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Simulation and Design of Prototype Boost Converter for Power Factor Correction

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ABSTRACT

This paper deals with the simulation and implementation of boost Converter with the need for power factor correction, the utilization of active clamping technique in the boost converter, this circuit incorporation of compound active clamping boost converter, its modes of operation and analysis of step of chopper. This analysis involves the simulation analysis of the compound active clamping boost PFC converter. It gives the details about the circuit implementation. The laboratory model is implemented and the experimental results are obtained. These experimental results are correlated with the simulation results.

Keywords: *Power Factor Correction, Diode, Rectifier, Boost Converter, Micro Converter, Step up Chopper.*

I. INTRODUCTION

Electromagnetic pollution of the power line introduced by power electronic systems include harmonic distortion due to nonlinear loads, typically, rectifiers [1]. So, various types of single phase PFC converter circuits to improve the ac current waveform have been developed and used [2, 3]. The PFC converter is constructed by a boost chopper circuit with a switching device in the dc side of the diode bridge rectifier circuit. Good characteristics such as a sinusoidal current waveform in phase with the ac line voltage and the constant dc voltage can be obtained from the PFC converter [4].

The concept of inductor design is presented and soft switching techniques in PWM converters. In the literature mentioned above, the hardware implementation of boost converter using Atmel microcontroller is not available. In this paper, the hardware details of embedded microcontroller based boost converter are presented.

II. BOOST POWER FACTOR CORRECTION CONVERTER

The non-ideal character of the input current drawn by the rectifiers creates a number of problems for the power distribution network and for other electrical systems in the vicinity of the rectifier including the phase displacement of the current and voltage fundamentals requires that the source and distribution equipment handle reactive power increasing their volt-ampere ratings, High input current harmonics and low input power factor, Lower rectifier efficiency because of the large rms values of the input current and the high reactive components size.

Zero voltage transition technique allows the main switch to be turned on and off with zero voltage condition. However, the auxiliary switch in the converter operates under hard switching condition and the converter needs an additional diode and a saturable inductor to reduce the resonance between the resonant inductor and the parasitic capacitance of the boost diode. Active clamping technique has been an attractive choice due to achieving ZVS for both the main switch and the auxiliary switch. However there exists a parasitic resonance between the resonant inductor and the parasitic capacitance of the boost diode when the main switch is on. To eliminate the parasitic ringing, a diode introduced to clamp the voltage on the boost diode at the value of the output voltage.

The thyristor for PFC converter with different firing angles will give less output power, more harmonics and less power factor as compared with Diode rectifier. Hence, the diode rectifier is used as a dc input source to the Boost converter as shown in Fig. 1. The voltage impressed across the inductor during on-period is V_d. During this period, the current rises linearly from a minimum level I_1 to a maximum level l_2. Therefore the voltage across inductor is,

$V_L = V_d$ (1)

Also,

$V_L = L(I_2 - I_1) / T_{on} = L(\Delta I) / T_{on}$ (2)

From (1) and (2),

$T_{on} = L(\Delta I) / V_d$ (3)

The voltage impressed across the inductor during off period is $(V_o - V_d)$ and the current drops linearly from the maximum level I_2 to the minimum level I_1. Therefore the voltage across the inductor is,

$V_L = (V_o - V_d)$ (4)

Also,

$V_L = L(I_2 - I_1) / T_{off} = L(\Delta I) / T_{off}$ (5)

From (4) and (5).

$T_{off} = L(\Delta I) / (V_o - V_d)$ (6)

From (3),

$L(\Delta I) = T_{on} * V_d$ (7)

From (6)

$L(\Delta I) = T_{off} * (V_o - V_d)$ (8)

(8)

From (7) and (8)

$T_{on} * V_d = T_{off} * (V_o - V_d)$

$V_o = V_d / (1 - \alpha)$ (9)

Where α = delay angle of the boost converter. As firing angle increase from 0 to 1, the output voltage ideally increases from V_d to infinity. Hence, the output voltage is boosted.

