Three Phase Double Boost PFC Rectifier Fed SRM Drive

M. Rajesh [1] B. Singh [2]

Abstract: **This paper deals with a three phase double boost PFC(power factor correction) rectifier fed SRM (Switched Reluctance Motor) drive. The proposed system consists of two boost converters with DC outputs connected in series to feed a midpoint converter fed SRM drive. This system needs only two active switches at rectifier side and a midpoint converter needs only one active switch per phase. Besides, it provides balanced DC link capacitor voltages with improved power quality at AC mains. The proposed three phase double boost PFC rectifier fed SRM drive is designed, modeled and its performance is simulated in MATLAB/Simulink. The performance of proposed system is compared with a six pulse diode bridge converter fed SRM drive.**

Keywords–Midpoint converter, power quality, switched reluctance motor, Boost PFC rectifier, Scott transformer.

I. INTRODUCTION

A switched reluctance motor (SRM) has the simplest construction and is economical among other electrical motors. It has several advantages as a variable speed drive as it can operate in wide speed range. However SRM cannot be operated directly from AC or DC supply, it requires power converts for its operation. The most commonly used converter is a midpoint converter since only one switch per phase is needed thus reducing the cost of drive [1]. All these converters need DC supply or AC supply with a rectifier. Fig.1 shows six pulses diode bridge rectifier fed midpoint converter based SRM drive. The disadvantage of this configuration is that it generates harmonics to the AC mains with low input power factor.

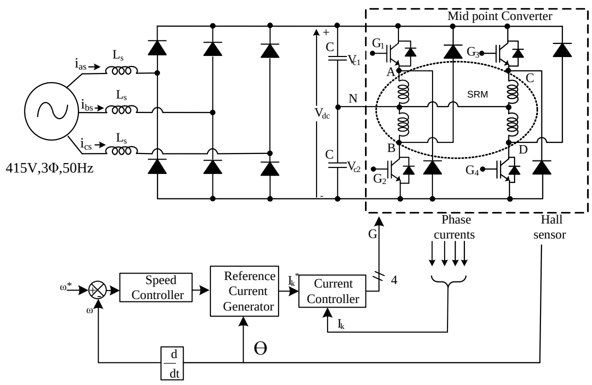

Fig.1: Six pulse diode bridge rectifier fed SRM drive

Three phase active PFC boost rectifiers are preferred in industries due to their high efficiency, low EMI emission and improved power quality at AC mains. Most commonly used PFC boost rectifiers are multilevel boost rectifier, Vienna rectifier and third harmonic modulated rectifiers. Different configurations of multilevel rectifiers are given in [2-5]. Multilevel reduce the voltage stress across active switches and operate at lower frequencies. However, these rectifiers need more number of active switches and control of capacitor voltages becomes difficult with increase in levels. A simple three phase NPC three level rectifier needs twelve active switches. The multilevel rectifiers are capable of operating in all four quadrants [6]. Vienna rectifier [7-12] is a boost rectifier which requires only three active switches and its control is simple. This rectifier has short circuit immunity to failure of control circuit, immunity towards voltage unbalance and voltage variations. Third harmonic modulated rectifier is explained in [13-15]. It consists of third harmonic current injection network to inject third harmonic current at AC side of rectifier to improve power quality at AC mains.

Minnesota rectifier [16] is one of the most commonly used rectifier which uses third harmonic current injection technique. This rectifier needs only two active switches and a zig zag transformer is used to inject third harmonic current at AC side of rectifier. All these converter topologies do not provide isolation. However in many applications isolation is required between AC mains and the drive.

Three phase double boost PFC rectifier fed midpoint converter based SRM drive is recommended in this paper for improving power quality at AC mains. In this system the outputs of two single phase boost PFC rectifier are connected in series to form split DC bus voltage. The input of these boost rectifiers is connected to Scott connected transformer which provides isolation. The voltage stress on the active switches and the diodes of this boost rectifier is equal to half of DC link voltage. The proposed SRM drive is designed, modeled and its performance is simulated using MATLAB/Simulink environment and the performance is also compared with a conventional six pulse diode bridge rectifier fed SRM drive. The power quality of the proposed drive system is found within IEEE 519 standard limit [17].

