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Three Level Boost PFC Converter for High Voltage AC-DC Applications

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ABSTRACT: In the present situation, the evolution of growing in of computers, laptops, uninterrupted power supplies, telecom and biomedical equipment has become overpowering. Hence the utilization of such equipment results high power consumption and small power density which provided a large market to Distributed Power System (DPS). Power conditioning, typically rectification is essential usually for electronics equipment. Rectifier behaves as nonlinear load producing non sinusoidal line current due to the non-linear input characteristic. The steady growth of use of electronics equipment is become a significant problem as per the line current harmonic is concerned. Their adverse effects on the power system are many. Hence in three-phase systems, the neutral current magnitude increase and becomes the cause of overheating of transformers and induction motors, as well as the dreadful conditions of system voltage waveforms. A reduction in line current harmonics or Power Factor Correction (PFC) is vital. Boost converter when used in high voltage applications makes the system bulky. Three Level Boost PFC Converter was designed for high voltage applications for improving PF and reduce THD. A controller was tested using MATLAB/SIMULINK for the voltage balancing across the capacitors and PFC of the three level Boost PFC converter. An experimental prototype has been made for low voltage applications. A comparison of the conventional and new converter is done for low and high voltages.

KEYWORDS: Three level Boost Converter, Power Factor Correction, SMR, Multiloop Interleaved control, Capacitor voltage balancing.

I.INTRODUCTION

In industry most of the load is inductive in nature which results in lagging power factor that is why there is loss and wastage of energy which results in high power bills and heavy penalties from electricity boards. If the load is uneven it is very difficult to maintain unity power factor. The devices generally used in industrial, commercial and residential applications need to undergo rectification for their proper functioning and operation. They are connected to the grid comprising of non-linear loads and thus have non-linear input characteristics which results in production of non-sinusoidal line current. Also current comprising of frequency components at multiples of line frequency is observed which lead to line harmonics. Due to the increasing demand of these devices, the line current harmonics pose a majorproblem by degrading the power factor of the system thus affecting the performance of the devices. Hence there is a need to reduce the line current harmonics so as to improve the power factor of the system. This has led to designing of Power Factor Correction circuits which maintains unity Power Factor. PFC is done in order to reduce the power transmission losses and increase the system stability. PFC circuits needs to shape the input current waveform and regulate output voltage simultaneously. Different methods like active and passive PFC topologies are thereto obtain PFC functions.

II.LITERATURE REVIEW

There are mainly two types of power factor correction methods are used. Active PFC topologies are advantageous over the passive topologies in PFC applications.

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A. Passive PFC

The easier way to control the harmonic current is to use apassive filter which passes current only at line frequency. Thiscan be done by adding an inductor in series at the AC side ofthe nonlinear load (rectifier), placing inductor at the dc side, using combinations of low-pass input and output filters orusing harmonic trap filter etc. Passive filter reduces theharmonic current, in a non-linear device by exhibiting linearcharacteristics. But these filters are large, expensive and bulkywhich requires high current inductors [1]. Passive methods of PFC have certain advantages. Theyare simple and reliable. The generation of high frequencyelectromagnetic interface (EMI) and switching losses due tohigh frequency are getting reduced. But, they are also wellknown for their drawbacks. Passive filters are heavy andbulky. Its dynamic response is very weak, voltage regulation isvery poor and the shape of its input current depends on theload. The fundamental component may show an excessivephase shift, even if the line current harmonics are reduced andit will reduce the power factor.

B. Active PFC

An active power factor corrector improves the power factor by using different types of dc-dc converters the main aim is to make the load circuitry purely resistive. The active power factor correction circuits can be selected as single-stage or multi-stage [2].They are mainly of three typesie.buck converter, boost converter and buck-boost converter topology having a self PFC capability which helps in improving the PF. Power factor correction using Buck converter topology and its advantages are presented in [3] and [4].

Boost converter topology used for PFC is outlined in [4]. In ac-dc Bridgeless Boost topology the output diodes operated in high voltage have severe reverse recovery problems due to high diode forward current and high output voltage. As the switching frequency increases the large reverse recovery currents of the output diodes affect the switches in the form of additional turn on losses and also produce electromagnetic interference (EMI) noises. Interleaved, half and full bridge Boost topologies are outlined in [4]. The main problem with operation of dc-dc converters are unregulated power supply, which leads to improper function of dc-dc converters. So various types of control schemes are used to enhance the efficiency of dc-dc converters [5].