The output voltage is greater than the input voltage. Boost converter is also called as step-up converter. A large inductor L in series with the source voltage is essential. When the switch is on, the input current flows through the inductor and switch and the inductor stores the energy during this period. When the switch is off, the inductor current cannot die down instantaneously; this current is forced to flow through the diode and the load during this off period. As the current tends to decrease, polarity of the emf induced in L is reversed. As a result, a voltage across the load is the sum of supply voltage and inductor voltage and it is greater than the supply voltage.

III. COMPOUND ACTIVE CLAMPING BOOST PFC CONVERTER

The compound active-clamping boost PFC converter circuit is shown in Fig.1.

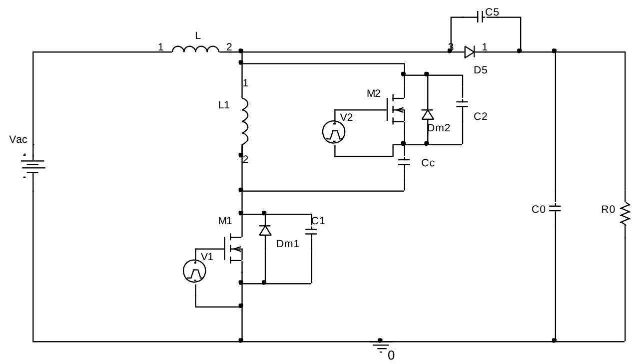

Fig.1. Compound Active Clamping Boost PFC Converter

The compound active-clamping boost PFC converter circuit consists of a input filter inductor L, resonant inductorL_1, main switch M_1, auxiliary switch M_2, clamping capacitor C_c, boost diode D_5 and output capacitor C_c. The auxiliary switch is always turned ON under zero voltage condition while the main switch can achieve zero voltage switching under certain condition. The off-state voltage across the main switch, the boost diode D_5, and auxiliary switch M_2 are clamped. There exists a parasitic resonance between junction capacitance of boost diode and resonant inductor. When M_1 is on, leading to high voltage stress on boost diode. To eliminate the parasitic ringing, the active clamping branch composed of a clamping capacitor and an active switch is placed in parallel with resonant inductor. The main switch, the auxiliary switch, the clamping capacitor, the boost diode and the output capacitor form a voltage loop. At any time, during operation, there are two switching devices are conducting among the main switch the diode and the auxiliary switch, so the voltage across the switch device that is off is clamped. The output filter capacitor C_0 is represented by a constant voltage source and the value of Cc is large enough so that the voltage ripple across it is small, thus can be seen as a voltage source. The resonant frequency of C_c and L_1 is much lower than the operation frequency of the converter. In this converter, the operating stages are almost same in the positive half line cycle and negative half line cycle. Thus, here only one switching cycle in the positive part of power line input is explained. The average output voltage V_0 greater than input voltage V_S can be obtained by a chopper called step up chopper. In the Fig.2 illustrates the step up chopper.

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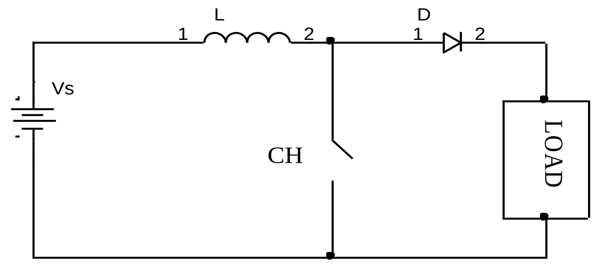

Fig.2. Step up chopper

In this chopper, a large inductor L in series with the source voltage V_S is essential. When the chopper CH is on, the inductor stores energy during the period of t_{on} When the CH is off, as the inductor cannot die down instantaneously, this current is forced to flow through the diode and load for a time t_{off}. As the current tends to decrease, polarity of the emf induced in L is reversed .As a result, voltage across the load given by $V_O = V_S + L\ (di/dt)$, exceeds the source voltage. In this manner, the circuit acts as a step up chopper and the energy stored in L is released to the load.

