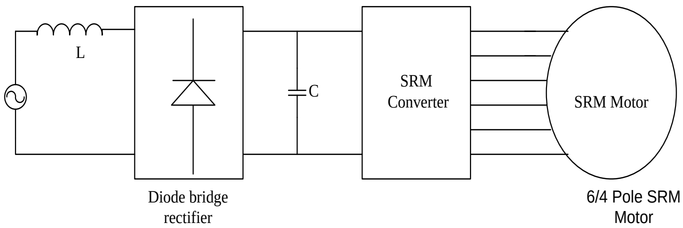

Figure 5. Block diagram of SRM Drive

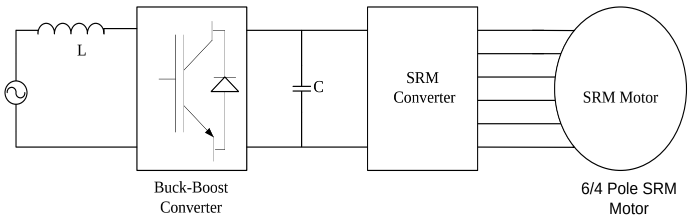

Figure 6. Proposed SRM drive

5. DESIGN OF BUCK-BOOST CONVERTER

Buck-Boost converter as shown in Figure 5(a), Buck-Boost converter switch is ON as shown in Figure 5(b), Buck-Boost converter switch is OFF as shown in Figure 5(c), and waveforms showing voltage output with change in inductor current along with change in capacitor voltage as shown in Figure 7.

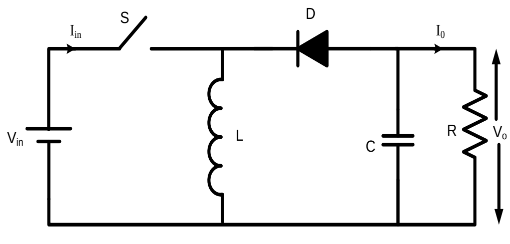

Figure 5(a). Buck-Boost converter

when switch is ON

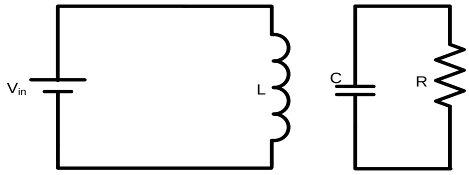

Figure 5(b). Buck-Boost converter switch is ON

$$V_{in} = L\frac{(I_2 - I_1)}{t_1} \quad ; \quad V_{in} = L\frac{\Delta I}{t_1} \; ; \qquad t_1 = \frac{\Delta I \times L}{V_{in}} \tag{1}$$

when S is OFF

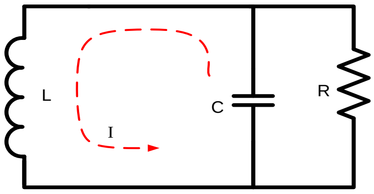

Figure 5(c). Buck-Boost converter switch is OFF

$$V_0 = -L\frac{\Delta I}{t_2}; \quad t_2 = -\frac{\Delta I \times L}{V_0} \tag{2}$$

$$T = \frac{1}{f} = t_1 + t_{2=}\frac{\Delta I \times L}{V_{in}} - \frac{\Delta I \times L}{V_0} \; ; \quad \Delta I = \frac{V_{in} \times V_0}{f.L(V_0 - V_{in})} \quad = \quad \Delta I = \frac{V_{in} \times D}{f.L} \tag{3}$$

Capacitor voltage ripple

$$\Delta V_C = \frac{I_0 t_1}{C} \Rightarrow t_1 = D.T_s \; ; \; \Delta V_C = \frac{I_0.D}{f.c} \tag{4}$$

Calculation parameters of Buck-Boost converter
Here we have considered 400W SRM drive, V_{in}=320V
V_0=200V, f_s=6kHz
Duty cycle : $\frac{V_0}{V_{in}} = \frac{D}{1-D} \Rightarrow \frac{320}{200} = \frac{D}{(1-D)}$
D=61.5%

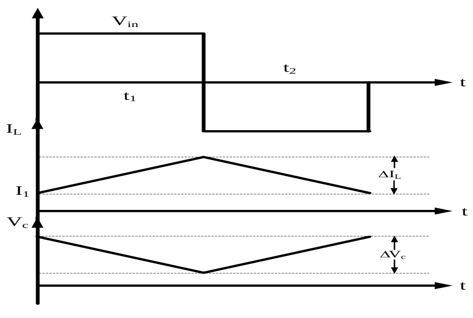

Figure 7. Waveforms Showing Voltage Output with Change in Inductor Current Along with Change in Capacitor Voltage