The idea of having circuits that generate three-level (TL) voltage waveforms can be traced back to two U.S. patents in the early 1960s. These TL circuits were invented for computer applications with the intention of transforming conventional computation methodology from binary logic form to ternary form. Later, Nabae*et al.* and Baker1 reported a different form of TL circuits specific to power conversion application in 1980 and 1981, respectively named the neutral-point-clamped (NPC) inverter the phase leg of this inverter can output not only the positive and negative bus voltages but also the neutral-pointvoltage. As a result, the output voltage of the NPC inverter has lower harmonics as compared to that of traditional inverters. Since the phase leg provides three levels of voltages, the NPC inverter is also called TL inverter. An additional advantage of the TL inverter is that the voltage stress of the switches is reduced to half of the input voltage, which makes it suitable for high input voltage power conversions the technique has application to dc–dc converters by Pinheiro and Barbi to reduce the voltage stress of the switches the application of which does not create a TL voltage state. Since the phase leg of this dc–dc converter is similar to that of the TL inverter it was named TL converter. The concept was applied to the Multilevel DC-DC converters.

The control methods for the three-level SMR (ac/dc application) can be found in [6] where gate signals *GT1* and *GT2* are generated from the lookup table with inputs *H*1, *H*2,and *H*3. It can be found that sensing capacitor voltage is required for the generation of inputs *H*2 and *H*3. Therefore for the control of the three-level SMR, it is necessary to sense individual capacitor voltage and to add voltage balancing loop in [8]. Similar voltage balancing loops can be also found in the dc/dc applications [8], [9].

III.THREE LEVEL BOOST PFC CONVERTER

Three level boost PFC converter consists of diode bridge rectifier,three level boost dc-dc converter supplying load and appropriate controller. Block diagram of the systemis shown in Figure 3.1.

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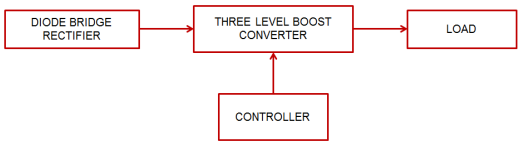

Figure 3.1Block diagram of Three level Boost PFC Converter

The input ac voltage $Vs = Vssin(\omega t)$is a sinusoidal function with peak amplitudeVs. Through the diode rectifier, the input voltage of the three level boosting converters canbe expressed with the rectified voltage Vs. By assuming that the switching frequency fs ismuch larger than the line frequency f, the control signals $vcont1$ and $vcont2$ can be regardedas two constants within the switching period Ts = 1/fs. The ideal inductor and the idealcapacitors are assumed. They are the inductor resistance and the capacitor resistances are assumed zero.

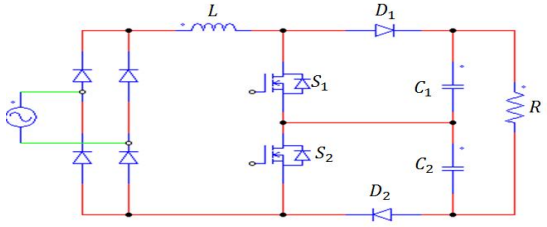

Figure 3.2 Three level Boost PFC Converter

In two level boost converter only one active switch is used and this leads to 2 (2 number of active switches=21) operating mods (0 or 1). In the Three Level Boost(TLB) convertertwo active switches ($S1$ *and* $S2$) are used and consequently 4(2 number of active switches=4)modes are available (00, 01, 10, 11). The output has a capacitor voltage divider.The increasein the operating modes and thus switching states will lead to n additional control freedomto charge and discharge the dc link capacitors independently. The circuit diagram is shownin Figure 3.2.

The voltage of the centre point is$V\ d/2$, which is obtained by choosing $C1, C2$ and thesymmetrical operation of the two boost switches. Due to the input inductor L and two diodes$D1$ *and* $D2$ in the three level boosting PFC converter, both switches can be conducting atthe same time without the concern of the short circuit damage. As shown in Figure thereare four switching states in the three level boosting PFC converters.