II. SYSTEM CONFIGURATION

The schematic diagram of three phase double boost PFC rectifier fed midpoint based SRM drive is shown in Fig.2a. Two single phase AC supplies with 90^0 phase shift are obtained from Scott connected transformer and given to two single phase boost rectifier. The outputs of single phase boost rectifiers are connected in series and form split DC bus voltages which are connected to a midpoint converter based SRM drive. The connection diagram and phasor diagram of Scott connected transformer is shown in Fig.2b. Two single phase transformers are used to obtain three phase to two single phase conversion. One of the transformers is called teaser transformer and has the turns ratios of 0.866V:V_1 and other transformer called main transformer has midpoint at primary winding having turns ratio of 0.5V - 0.5V:V_2. Where V is the magnitude of

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[1] Department of Electrical Engineering, Indian Institute of Technology Delhi, E-mail: mrajeshkerala@gmail.com
[2] Department of Electrical Engineering, Indian Institute of Technology Delhi E-mail: bsingh@ee.iitd.ac.in

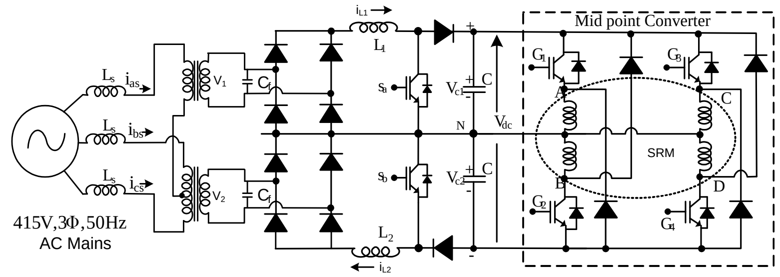

Fig.2 (a): Three phase double boost PFC rectifier fed SRM drive diagram

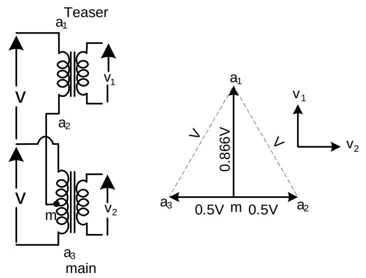

Fig.2 (b): Scott connected transformer and its phasor

supply line voltage, V_1 and V_2 are secondary voltages of

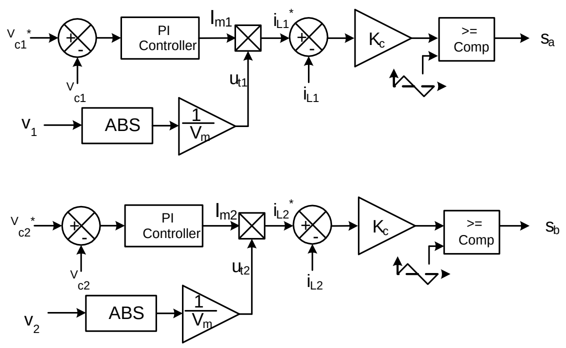

Fig.2 (c): Control of three phase double boost PFC rectifier

the transformers. Two single phase boost rectifiers are controlled independently by sensing their inductor currents. A small rating capacitor C_f is connected at the secondary terminals to eliminate higher order harmonics.

III. Design of Three Phase Double Boost PFC Rectifier

Three phase double boost PFC rectifier consists of a two single phase transformers, two boost inductors, two DC link capacitors, two active switches and ten diodes. The design of proposed converter system is explained below.

A. *Design of Boost Inductor*

For a 4kW, 8/6 pole SRM drive, an input power is considered as 4.4kW including losses. The value of boost inductor ($L=L_1=L_2$) is calculated as [18],

$$L = \frac{V_{in} D}{\Delta I f_s} \tag{1}$$

where V_{in} and D are defined as,

$$V_{in} = \frac{2\sqrt{2}V_1}{\pi} \tag{2}$$

$$D = \frac{V_{c1} - V_{in}}{V_{c1}} \tag{3}$$

where V_{in} is the DC output voltage of bridge rectifier, V_1 is the secondary terminal voltage of transformer, D is duty ratio, ΔI is the inductor ripple current, V_{c1} is the output voltage of boost rectifier and f_s is switching frequency.

The input power 4.4kW is shared by PFC boost rectifier equally. Hence the supply current drawn by the boost rectifier with transformer secondary voltages $V_1 = V_2 = 180V$ is calculated as,

$$I = \frac{P_{boost}}{V_1} = \frac{2200}{180} = 12.22A \tag{4}$$

Since same current flows through inductor the ripple current (ΔI) in the inductor at 12% ripple is calculated as,

$$\Delta I = 10\% \times I = 1.222A \tag{5}$$

Taking duty switching frequency f_s as 20 kHz, DC link voltage V_{dc} as 560V and V_{c1} as 280V ($V_{dc}/2 = 560/2$), from eqns. (1-5), the obtained value of boost inductor is L is 2.8mH, hence L_1 and L_2 are selected as $L_1 = L_2 = 3mH$.