When CH is on, the current through the inductor would increase from I_1 to I_2.When the CH is off, the current would fall from I_2 to I_1. Assuming linear variation of output current, the energy input to inductor from source during the period t_{on} is,

Win = (voltage across L)(average current through L) t_{on}

$$=V_S\,(I_1+I_2)/2\ t_{on} \qquad (10)$$

During the time t_{off} , when chopper is off, the energy released by inductor to the load is

Woff = (voltage across L)(average current through L) t_{off}

$$Woff = (V_0-V_S)\,(I_1+I_2)/2\ \ t_{off} \qquad (11)$$

Considering the system to be lossless these two energies given by equations (10) and (11) will be equal.

$$V_S\,(I_1+I_2)/2\ t_{on} = (V_0-V_S)(I_1+I_2)\ t_{off}$$

$$V_0 = V_S\ T\ /(T-t_{on})$$

$$V_0 = V_S/(1-\alpha) \qquad (12)$$

It is seen from the equation (12) that average voltage across the load can be stepped up by varying the duty cycle (α). If chopper of Fig.2 is always off, α =0 and V_0=V_S. If this chopper is always on, α=1 and V_0 is equal to infinity. In practice, chopper is turned on and off so that α is variable and the required output voltage is obtained. The principle of step up chopper can be employed for regenerative braking of dc motors. Then, V_S represents the motor armature voltage and V_0 the dc source, the power can be feedback to the dc source if $V_S/(1-\alpha\ )$ is more than $V_{0.}$ In this manner, regenerative braking of dc motor occurs. Even at decreasing motor speeds, regenerative braking can be made to take place provided duty cycle α is so adjusted so that $V_S/(1-\alpha\ )$ exceeds the fixed source voltage $V_{S.}$

The average value of the source current can be obtained from

$P_i = P_0$

i.e. $V_i I_i = V_0^2/R$

$I_i = (V_0^2/V_i) /(1/R)$

$I_0 = I_1$ (toff / T)

$I_0 = I_i (1-\alpha)$

The input power and output power are given in equations (13) and (14)

$P_i = V_i * I_i$ (13)

$P_0 =V_0^2 / R$ (14)

Neglecting the losses, the output power must be the same as the power supplied by the source.

V_i *Ii = $V_0^2/R = V_i^2/(1- \alpha)^2 R$

$I_i = V_i / (1- \alpha)^2 R$

$I_L = (I_{max} + I_{min}) / 2$

$(I_{max} + I_{min}) / 2 = I_i$

$I_{max} + I_{min} = 2 I_i$ (15)

The voltage across the inductor is

$V_L = V_i = L\ di/dt$

$di/dt = V_i /L$

With the switch closed (t_{on}),

Ii = $V_i /L * t_{on}$

Imax –Imin = $V_i /L * t_{on}$ (16)

Adding the equations (15) and (16)

$2 * I_{max}$ = 2 Ii + $V_i /L * t_{on}$

Imax = Ii +$V_i /2L * t_{on}$

= $V_i / (1- \alpha)^2 R + V_i /2L * t_{on}$

Imax is given in the equation (17).

Imax =$V_i [1/ (1- \alpha)^2 R + t_{on} /2L]$ (17)

Similarly Imin is given in the equation (18)

Imin = $V_i [1/ (1- \alpha)^2 R - t_{on} /2L]$ (18)

The peak-to-peak ripple in the input current is given by

Ip-p = Imax – Imin = $V_i * t_{on} /L$

For continuous current conditions, the minimum value of current required is equal to zero. Equating (18) to zero,

Imin= $V_i [1/ (1- \alpha)^2 R - t_{on} /2L] = 0$

$1/ R (1- \alpha)^2 = t_{on} /2L$

The value of the inductance is given in equation (19).

$L = [R * ton (1- \alpha)^2] / 2$ (19)

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The description of the compound active clamping boost PFC converter, its modes of operation and the analysis of step up chopper are analyzed.

IV. SIMULATION RESULTS

The simulation circuit diagram of the compound active clamping boost PFC converter with R load and RL load are shown in Fig.3 and Fig.4. The gate pulses for the switches are shown in Fig.4. The Fig.5 and Fig.6 show the voltage across the switches M_1 and M_2.The Drain Source voltage (V_{DS}) and Gate Source voltage (V_{GS}) for the MOSFET M1 is shown in Fig.7. The current through inductor L1 is shown in Fig.8. The voltage across the R and RL loads are shown in Fig.9 and Fig.10.