Mode 1: As shown in Figure 3.3 both switches turn on in the switching state 1. Thusthe inductor voltage VL in the three level boosting PFC converters equals the rectified inputvoltage $VL = mode\ of\ Vs$ and both capacitors supply energy to the load $iC1 = iC2 = id < 0$. In thismode the inductor is always in charging mode and charged capacitors supply the current tothe load.

$$vL = vs \quad (3.1)$$

$$ic1 = ic2 = -id \quad (3.2)$$

$$= vC1 + vC2 \quad (3.3)$$

Mode 2: In the switching state 2 in Figure 3.4 ,the top switch turns on and thebottom switch turns off. The resulting inductor voltage VL equals the rectified input voltage minus the bottom capacitor voltage. The capacitor $C1$ supplies energy to the load. Butthe capacitor$C2$stores the energy from the input voltage ie. is in charging mode. Similarlythe resulting inductor voltage in equals the rectified input voltage minus the top capacitorvoltage. In this mode inductor may be in charging mode or discharging mode.

$$vL = vs + vC2 \quad (3.4)$$

$$ic1 = -id \quad (3.5)$$

$$ic2 = iL - id \quad (3.6)$$

$$vd = vC1 + vC2 \quad (3.7)$$

Mode 3:In the switching state 3, the top capacitor C1 is in charging mode but thebottom capacitor $C2$ is in discharging mode ie. it supplies the load current. In this modeinductor may be in charging mode or discharging mode

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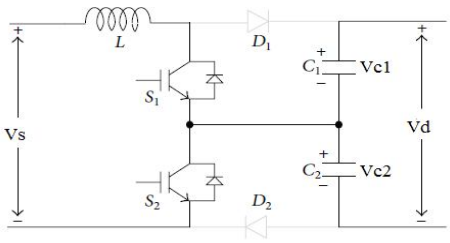

Figure3.3Mode 1

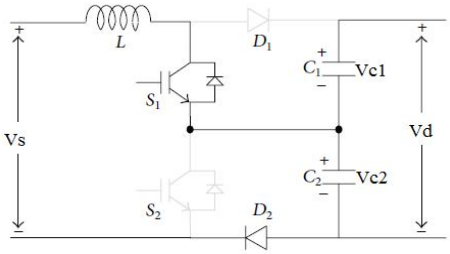

Figure3.4Mode 2

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$$v_L = v_s + v_{C1} \quad (3.8)$$

$$i_{C1} = i_L - i_d \quad (3.9)$$

$$i_{C2} = -i_d \quad (3.10)$$

$$v_d = v_{C1} + v_{C2} \quad (3.11)$$

Mode 4:When both switches turn off in Figure 3.5, the resulting inductor voltageequals the rectified input voltage minus the output voltage. The rectified input voltagesupplies the load current and charges both capacitors simultaneously. Due to boostingoperation $vC1 + vC2 > Vs$, so in this mode inductor always is in discharging mode and bothcapacitors are in charging mode and input supplies the current to the load.

$$v_L = v_s - v_{C1} - v_{C2} \quad (3.12)$$

$$i_{C1} = i_{C2} = i_L - i_d \quad (3.13)$$

$$v_d = v_{C1} + v_{C2} \quad (3.14)$$

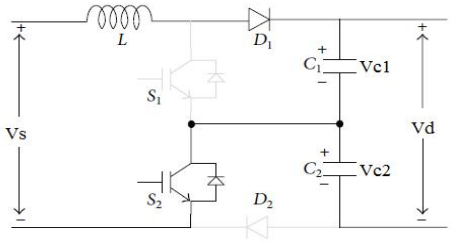

Figure3.5Mode 3

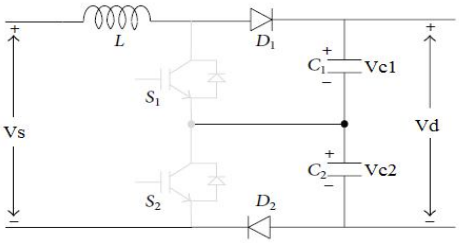

Figure3.6Mode 4

Two gate signals of switches GT1 and GT2 are generated from the comparisons ofcontrol signal and two unit sawtooth signals vtri1 and vtri2. Two sawtooth signals have unitamplitude and identical period Ts and there is a 180deg phase difference between them.Both duty ratios of switches are equal to the control signal. As the two carrier triangularsignals intersect at duty ratio 0.5 there are two regions where this converter can operatedepending on whether the input voltage is lower or higher than half of the output voltage.

In region 1,$Vs > Vd/2$; hence $VL = Vs\,Vd/2 > 0$ so inductor current raising polarity is positive in modes 3 and 2 as shown in Figure. This will occur only when duty ratios ofupper switch SW2 and of lower switch SW1 are less than 0.5. In this region both switchesmust not be ON at the same time.