Calculation of Inductance:
Assuming ripple current of 5%
I_0 of SRM drive fixed at 15A
when switch is ON, inductor is carrying output current

$$\frac{I_{in}}{I_0} = \frac{D}{1-D}; \quad I_{in} = I_0 \frac{D}{1-D} = 15 \times \frac{0.615}{1-0.615} = 24A$$

$$\Delta I = \frac{V_{in} \times D}{f.L} => \quad L = \frac{V_{in} \times D}{\Delta I \times f} = \frac{320 \times 0.615}{1.2 \times 6 \times 10^3} = 27.3mH$$

Calculation of capacitance

$$\Delta V_C = 1\% \text{ of } V_0 = \frac{1}{100} \times 200 = 2$$

Assume ripple frequency 2F

$$\Delta V_C = \frac{I_0.D}{f.C} \times 2 \Rightarrow C = \frac{I_0 \times D}{f.\Delta V_c} \times 2 \Rightarrow C = \frac{15 \times 0.615 \times 2}{2 \times 6 \times 10^3} = 1537\mu F$$

Since practical capacitor exist only for rating of 2000μF
Critical Inductance to operate in DCM mode:

$$\frac{DV_{in}}{f.C} = 2 \times I_{in} \, ; R = \frac{200}{15} = \left(\frac{V}{I}\right) = 13.33\Omega$$

$$\boldsymbol{L_c = \frac{(1-D)R}{2 \times f} = \frac{(1-0.615) \times 13.33}{2 \times 6 \times 10^3} => L_c = 427\mu F}$$

6. MATEMATICAL MODELLING OF SRM DRIVE

SRM drive with diode bridge rectifier at the input side and asymmetrical converter driving SRM is shown in Figure 8. Represents the equivalent circuit of SRM of a phase as shown in Figure 9. Flux linkage to the phase controls the induced EMF in that particular phase and the flux linkage depends on current in the windings and rotor position.

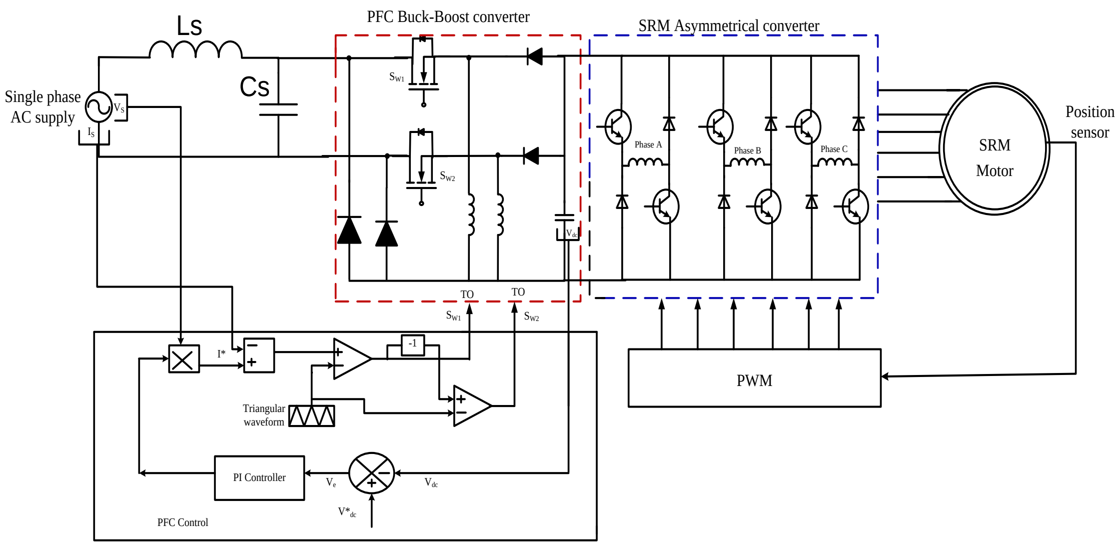

Figure 8. Control Scheme for PWM rectifier fed SRM Drive with PFC Buck-Boost converter