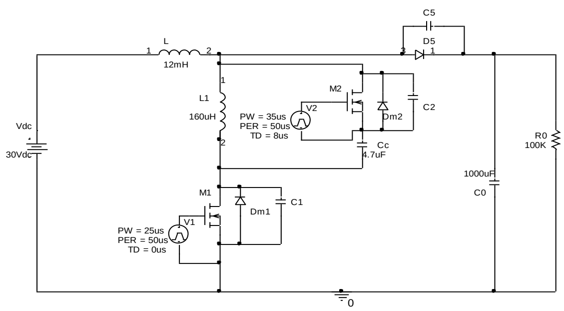

Fig.3.Simulated Circuit Diagram Of Compound Active Clamping Boost PFC Converter (With R Load)

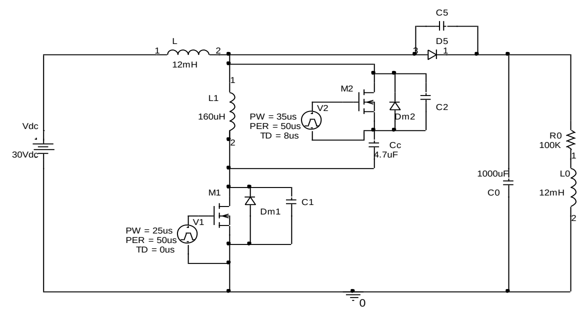

Fig.4. Simulated Circuit Diagram of Compound Active Clamping Boost PFC Converter (With RL Load)