In region 2, $D1 = D2 > 0.5$, input voltage is $Vs < Vd/2$ then, inductor current raising polarity is negative $VL = Vs, Vd/2 < 0$ in modes 2 and 3 as shown in Figure. In this regionboth switches must not be OFF at the same time. The operating modes in two regions are as shown in Figure 3.7 and 3.8.

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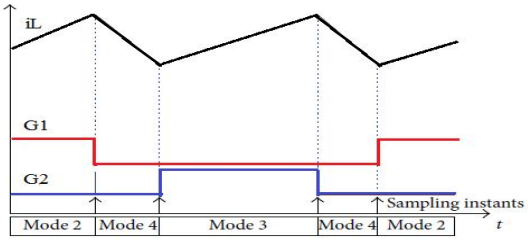

Figure3.7Region 1

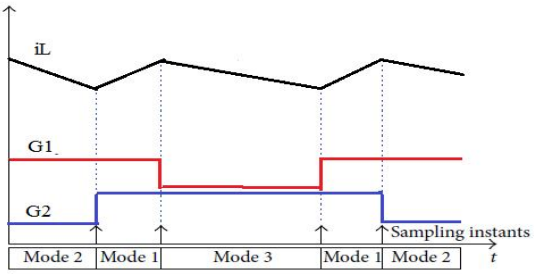

Figure3.8Region 2

DESIGN EQUATIONS

Inductor value capacitor values and ripple in inductor current is obtained as shown in equations.

$$L = \frac{V_d}{4f_s}\Delta I \quad (3.15)$$

$$C_1 = C_2 = \frac{I_d}{2\omega\Delta v_{C1}} \quad (3.16)$$

$$I_d = \frac{P}{V_d} \quad (3.17)$$

$$For\ V_s < \frac{V_d}{2}, \Delta I_{max1} = V_{in}T_sD/2L$$

$$For\ V_s > \frac{V_d}{2}, \Delta I_{max2} = V_s - 0.5V_dT_sD/2L$$

$$\Delta I_{max} = V_sT_s/16L$$

The voltage equation of three level boost converters is shown below.

$$V_d/V_s = 2/1 - D \quad (3.18)$$

CONTROL STRATEGY

Control combines the conventional multi loop control,the feed forward loop, andthe interleaved PWM scheme. Both the voltage controller and the current controller areproportional integral type controllers (PI). Two gate signals GT1 and GT2 are generated fromthe comparisons of control signals $vcont1$ and $vcont2(vcont)$ and two unit sawtooth signals vtri1and vtri2, respectively. The two saw tooth signals have unit amplitude and identical periodTs. There is a 180 phase difference between them. Both duty ratios of switches $SW1$ and$SW2$ are equal to the MIC control signal $vcont$.

Both current and voltage controllers are PI controllers.Inner current controller isused for current shaping.Outer voltage controller is used for voltage regulation. In the outervoltage loop, the current amplitude is obtained by the voltage controller and the error voltageis the difference between the output voltage command $Vd*$ and the output voltage Vd.Thenthe peak value of the input current multiply with the rectified signal to ensure the inductorcurrent command is in phase with the rectified input voltage.In the inner current loop, theinductor current command minus sensed inductor current to obtain the current error. The multi loop interleaved controlwith conventional capacitor voltage balancing control (CVBC) shown in Figure 3.8. Onecontrol signal is generated by the multi loop control, and the other control signal is yieldedby CVBC with sensing the capacitor voltages. The average value current IL is input to themulti loop control to yield the desired PFC function and obtain the control signal$vcont1$. Thedifference IvC between two values $IvC1$ and $IvC2$ is calculated and the compensating signal$vcont$ is obtained by the P controller.

$$\Delta v_{cont} = k_p\,(I_{vC2} - I_{vC1}) \quad (3.19)$$

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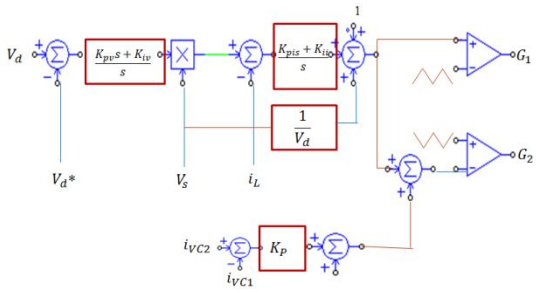