B. *Design of Capacitor*

To assure DC link voltage within limit for three phase double boost PFC rectifier the DC link capacitor (C_1, C_2) is calculated as [18],

$$C_1 = C_2 = \frac{I_d}{2\omega \Delta V_{c1}} \tag{6}$$

where ΔV_{c1} is the ripple voltage across capacitor, $\omega = 2nf$ is angular frequency of supply voltage and f is supply frequency and I_d is DC link current.
DC link current I_d is calculated as,

$$I_d = \frac{P_{in}}{V_{dc}} \tag{7}$$

Taking P_{in} as 4.4kW, V_{dc} as 560V, f as 50Hz and ΔV_{c1} as 2% of V_{c1}, the obtained value of I_d is 7.851A and obtained value of C_1 is 2233µF, hence C_1 and C_2 are selected as 2200µF.

C. *Design of Transformer*

For converting three phase 415V AC mains to two single phase voltages of each of 180V, the required turns ratio(n_1, n_2) of single phase transformers needed for Scott's connection is calculated as,

$$\text{Teaser transformer } n_1 = \frac{0.866V}{V_1} \tag{8}$$

Main transformer $n_2 = \dfrac{0.5V - 0.5V}{V_2}$ (9)

where V is the AC mains voltage, V_1 and V_2 are secondary voltage of transformers, with V = 415V and $V_1 = V_2$ as 180V, the calculated value of turns ratio are n_1 = 359.5/180 and n_2 = 207.5-207.5/180.

IV. CONTROL OF THREE PHASE DOUBLE BOOST PFC RECTIFIER FED SRM DRIVE

The control algorithm of three phase double boost PFC rectifier is shown in Fig.2c. The boost rectifiers are controlled independently by sensing boost inductor current. The gate signals are generated by carrier based PWM controller. Each boost rectifier consists of capacitor voltage controller, reference boost inductor current estimator and boost inductor current controller.

A. Capacitor Voltage Controller

The reference capacitors voltages (V_{c1}^* and V_{c2}^*) of two boost PFC rectifier are compared with the sensed capacitors voltages (V_{c1} and V_{c2}). The resulting capacitors voltage errors (V_{c1e} and V_{c2e}) at nth instant are given as,

$$V_{c1e}(n) = V_{c1}^*(n) - V_{c1}(n) \quad (10)$$

$$V_{c2e}(n) = V_{c2}^*(n) - V_{c2}(n) \quad (11)$$

The PI (Proportional Integral) voltage controllers are used to get reference currents I_{m1}^* and I_{m2}^* and are given at nth sampling instant as,

$$I_{m1}^*(n) = I_{m1}^*(n-1) + K_{p1}\{V_{c1e}(n) - V_{c1e}(n-1)\} + K_{i1}V_{c1e}(n) \quad (12)$$

$$I_{m2}^*(n) = I_{m2}^*(n-1) + K_{p1}\{V_{c2e}(n) - V_{c2e}(n-1)\} + K_{i1}V_{c2e}(n) \quad (13)$$

where the outputs of capacitor voltage controllers at nth are $I_{m1}^*(n)$ and $I_{m2}^*(n)$ and for (n-1)th instant are $I_{m2}^*(n\text{-}1)$ and $I_{m2}^*(n\text{-}1)$. These capacitors voltage error at nth instant is given by $V_{c1e}(n)$ and $V_{\backslash c2e}(n)$ and for (n-1)th sampling instant are $V_{c1e}(n\text{-}1)$ and $V_{\backslash c2e}(n\text{-}1)$; K_{p1} and K_{i1} are proportional and integral gains of the DC capacitor voltage controllers.

B. Reference Boost Inductor Current Estimation

Unit templates of secondary side voltage of Scott's transformer are given as,

$$u_{t1}(\omega t) = \frac{abs(v_1(\omega t))}{V_m} = |\sin(\omega t)|;$$
$$u_{t2}(\omega t) = \frac{abs(v_2(\omega t))}{V_m} = |\sin(\omega t - 90^0)| \quad (14)$$

where V_m is the amplitude of transformer secondary voltages.

The reference inductors currents (i_{L1}^* & i_{L2}^*) are estimated as,

$$i_{L1}^* = I_{m1}^* u_{t1}(\omega t) \text{ and } i_{L2}^* = I_{m2}^* u_{t2}(\omega t) \quad (15)$$

C. Boost Inductor Current Controller

Fig.2c shows the controller of the three phase double boost PFC rectifier. The reference boost inductor currents are compared with sensed currents and the current error is processed through a proportional current controller of gain K_c. This output of current controller is fed to the carrier based PWM generator. The carrier based PWM generator consists of a comparator and a triangular carrier wave of 20kHz. The output of current controller is compared with carrier wave to generate PWM signal and given to switches S_a and S_b.