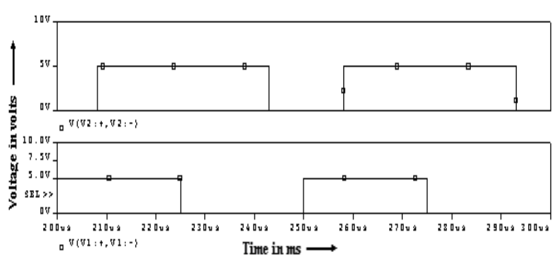

Fig.4a. Gate Pulses For Switches M1 And M2

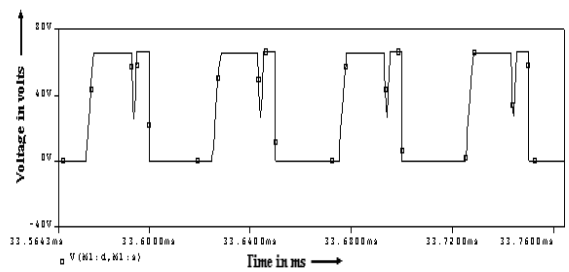

Fig.5. Voltage across M1

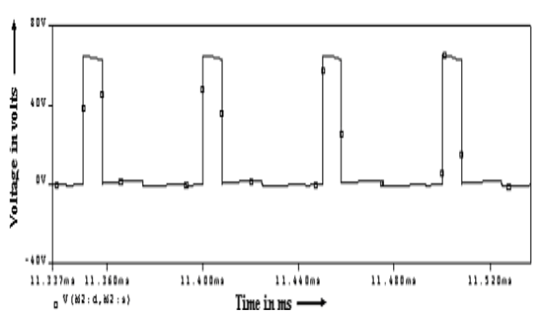

Fig.6 Voltage across M2

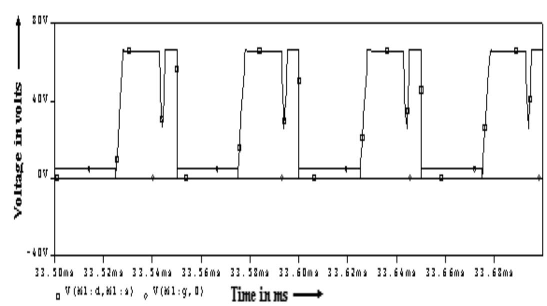

Fig.7.V_{DS} and V_{GS} of MOSFET M1

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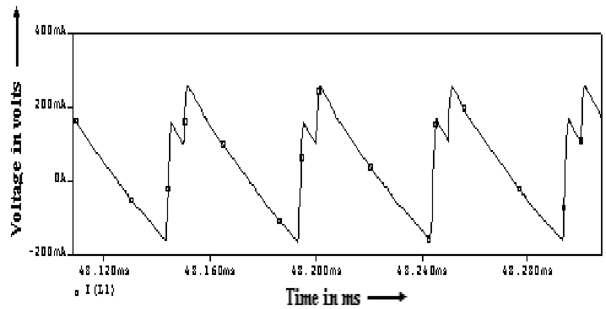

Fig.8.Current through Inductor L1

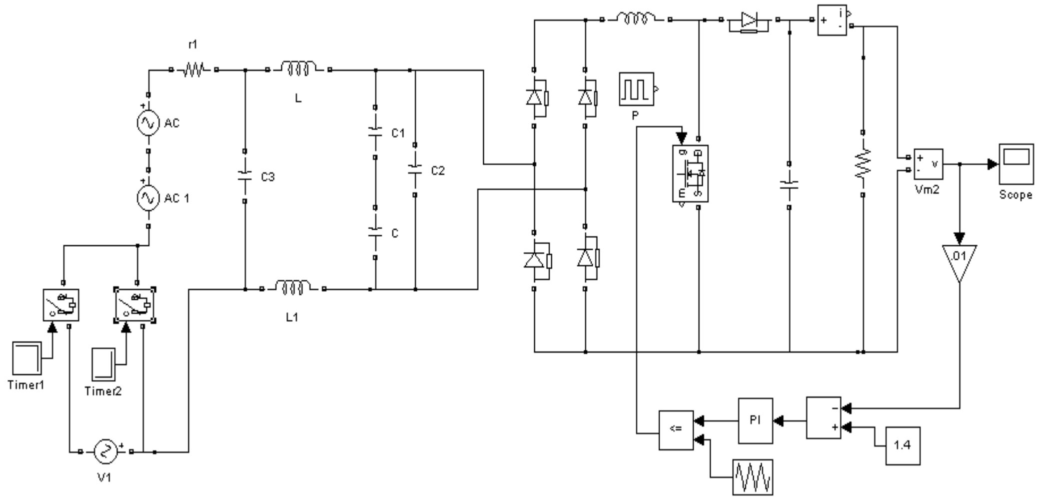

Fig.11. Closed loop controlled Boost converter

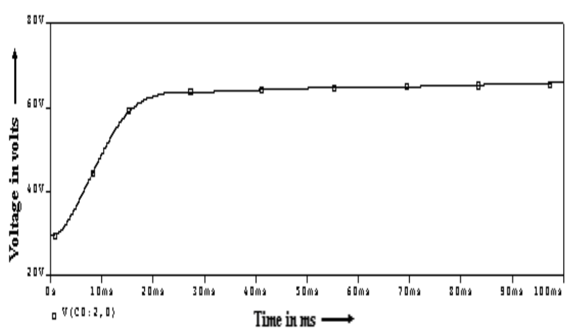

Fig.9. Voltage across R Load

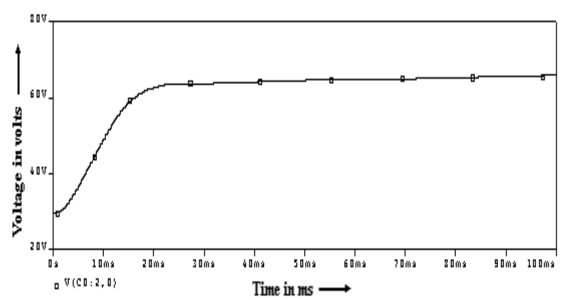

Fig.10.Voltage across RL Load

From the Fig.7, it can be seen that the gate pulse is given when the voltage across the MOSFET M1 is zero. Thus the ZVS condition is achieved. This simulation results presence the compound active clamping boost PFC converter including the gate pulses applied to the switches. The thyristor for PFC converter with different firing angles will give less output power, more harmonics and less power factor as compared with Diode rectifier. Hence, the diode rectifier is used as a dc input source to the boost converter as shown in Fig. 11.