Figure3.7Multiloop interleaved control

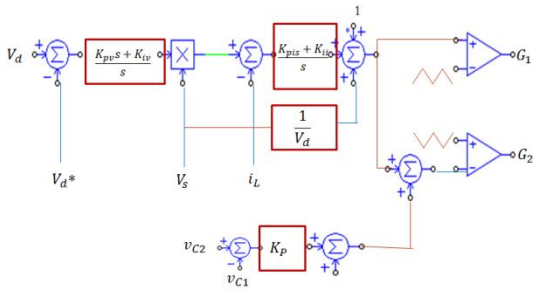

Figure3.8Sampling and control strategy

Current sampling technique is required for sampling the inductor current.There isno capacitor voltage sensing and balancing is done by sensing the input voltage ,inductorcurrent and output voltage. So a signal is saved. It reduces cost, complexity. The Figureshows the sampling of inductor current. The multi loop interleaved control and the SCVBCwith the sampling and hold strategy is shown above where only the input voltage , theoutput voltage vd and the inductor current iL are sensed. Then, the other control signal $vcont2$ is generated by adding the compensating signalto the control signal$vcont1$.

$$v_{cont2} = v_{cont1} + \Delta v_{cont}\, v_{cont1} + k_p\,(I_{vC2} - I_{vC1}) \quad (3.20)$$

The sampling/hold strategy samples the inductor current thrice per switching period Ts andobtains the average value IL and the other two values $IvC1$and $IvC2$.Proportional controller value is obtained by equation below.

$$0 < k_p < 2L/T_s v_{C2\,\max} \quad (3.21)$$

IV.SIMULATION ANALYSIS

Software simulation of the power factor correction circuit with single phase diode bridge rectifier is done in MATLAB/Simulink. In the sample circuit of the considered system, a single phase diode bridge rectifier having four diodes connected in two arms is taken as the non-linear load. The input supply is 110V and the switching frequency is set to 20 kHz. The inductor and capacitor values taken are 0.5mH, 2240 µF and 1410µF respectively.

A. Simulink Model of open loop PFC Three Level Boost PFC Converter

Open loop operation of Three level Boost PFC Converter is as shown in figure. The converter operates with input of 110V. The power factor obtained is 0.98. The output voltage remains regulated at 330V but with the presence of voltage transients. The waveforms are shown below at 300W.

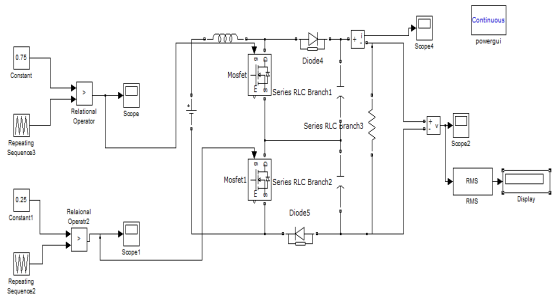

Figure 4.1 Simulink model of Open loop Three level Boost

The output voltage waveform is as

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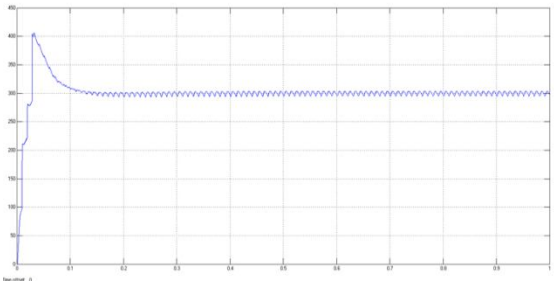