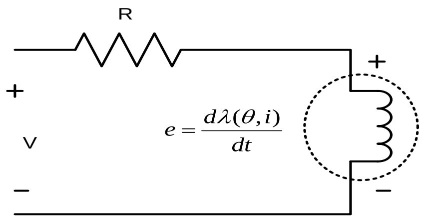

Figure 9. Equivalent circuit of switched reluctance motor

$$V = Ri + \frac{d\lambda(\theta,i)}{dt} \tag{9}$$

where V is the applied phase voltage to phase, R is the phase resistance, and e is back EMF. Ordinarily, e is the function of phase current and rotor position, and flux λ can be expressed as the product of inductance and winding current:

$$\lambda(\theta,i) = iL(\theta,i) \tag{10}$$

and from (8) the function can be rewritten as:

$$V = Ri + \frac{d\lambda(\theta,i)}{di}\frac{di}{dt} + \frac{d\lambda(\theta,i)}{d\theta}\frac{d\theta}{dt} \tag{11}$$

The general torque expression is:

$$T(\theta,i) = \frac{\partial \int_0^1 \lambda(\theta,i)}{\partial\theta} \tag{12}$$

In general, the dynamical model of a SRM is characterized by the rotor angular speed and angular position relationship:

$$\omega = \frac{d\theta}{dt} \tag{13}$$

$$\text{T-}T_{load} = J\frac{d\omega}{dt} + F\omega \tag{14}$$

$$V = Ri + L(\theta,i)\frac{di}{dt} + i_{\omega}\frac{dL(\theta,i)}{d\theta} \tag{15}$$

The average torque can be written depending on the number of phases of the SRM as:

$$\text{T}=\sum_{phase=1}^{n} T_{phase} \tag{16}$$

7. SIMULATION ANALYSIS

Table 1 gives us the data used in the simulation process and Table 2 is the data used in drive system. By using the above data simulation results were obtained. Different cases were obtained with different speeds.

Table 1. System Parameters

Parameter	Value
Power	4KW
Input Voltage	320V
Output Voltage	200V
Inductance	27.3mH
Capacitance	1537 μF
Switching Frequency	6 KHz
Duty Cycle	61.5%
Critical Inductance	427μH
Critical Capacitance	6.25 μF

Table 2. Drive Parameters

Parameter	Value
Stator Resistance	0.5Ω
Aligned Inductance	20mH
Unaligned Inductance	330 μH
Maximum Current	20A

7.1. Case 1: When rotor is rotating at 500 RPM

As case 1 we have considered the discussed Buck-Boost converter fed SRM drive running at 500 rpm. Figure 10 shows the simulation result of source voltage, source current, torque in Nm and also armature currents feeding the phases of SRM. Figure 11 shows the DC link voltage which is output of Buck-Boost converter. Even the speed of SRM drive system shown in Figure 12 is 500 rpm, the DC link voltage imaintained constant at 200 V.

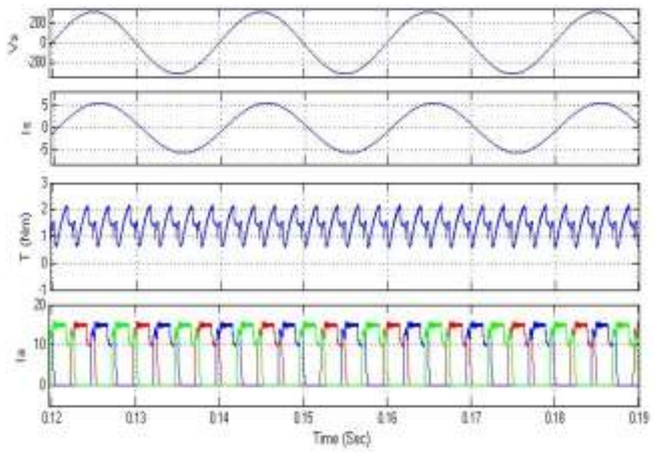

Figure 10. Simulation results of source voltage, source current, torque and armature currents