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V. PROTOTYPE MODEL

The Circuit Diagram of Boost PFC Converter with Compound Active Clamping is shown in Fig.12.

The Power circuit consists of the Transformer, Rectifier, Capacitor and Voltage regulator as shown in Fig.13 and Figure 14. The transformers are used to give 12V supply to the V_{cc} of the optocouplers (MCT2E) which forms a part of the control circuit and 5V supply to the microcontroller. The transformer output is given to the bridge rectifier and the output of the rectifier is an unregulated dc voltage with ripples. Hence to reduce the ripples a capacitor filter is used.

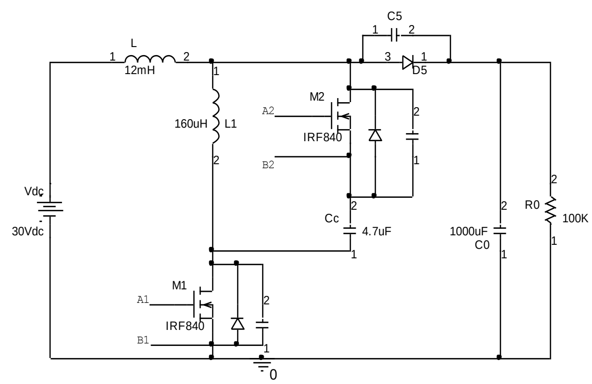

Fig.12 Circuit Diagram of Boost PFC Converter with Compound Active Clamping

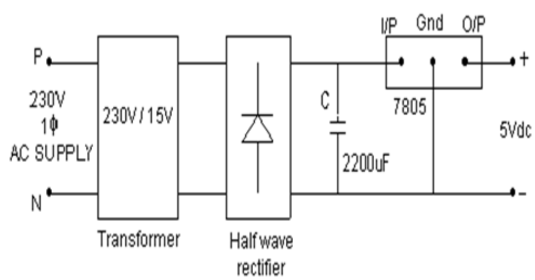

Fig.13 Power Supply Circuit For The Microcontroller

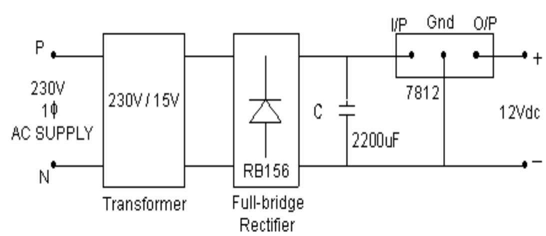

Fig.14.Power Supply Circuit For The Optocoupler

The output of the capacitor is given to the voltage regulator IC which stabilizes the voltage and gives a constant dc voltage. The voltage regulators used are 78XX series. Depending on the voltage required the regulator number varies, for example, for the microcontroller the voltage required is 5V and hence the regulator used is 7805. The above components together constitute the power circuit.

The control circuit consists of optocouplers (MCT2E), a buffer IC (74LS245) and a microcontroller (AT89C51) as shown in Fig.15. By using the optocouplers the microcontrollers can be protected from the power circuits in case a short circuit across the MOSFET. In this circuit the buffer is connected to the LED of the MCT2E which triggers the transistor base. The collector of the transistor is connected to the regulated voltage supply of 12V. The emitters of the optocouplers are connected to the gate of the MOSFETs are used through the biasing resistors whose values are given in the circuit. The buffers (74LS245) are used to protect the microcontroller from reading data from the LED of the optocouplers in case the optocouplers fail due to internal short circuit. The microcontroller (AT89C51) is used to control the timing of the gate signals. One of the four ports is used to give the triggering pulse for the MOSFETs. Two MOSFETs require two pins from the port. Port 1 has been programmed to drive the MOSFETs. The delay program is written using the registers inside the microcontroller.