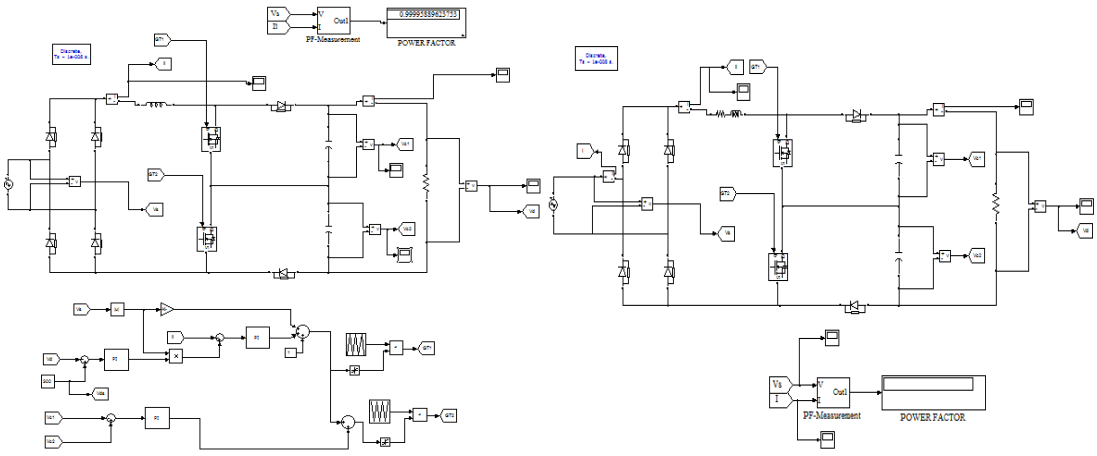
Figure 4.2Output Voltage Waveform of Open loop Three level Boost Converter

B. Simulink Model of Closed loop PFC Three Level Boost PFC Converter

The Simulink model of the Three level Boost PFC Converter with Multiloop Interleaved control and the control with the help of sampling and control strategy is shown Figure 4.4 . The input voltage and current obtained are sinusoidal with power factor of 0.99995and 0.99997 respectively. Output voltage remains regulated at 300W with fewer transients.The three level Boost PFC Converter with SCVBC designed for high voltage hashigh PF of 0.999972and low THD of 9% compared with that of low voltage design with PFof 0.9997 and high current harmonics. The comparison table of different parameters is as shown. Three level Boost converter also obtained better PF and low current harmonics compared to the conventional Boost converter.

Table 4.1 Comparison of different parameters

.Duty cycle (%)	Load (ohm)	Power rating (W)	Power Factor	THD
10	1500	60	0.999	9.54
20	750	120	0.9999 7	9.51
50	300	300	0.9998 8	9.41
100	150	600	0.9984	9.25



The capacitor voltages obtained remains regulated at 160V.

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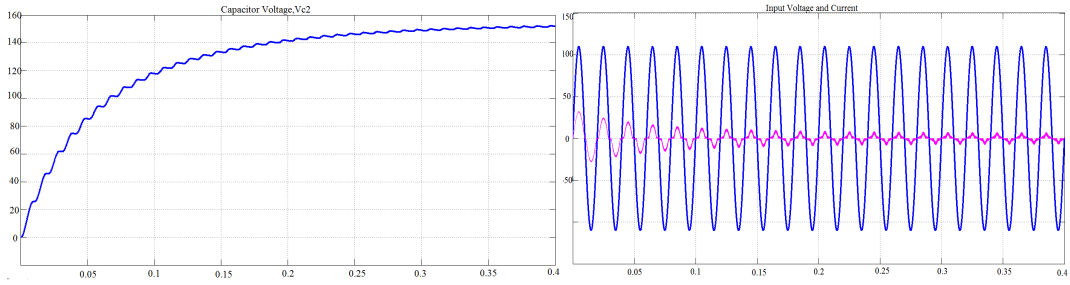
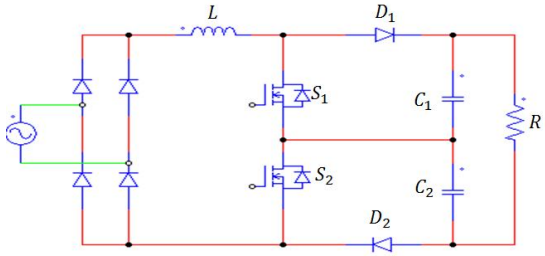
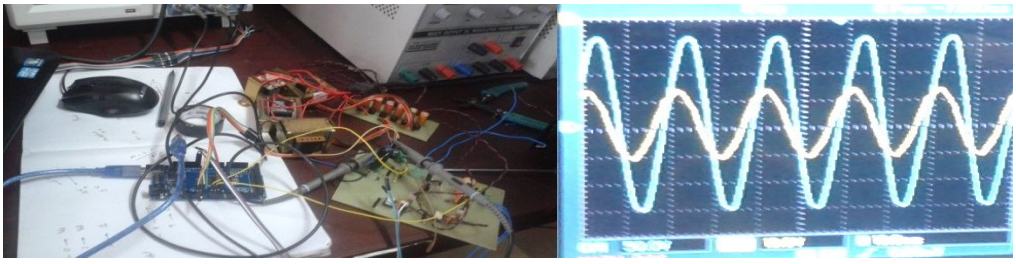