V. CONTROL OF SRM

The rotor speed of SRM is compared with reference speed and the speed error is processed through a speed proportional integral (PI) controller. The error speed ($\Delta\omega_e$) at nth instant is given as,

$$\Delta\omega_e(n) = \omega_e^*(n) - \omega_e(n) \quad (16)$$

The PI speed controller generates reference motor current magnitude I* and at nth sampling instant the magnitude of reference current is given as,

$$I^*(n) = I^*(n-1) + K_{p2}\{\omega_e(n) - \omega_e(n-1)\} + K_{i2}\omega_e(n) \quad (17)$$

where $I^*(n)$ and $I^*(n\text{-}1)$ are magnitude of reference phase current of SRM at nth and (n-1)th sampling instants. K_{p2} and K_{i2} are proportional and integral gain constants of the PI speed controller. This reference current magnitude is given to reference current generator. The reference current generator generates all four phases reference currents by multiplying unit pulse obtained from Hall effect position sensors.

Reference current of kth phase of SRM is given as,

$$I_k^* = I^* U_k \quad (18)$$

where U_k is unit pulse of k^{th} phase obtained from the information of Hall effect position sensor, turn on and turn off angles.

The phase currents SRM windings are compared with generated reference currents and given to the hysteresis current controller. The output of hysteresis current controller is used for gating insulated gate bipolar transistors IGBT (G_1) - IGBT (G_4) of a midpoint converter.

The angle where the IGBT of the phase of SRM is excited is called turn on angle (Θ_{on}) and the angle at which IGBT of the phase of SRM winding is turned off is called turn off angle (Θ_{off}). If the phase commutation is made faster by adjusting Θ_{on} and Θ_{off}, the current in the winding increases at minimum inductance position and thereby getting the advantage of reducing the current before the rotor reaches the negative torque region. This is achieved by advancing Θ_{on} by an advance angle (Θ_{adv}) from the position Θ_m where the inductance starts increasing. The

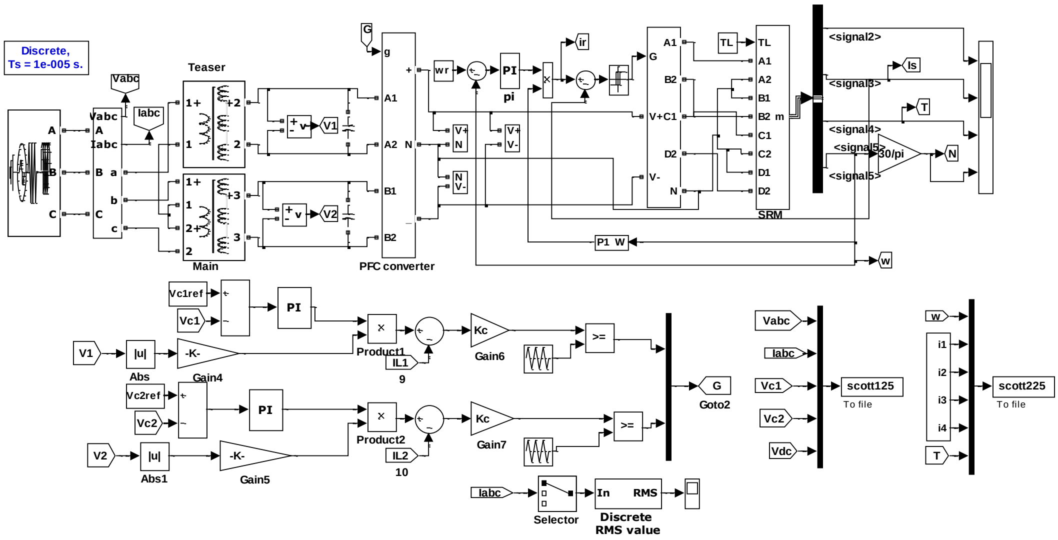

Fig.3. Matlab model of three phase double boost PFC rectifier fed SRM drive.

advance angle (Θ_{adv}) is calculated as per following equation.

Near turn on the voltage - Ampere equation can be approximated as,

$$V_{c1} = \frac{\partial \varphi}{\partial i}\frac{di}{dt} = L_u \frac{di}{dt} \tag{19}$$

Using first order approximations, (19) can be written as,

$$V_{c1} = L_u \frac{di}{d\theta}\frac{d\theta}{dt} = L_u \frac{di}{d\theta}\omega \tag{20}$$

(18) is used for calculating advance angle, Θ_{adv} as,

$$\theta_{adv} = \frac{L_u i_p}{V_{C1}}\omega \tag{21}$$

where L_U is the unaligned inductance, V_{c1} $(=V_{dc}/2)$ is the applied voltage across a phase of SRM, ω angular speed and i_p is the desired phase current of SRM for obtaining required torque.