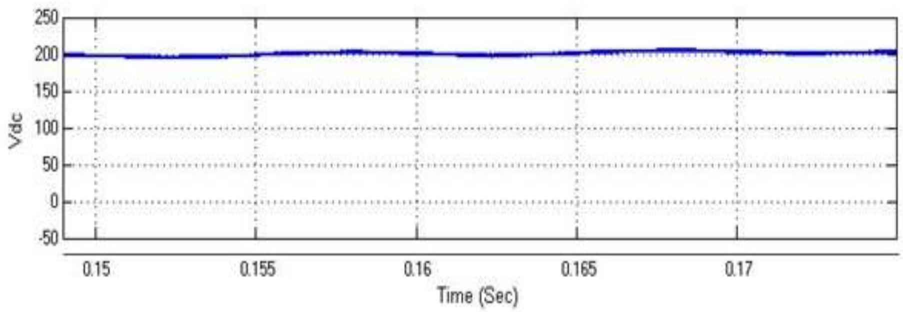

Figure 11. Simulation results of DC link voltage when speed is 500 rpm

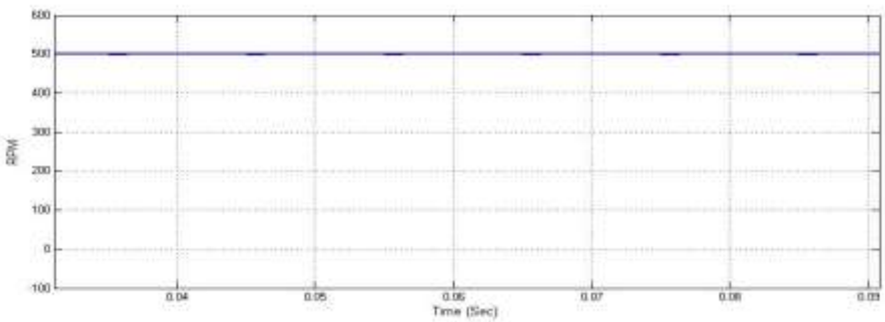

Figure 12. Simulation results of speed

Figure 13 shows the power factor with voltage and current being in phase maintaining unity. We can observe there are no disturbances in source voltage and source current which are in-phase thus maintaining the power factor nearer to unity. THD in Figure 14 is observed to be 0.20% which is very less. Buck-Boost converter acting as PFC with control strategy regulates the source voltage and current when SRM is running at 500 rpm.

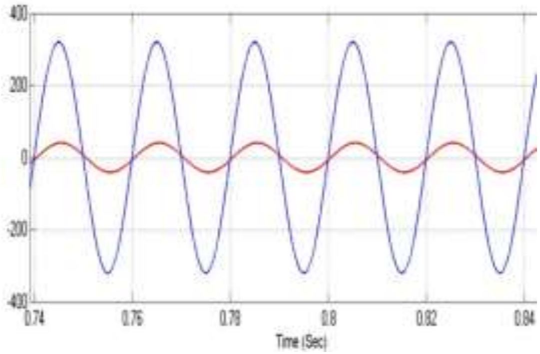

Figure 13. Simulation results of power factor with voltage and current signal

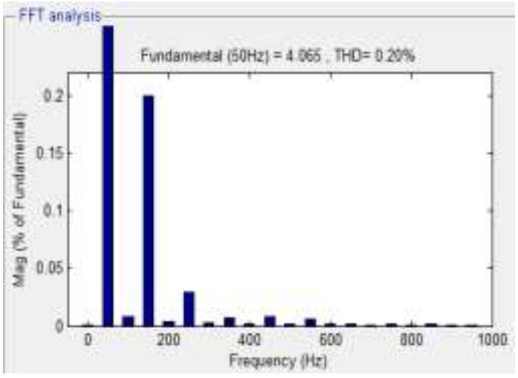

Figure 14. Simulation results THD when the speed is 500 rpm

7.2. Case 2: When rotor is rotating at 1000 RPM

As case 2 we have considered the discussed Buck-Boost converter fed SRM drive running at 1000 rpm. Figure 15 shows the simulation result of source voltage, source current, torque in Nm and also armature currents feeding the phases of SRM.

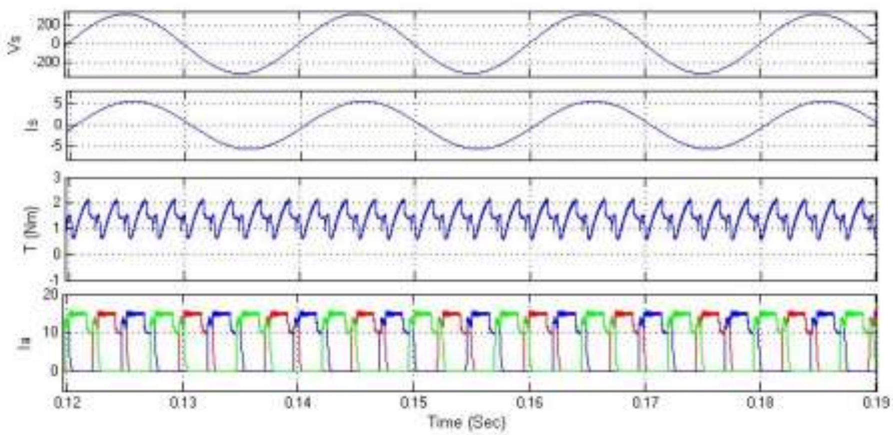

Figure 15. Simulation results of source voltage, source current, torque and armature currents

The DC link voltage which is output of Buck-Boost converter as shown in Figure 16. Even the speed of SRM drive system shown in Figure 17 is 1000 rpm; the DC link voltage is maintained constant at 200 V. We can observe there are no disturbances in source voltage and source current which are in-phase thus maintaining the power factor nearer to unity. THD shown in Figure 18 is observed to be 0.53% which is less and accepTable. Buck-Boost converter acting as PFC with control strategy regulates the source voltage and current when SRM is running at 1000 rpm.