V. HARDWARE RESULTS

A prototype of single phase closed loop Three Level Boost converter topology, forPFC is modelled at 1kHz switching frequency. The components includes MOSFET (IRF640) used as the switch, Diodes (IN4007), Capacitors (220µF,300µF), Inductor (60mH) and Resistor (300K) as load.Power supply unit is used to generate regulated power supply. The output 12V of thetransformer is rectified with the help of diode bridge rectifier and fed to the driver circuitas input. The driver output of 12V is used to drive the Power switches. The varying gatepulse to the switch is generated with the help of ArduinoMegha. The circuit of three levelboost converters is used in PFC high voltage applications. Here a prototype model of theconverter is designed for low voltages with input of 15V. The hardware circuit diagram of the prototype model is as shown in Figure 5.1. Output voltage remained regulated at 50V.



Improved power factor was obtained.Input voltage and current waveforms obtained in DSO are as shown in Figure 5.3.



VI.CONCLUSION

Traditional diode rectifiers are commonly used for AC toDC power conversion. These electrical equipments generateharmonic waves and suffer low power factor. Now converterswith power factor correction have received greater attentiondue to improved power factor and low harmonics. The Three Level Boost PFC topology has the ability to regulate the outputvoltage to a desired value by varying the duty ratio. Three Level Boost PFC circuit with open loop control and closed loop Sampling and Control strategy is simulated inMATLAB/Simulink. In closed loop control the input powerfactor is better than the open loop control. Thepower factor is improved to a value 0.9998 and the inputvoltage and current waveforms are in phase to eachother. A prototype is also designed in low voltages and implemented usingPCB, the converter shows an excellent ability toimprove the input power factor of the system.

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REFERENCES

[1]B. SinghB. N. Singh,A. Chandra,K. Al-Haddad,A. Pandey and D. P. Kothari, "A review
of single-phase improved power quality AC-DC converters," ACTA ELECTROTECHNICA, vol. 48, no. 1, pp. 962-981, October 2007.
[2]Damodhar Reddy K.Pavan Kumar Goud, ", Analysis of different topologies for active power
factor correction using DC-DC converters,"International Journal of Advanced Technology& Engineering Research", vol. 4, no. 1, pp. 1045-1053, January 2014.
[3] L. S. YangT. J. Liang, H. C. Lee, and J. F. Chen,"Novel high step-up DC-DC converter with coupled-inductor and voltage-doubler ircuits",IEEE Transactions on Industrial Electronics, vol.58 , no. 9, pp. 4196-4206, September 2011.
[4]A. ShahinM. Hinaje,J. P. Martin,S.erfederici,S. Rael and B. Davat,"Novel high step-up DC-DC converter with coupled-inductor and voltage-doublercircuits",IEEE Transactions on Industrial Electronics, vol.58 , no. 9, pp. 4196-4206, September 2011.
[5]XinboRuan,Qianhong Chen,"Fundamental Considerations of Three-Level DC-DC Converters: Topologies, Analyses and Control," Control",IEEE Transactions on Circuits and Systems, vol. 55, no. 11, pp. 3733-3743, December 2008.
[6]XinboRuanQianhong Chen, "Fundamental Considerations of Three-Level DC-DC Converters: Topologies, Analyses, and Control," Control",IEEE Transactions on Circuits and Systems, vol. 55, no. 11, pp. 3733-3743, December 2008.
[7] V.I. Meleshin, D.V. Zhiklenkov, ", Efficient Three-Level Boost Converter for Various Applications ", Control Conference, EPE-PEMC 2012 ECCE Europe, pp. 91-98, April 2012.
[8] B. R. LinH, H. Lu, ",A novel PWM scheme for single-phase three-level power-factor-correction circuit", Transactions on Energy Conversions, vol. 47, no. 2, pp. 245-252,April 2000.
[9] M. T. Zhang,Y. Jiang, F. C. Lee, and M. M. Jovanovic, ", Single-phase three-level boost power factor correction converter",IEEE App. Power Electron. Conf., pp.434-439, 1995.
[10] Hung-Chi Chen,Jhen-Yu Liao, ",Design and implementation of sensorless capacitor voltage balancing control",IEEE Transactions on Power Electronics, vol. 29, no. 7, pp. 2319-2327, July 2014.