Turn on angle (Θ_{on}) to achieve desired phase current i_p at Θ_m is given as,

$$\theta_{on} = \theta_m - \theta_{adv} \tag{22}$$

VI. MATLAB BASED MODELING OF PROPOSED SRM DRIVE

The developed MATLAB/Simulink model of three phase double boost PFC rectifier fed midpoint convert based SRM drive is shown in Fig.3. A filter capacitor is used at line to reduce higher order harmonics. Three phase 415 V, 50 Hz AC supply voltage is fed to a three phase double boost PFC rectifier based SRM drive. The reference DC link capacitor voltages (V_{c1}, V_{c2}) are selected as 280V and the reference speed (ω_r) is considered as 157.08rad/sec. The rating of SRM and other data are given in Appendix. The data of SRM motor used in this simulation is obtained from experimental data of 4kW, 8/6 pole, 1500rpm. Turn on angle is selected as per (21-22).

VII. RESULTS AND DISCUSSION

The performance of proposed three phase double boost PFC rectifier fed midpoint convert based SRM drive is simulated and the performance is compared with a conventional six pulse diode bridge converter fed SRM drive. The simulated results are shown in Fig.4a-5e , V_{sph} and I_s represent AC mains phase voltage and line currents. I_a represents line current of AC mains phase A. $I_1 - I_4$ represents the phase currents of SRM. ω is motor speed in rad/sec and T is the developed motor torque in Nm. Simulated results of six pulse bridge rectifier fed SRM drive at 25Nm load torque are shown in Fig.4a-4b. The simulated results show that at rated load torque, the supply current THD is 61.7%, CF (crest factor) is 2.1754 and the supply rms current(I_{rms}) is 6.9A. Hence the supply current THD and CF of six pulse rectifier fed SRM drive are very high which are not within the limits of IEEE -519 standard [17].

Simulated results of the proposed three phase double boost PFC rectifier fed SRM drive at rated load torque of 25Nm are shown in Figs.5a-5b. The steady state response at rated load is shown in Fig.5a and its harmonic spectrum of supply current is shown in Fig.5b. Simulated results of the proposed drive system show that at rated load the supply current THD is 2.04%, CF(crest factor) is 1.4224 and the supply rms current(I_{rms}) is 6.05A. Simulated results of the proposed SRM drive at 20% rated load torque of 5Nm are shown in Figs.5c-5d. Simulated results show that at 20% of rated load torque the supply current THD is 4.23%, CF(crest factor) is 1.3928 and the supply rms current(I_{rms}) is 2.15A. Hence these results show that the THD and CF of AC mains current for the proposed drive are within IEEE - 519 standard limit [17]. Fig.5e shows the dynamic response of proposed drive. Steady state operation is reached in 0.255s and the starting current is well within the limit.

Table 1 shows the performance of six pulse diode bridge converter fed SRM drive at different loads. It is seen that the THD and CF of AC mains current of six pulse diode bridge converter fed SRM shown are very high and power factor is very low even at full load. Table 2 shows the performance of proposed three phase double boost PFC rectifier fed SRM drive at different loads. It is observed that the THD and CF of AC mains current of proposed drive are well within the limit for all loads and the power factor is also very high even at light loads.

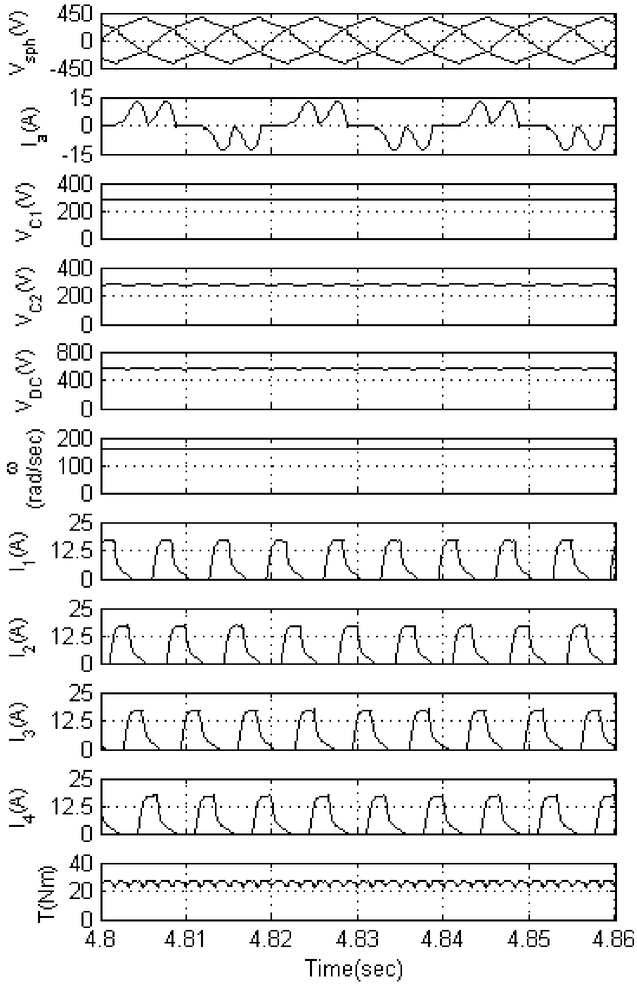

Fig.4 (a): Steady state response of six pulse AC-DC converter fed SRM drive at rated torque of 25Nm.