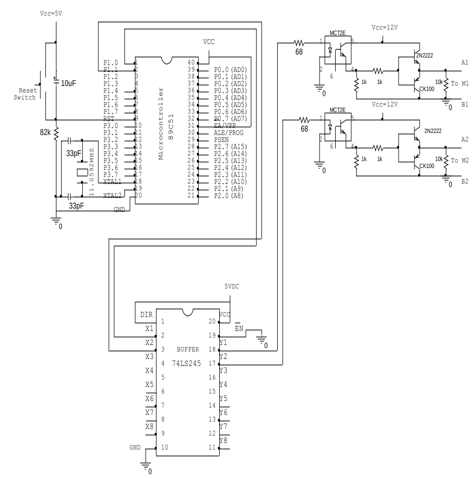

Fig.15. Control Circuit to implement Boost PFC Converter

The top view of the hardware implementation of the boost PFC converter with compound active clamping is shown in Fig.19. The pulses to the MOSFETs are shown in Fig.16 and Fig.17 Fig.18 shows the load voltage which is observed to be constant.

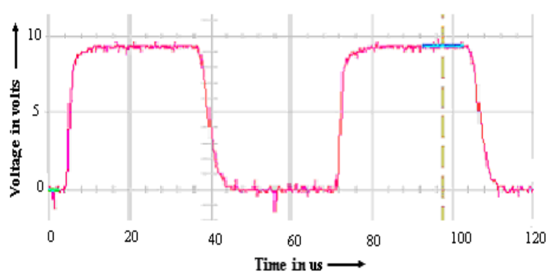

Fig.16.Gate Pulse for MOSFET M1

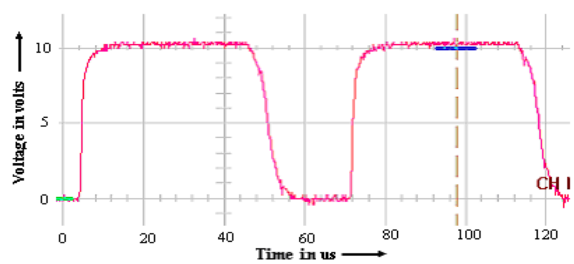

Fig.17.Gate Pulse for MOSFET M2

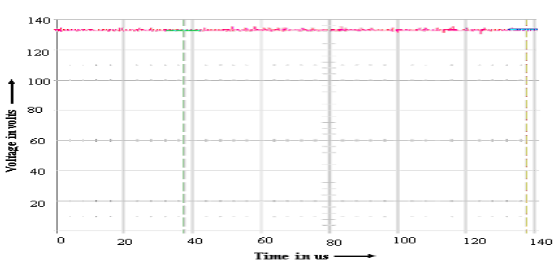

Fig.18. Load Voltage

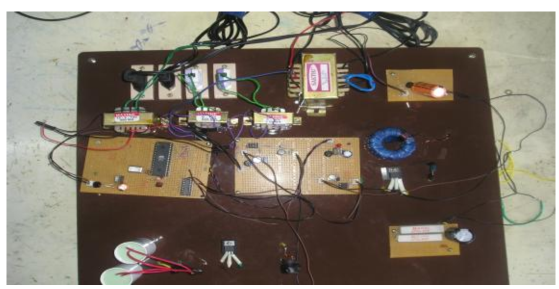

Fig.19.Top view of hardware model

The microcontroller, optocoupler and their power supply circuits are described. The control circuit used in hardware is also presented. This is followed by the switching pattern of the MOSFETs and the look-up table. The flow chart shows the manner in which the microcontroller has been programmed. It is observed that the experimental results match with the simulation results.

VI. CONCLUSION

The operation of compound active clamping boost PFC converter, the mathematical analysis of the step-up chopper and the simulation results of the circuit are presented. The Boost PFC converter with compound active clamping is implemented in hardware. The various hardware components are represented. The simulation studies prove that the Boost PFC Converter will operate for alternative power factor improvement. The laboratory model for boost converter is implemented. The circuit is tested with resistive load. The experimental results are presented in this paper. The experimental results closely agree with the simulation results.

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