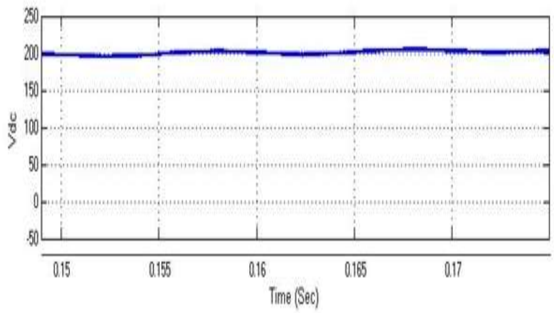

Figure 16. Simulation results of DC link voltage when speed is 1000 rpm

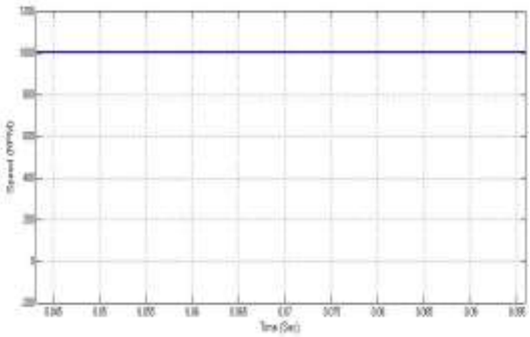

Figure 17. Simulation results of speed

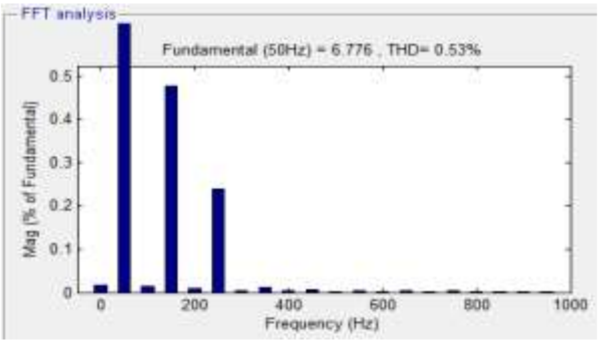

Figure 18. Simulation results THD when the speed is 1000 rpm

7.3. Case 3: When rotor is rotating at 1500 RPM

As case 3 we have considered the discussed Buck-Boost converter fed SRM drive running at 1500 rpm. Figure 19 shows the simulation result of source voltage, source current, torque in Nm and also armature currents feeding the phases of SRM. Figure 20 shows the DC link voltage which is output of Buck-Boost converter. Even the speed of SRM drive system shown in Figure 21 is 1500 rpm; the DC link voltage is maintained constant at 200 V. We can observe there are no disturbances in source voltage and source current which are in-phase thus maintaining the power factor nearer to unity. THD shown in Figure 22 is observed to be 0.38%. Buck-Boost converter acting as PFC with control strategy regulates the source voltage and current when SRM is running at 1500 rpm.

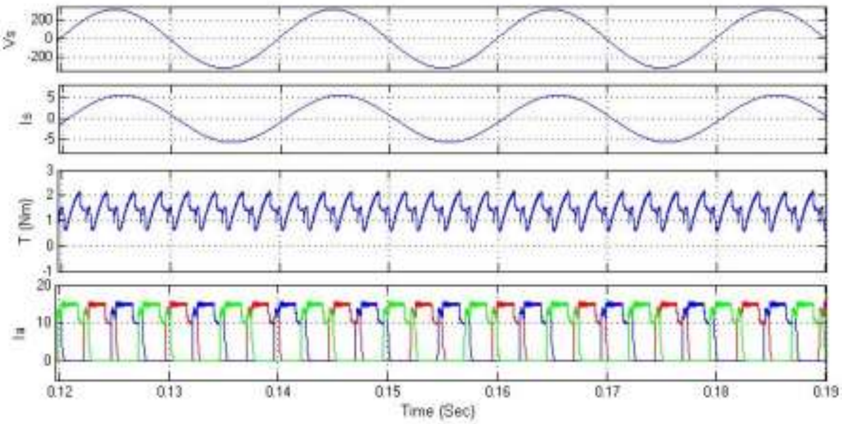

Figure 19. Simulation results of source voltage, source current, torque and armature currents