VIII. CONCLUSION

The proposed three phase double boost PFC rectifier fed midpoint converter based SRM drive has been designed and modeled using MATLAB/Simulink environment. The performance of proposed SRM drive has been compared with a six pulse converter fed SRM drive. A three phase double boost PFC rectifier fed SRM drive along with capacitor filter on secondary winding of the transformer has reduced the THD of supply current to less than 5%. The THD and CF of AC supply current have been maintained within IEEE - 519 standard limit even with 20% rated load torque with a high power factor. The dynamic response of the proposed three phase double boost PFC rectifier fed SRM drive has shown the smooth operation which is required in many industrial applications. The ripple in DC link voltage is found negligible and the voltages across the capacitors are found well balanced which is needed for smooth operation of SRM.

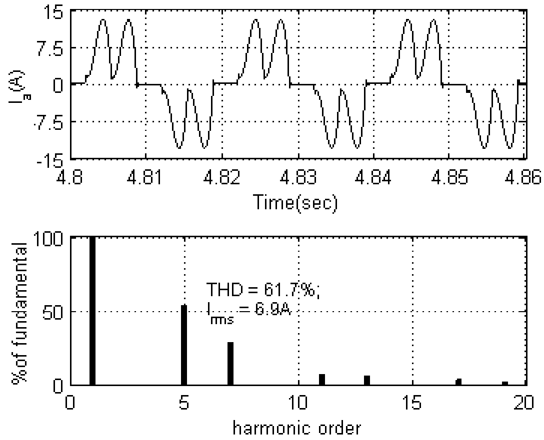

Fig.4 (b): Harmonic spectrum of six pulse AC-DC converter fed SRM drive at rated torque of 25Nm.

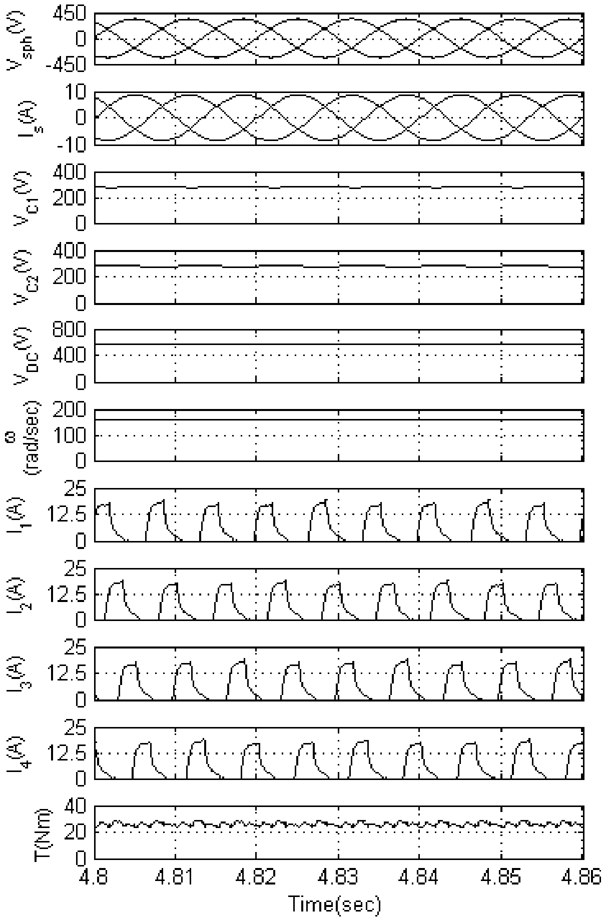

Fig.5 (a): Steady state response of three phase double boost PFC rectifier fed SRM motor drive at rated torque of 25Nm.

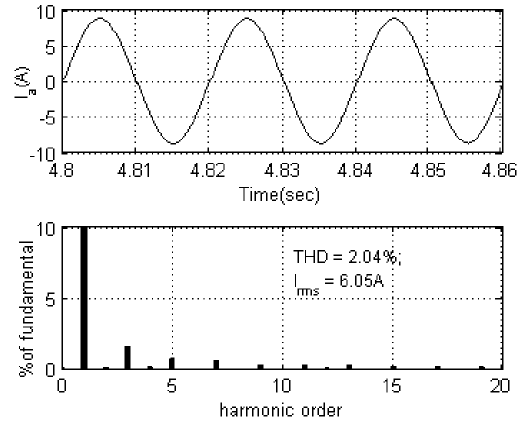

Fig.5 (b): Harmonic spectrum of three phase double boost PFC rectifier fed SRM motor drive at rated torque of 25Nm.

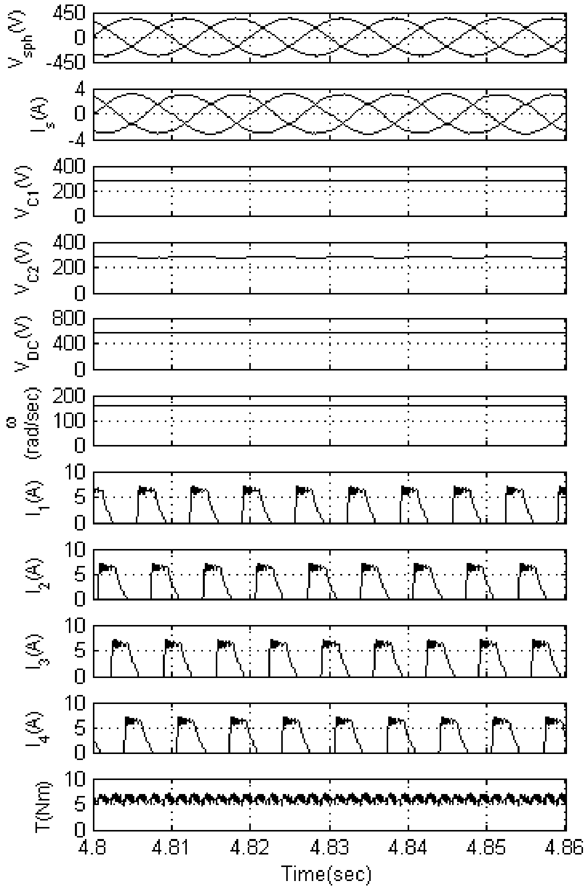

Fig.5 (c): Steady state response of three phase double boost PFC rectifier fed SRM motor drive at 20% rated torque of 5Nm.

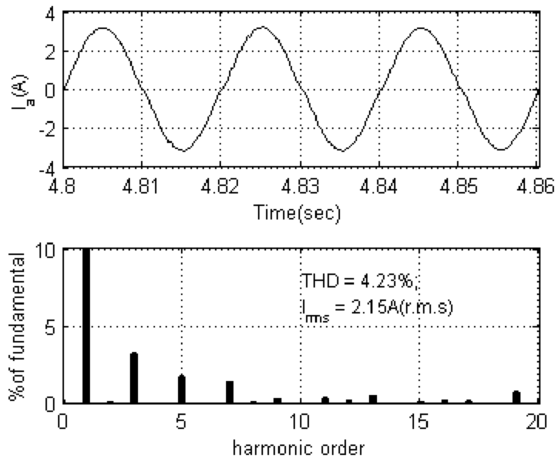

Fig.5 (d): Harmonic spectrum of three phase double boost PFC rectifier fed SRM motor drive at 20% rated torque of 5Nm

Table 1: Performance of six pulse AC-DC converter FED SRM drive at varying load torque at 415V supply voltage

T_L(N.m)	THD %	I_{rms} (A)	CF	DPF	DF	PF
5	91.43	2.81	2.8675	1	0.405	0.405
10	83.47	3.85	2.6378	1	0.551	0.5507
15	77.18	4.90	2.4852	1	0.636	0.6359
20	70.07	5.93	2.3270	1	0.713	0.7135
25	61.70	6.90	2.1754	1	0.787	0.787

Table 2: Performance of three phase double boost PFC rectifier FED SRM motor drive at varying load torque at 415V supply voltage

T_L(N.m)	THD %	I_{rms} (A)	CF	DPF	DF	PF
5	4.23	2.15	1.39276	1	0.999	0.999
10	3.20	3.00	1.35878	1	0.999	0.999
15	2.65	4.00	1.41343	1	1.000	1.000
20	2.30	5.00	1.40562	1	1.000	1.000
25	2.04	6.05	1.42243	1	1.000	1.000