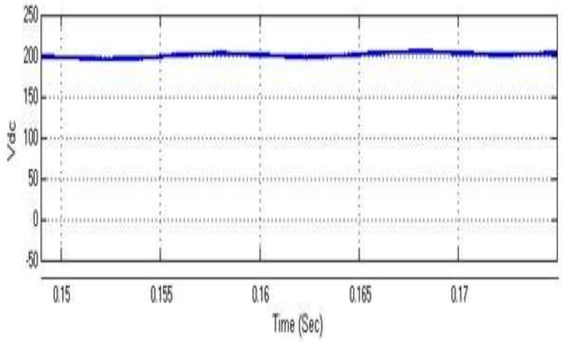

Figure 20. Simulation results of DC link voltage when speed is 1500 rpm

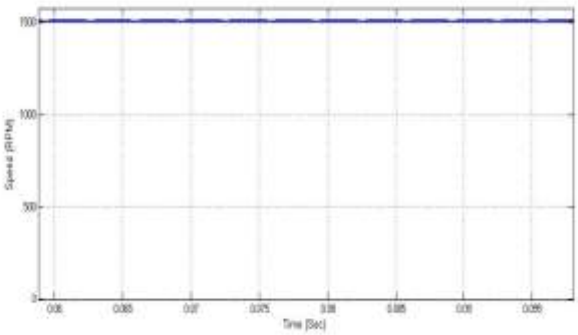

Figure 21. Simulation results of speed

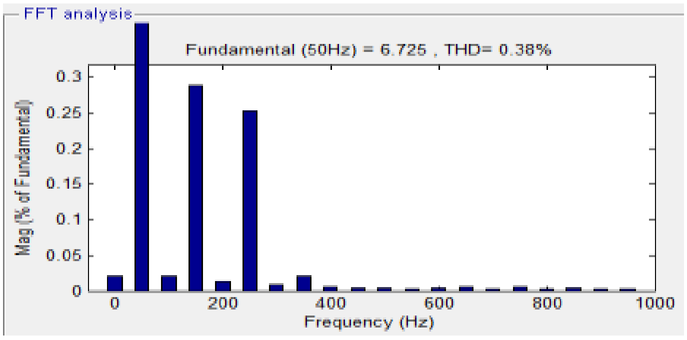

Figure 22. Simulation results THD when the speed is 1500 rpm

7.4. Case 4: When rotor is rotating at 2000 RPM

As case 4 we have considered the discussed Buck-Boost converter fed SRM drive running at 2000 rpm. Figure 23 shows the simulation result of source voltage, source current, torque in Nm and also armature currents feeding the phases of SRM. Figure 24 shows the DC link voltage which is output of Buck-Boost converter and the speed at which the motor is rotating. Even the speed of SRM drive system shown in Figure 24 is 2000 rpm; the DC link voltage is maintained constant at 200 V. We can observe there are no disturbances in source voltage and source current which are in-phase thus maintaining the power factor nearer to unity. Buck-Boost converter acting as PFC with control strategy regulates the source voltage and current when SRM is running at 2000 rpm. Figure 25 shows the Simulation results of current through inductor 1 and inductor 2, voltage across switches and current through switches 1 and 2. This switching is same for all the discussed cases. THD shown in Figure 26 is observed to be 0.26%.

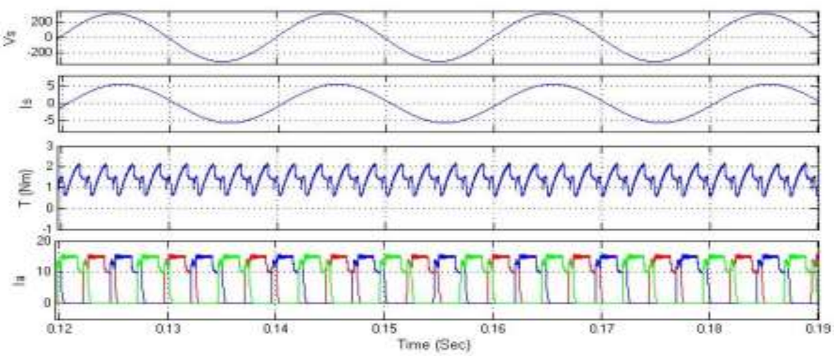

Figure 23. Simulation results of source voltage, source current, torque and armature currents