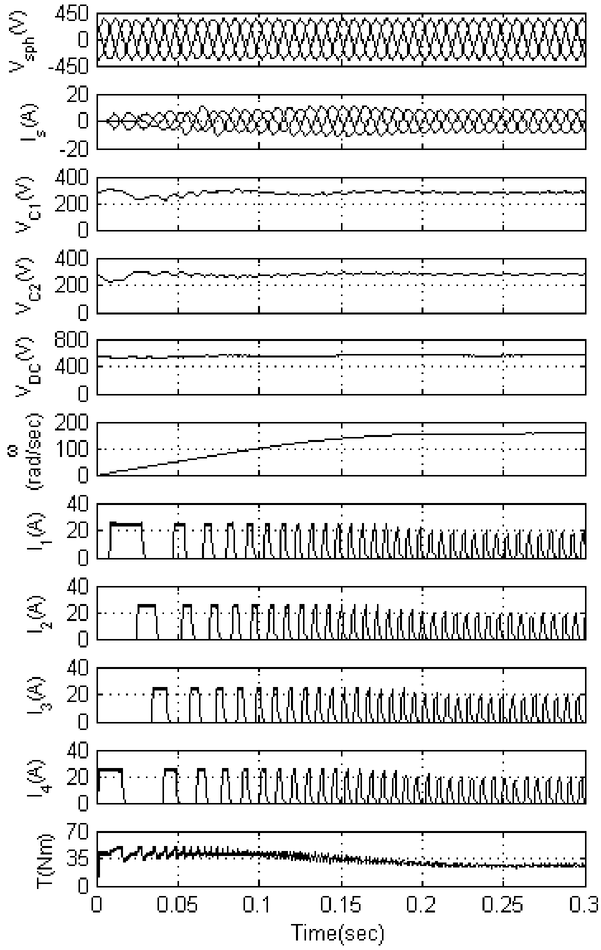

Fig.5 (e): Dynamic response of three phase double boost PFC rectifier fed SRM motor drive at rated torque of 25Nm.

APPENDIX

Switched Reluctance Motor Specifications:
4kW, 8/6pole, 1500rpm, R (Phase Resistance) =0.7 Ω, L_u (unaligned inductance) = 12mH, L_a (aligned inductance) = 110mH, J=0.016kg-m^2, B=0.0065Nms.
Reactor: Boost inductor L = 3mH
Midpoint Converter Capacitors: $C_1 = C_2$ = 2200 μF.
AC Mains: 415 V $_{L-L}$, 50 Hz, source inductance, L_s = 2mH, R_s = 0.09Ω.
Passive Filter Parameters: C_f = 5 μF.
Transformer:
Teaser transformer- 2.5kVA, 359.4V/180V
Main transformer- 2.5kVA, 207.5V-207.5V/180V
Gains of PI Controllers: K_c=40, K_{p1} = 0.01, K_{i1} = 20, K_{p2} = 0.077, K_{i2} = 50.

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BIOGRAPHIES

M. Rajesh received his B.Tech. in Electrical and Electronics Engineering from the University of Calicut, Kerala, in 1995 and his M.Tech. in Power Electronics and Drives from the National Institute of Technology Warangal(NITW), Warangal, Andhra Pradesh, in 2005. In 2000, he joined Department of Electrical Engineering and Electronics Engineering, Govt: College of Engineering, Kannur, Kerala as a Lecturer. He is currently on deputation for doing research at Department of Electrical Engineering, IIT Delhi. His area of interest includes power quality improvements, power electronics and drives.

Bhim Singh received the Bachelor of Engineering (Electrical) degree from the University of Roorkee, Roorkee, India, in 1977, and M.Tech. (Power Apparatus and Systems) and Ph.D. degrees from the Indian Institute of Technology Delhi (IITD), New Delhi, India, in 1979 and 1983, respectively. In 1983, he joined the Department of Electrical Engineering, University of Roorkee, as a Lecturer. He became a Reader there in 1988. In December 1990, he joined the Department of Electrical Engineering, IIT Delhi, India, as an Assistant Professor. Where he has became an Associate Professor in 1994 and a Professor in 1997.

He has received Khosla Research Prize of University of Roorkee in the year 1991. He is recipient of JC Bose and Bimal K Bose awards of The Institution of Electronics and Telecommunication Engineers (IETE) for his contribution in the field of Power Electronics. He is also a recipient of Maharashtra State National Award of Indian Society for Technical Education (ISTE) in recognition of his outstanding research work in the area of Power Quality. He has received PES Delhi Chapter Outstanding Engineer Award for the year 2006.

He has been the General Chair of the IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES'2006) held in New Delhi. He has guided 42 Ph.D. dissertations 139 ME/M.Tech theses and 60 BE/B.Tech. projects. He has been granted one US patent and filed ten Indian patents. He has executed more than sixty sponsored and consultancy projects.

His fields of interest include power electronics, electrical machines, electric drives, power quality, FACTS (flexible ac transmission systems), HVDC (High voltage direct current) transmission systems.

Prof. Singh is a Fellow of the Indian National Academy of Engineering (FNAE), The National Academy of Science, India (FNASc), The Indian Academy of Sciences, India (FASc), Institute of Electrical and Electronics Engineers (FIEEE), the Institute of Engineering and Technology (FIET), Institution of Engineers (India) (FIE), and Institution of Electronics and Telecommunication Engineers (FIETE) and a Life Member of the Indian Society for Technical Education (ISTE), System Society of India (SSI), and National Institution of Quality and Reliability (NIQR).