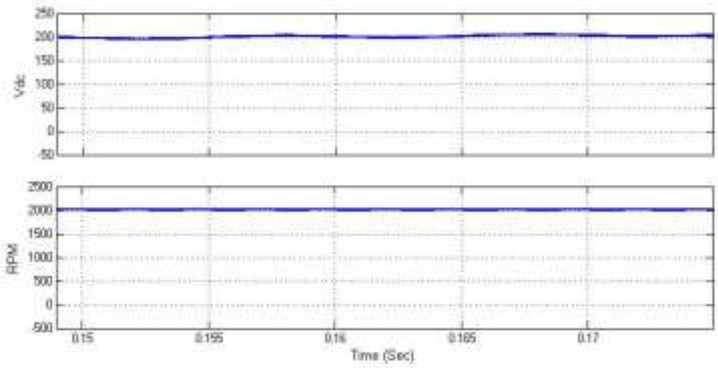

Figure 24. Simulation results of DC link voltage and speed

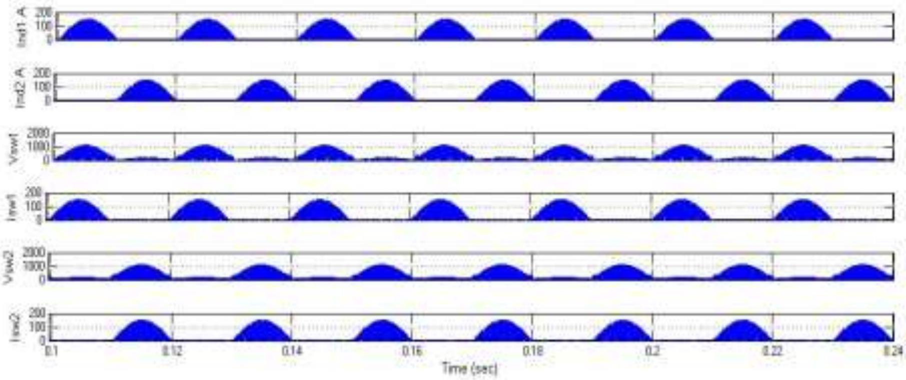

Figure 25. Simulation results of current through inductor 1 and inductor 2, voltage across switches and current through switches 1 and 2

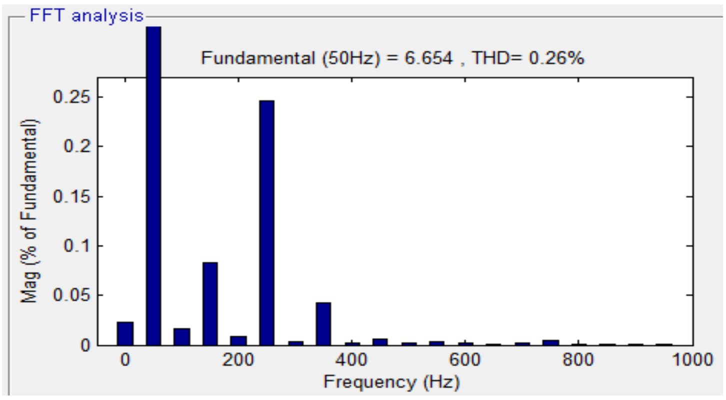

Figure 26. Simulation results THD when the speed is 2000 rpm

7.5. Case 5: With input AC variation

As case 5 we have considered the discussed Buck-Boost converter fed SRM drive running at 2000 rpm with variation in input. We can observe the change in input voltage decreases with increase in current. Figure 27 shows the simulation result of source voltage, source current Figure 28 shows torque in Nm and also armature currents feeding the phases of SRM. Figure 29 shows the DC link voltage which is output of Buck-Boost converter and the speed at which the motor is rotating. Even the speed of SRM drive system is 2000 rpm with change in input; the DC link voltage is maintained constant at 200 V.

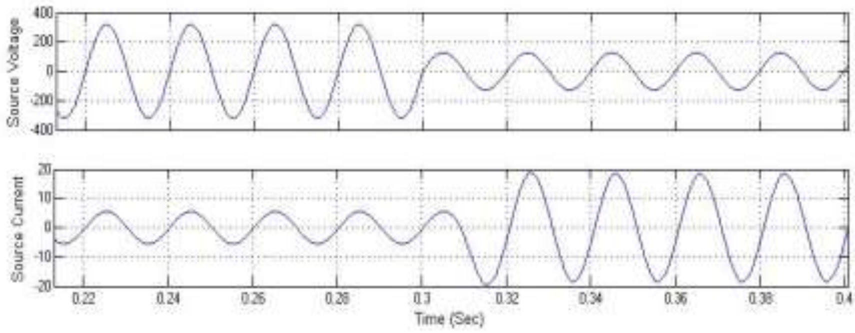

Figure 27. Simulation results of source voltage, source current

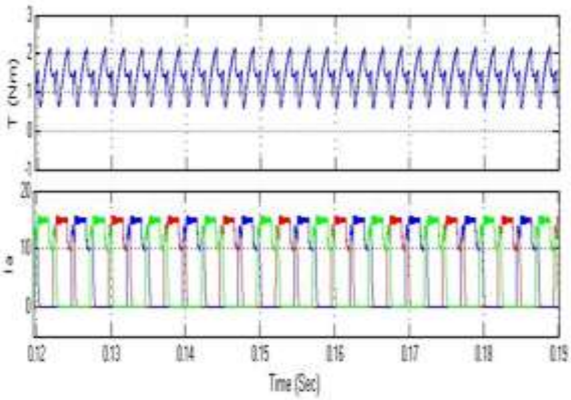

Figure 28. Simulation results of torque and armature currents

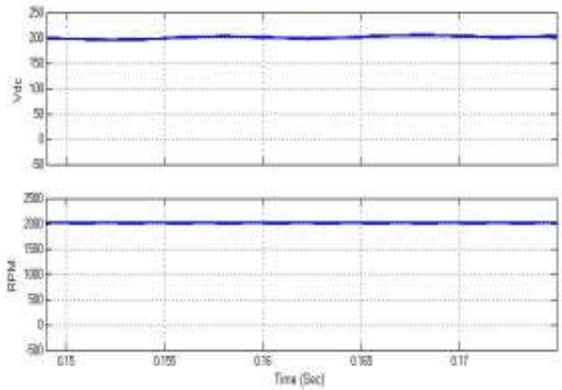

Figure 29. Simulation results of DC link voltage and speed

We can observe there are no disturbances in source voltage and source current which are in-phase thus maintaining the power factor in Figure 30 nearer to unity. THD in Figure 31 is found to be 0.78%. Buck-Boost converter acting as PFC with control strategy regulates the source voltage and current when SRM is running at 2000 rpm with change in input. The comparison of THD for different conditions were shown in Table 3.

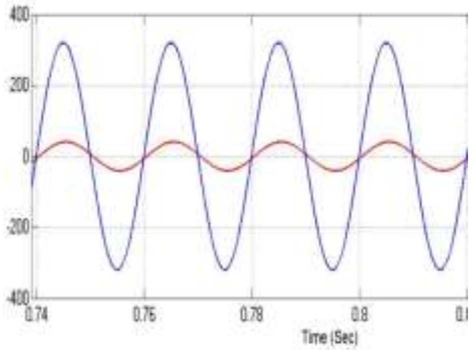

Figure 30. Simulation results of power factor with voltage and current signal

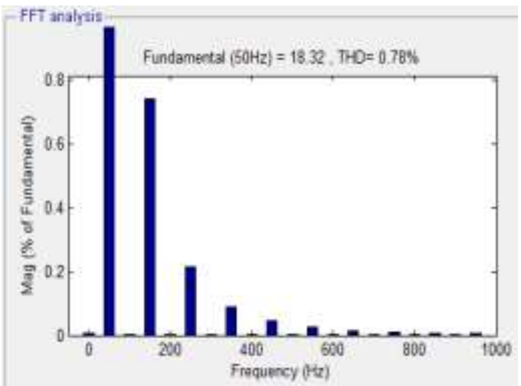

Figure 31. Simulation results THD when there is input variation

Table 3. Comparison of THD’s for different conditions

Condition	THD
When speed is 500 rpm	0.20%
When speed is 1000 rpm	0.53%
When speed is 1500 rpm	0.38%
When speed is 2000 rpm	0.26%
When there is input variation with speed 2000 rpm	0.78%

8. CONCLUSION

Maintain power factor is very much important in the present pollutant systems. The pollution is produced in the power system network when non-linear loads are connected. When drive system is connected, this induces harmonics which are not desirable. Here in this paper when SRM drive system is connected the power factor correction is done with the help of converter which is used to drive SRM. The converter switches the phases of SRM and thus SRM produces continuous torque. Here we have employed a Buck-Boost converter to drive SRM and also as power factor correction. By employing a suiTable control strategy for Buck-Boost converter, power factor correction was done. This system is validated with the results considering different cases with different SRM drive speeds and with input variation. THD is found to be very less for different conditions and THD were shown for all cases. Power factor was maintained nearer to unity and shown. Results were obtained using Matlab/Simulink and the results for different cases were validated maintaining constant output of Buck-Boost converter, nothing but DC link voltage when drive system speed was changed.

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