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Hardware Implementation of Single Phase Power Factor Correction System using Micro-Controller

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Article Info	ABSTRACT
	Rapid increase of consumers in electronics devices and the use of mains rectification circuits inside these electronic devices is the root cause of mains harmonic distortion. Automatic power factor correction techniques can be applied to the industries, power systems and households to make them stable inturns increases the efficiency of system as well as the apparatus. This paper deals with the hardware design of active power factor correction circuit employing boost converter which is used to boost the DC voltages with a controller based on PID control strategy. The pulses given to power switches by pulse width modulation techniques generated by utilizing micro-controller board, Arduino thus obviating the need of complex hardware circuitry. MATLAB/SIMULINK was used to design and tune the PID controller parameters. The simulation results are matching with the predictions and the same was implemented as hardware. The waveforms various test points and across capacitors were obtained, studied and compared with the theoretical waveforms and are found to be in precise proximity of theoretical waveforms.

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1.   INTRODUCTION

The advancements in power electronic converters uses semi-conductor switches reduces the weight and, size and simultaneously the performance of such converters becoming preferable for industrial, commercial and residential purposes. Electrical and Electronic devices requires an ac-dc power converters which need the output dc voltage to be well regulated with good steady-state and transient performance. These devices are non-linear load generating harmonics that causes interference with communication signals, overheating of the neutral line, overvoltage due to resonance conditions, overheating of the distribution transformer and distribution lines [1]. The diode rectifier-capacitor filter is cost effective for the utility interface, but it severely deteriorates the quality of the utility supply thus affecting the performance of loads connected to it. In order to maintain the quality of utility supply, several national and international agencies have started standardizing and recommending for electronic equipment connected to the utility. Thus, standardization is the most effective means to influence the equipment design and to control the distortion in power systems [2]. These new circuits with standardization have been collectively called power factor correction (PFC) circuits reduces the input current harmonics thus improving power factor as well. For better input current wave, typically the switching frequency should be at least an order of magnitude greater than 3 kHz (= 60 x 50 Hz=60th harmonic of line frequency). In order to improve the power quality a standards such as IEC 61000-3-2 and IEEE STD 519 on the quality of input current is proposed [3] [4].

A review on the status of improved power quality converters (IPQCs) technology to researchers, designers working on application of switched mode ac–dc converters has been reported [5]. The major advantages and disadvantages of the solutions for single phase and low power applications are highlighted and the field of application is found attending to the number of switches, line current waveform, energy processing, control loops, etc [6]. The basic feature of PFC are sinusoidal input current nearly unity power factor, reduce EMI, good input-output response, low output voltage ripple, high power conversion, universal input range (100-250volts) ac rms, low cost. The PFC techniques can be either active PFC approach or passive PFC approach [7]. A passive PFC technique involves reactive elements (LC filters) between the supply line and diode rectifier to improve the shape of line current. The technique being simple, robust, reliable and rugged, it increases the size, weight and volume of the converter. Moreover, in this technique output voltage is not controllable and power factor cannot be highly improved. Active switches are used with the reactive elements in active PFC approach for improving the shape of line current and to obtain controllable output voltage [8] [9]. DC-DC converter is employed at higher frequency to obtain a sinusoidal line current waveform as where the control strategies for PFC converters are investigated and control techniques reviewed and analyzed [10].

The boost converter for PFC is more favourable than buck and buck-boost converters in terms of peak current stress and efficiency. Design, detailed modelling and simulation of a DC/DC boost converter connected to PV system have proposed [11]. Application of boost converter for plug-in hybrid electric vehicle (HEV) battery chargers have been implemented [12]. Various methods are available for the improvement of the functionality of the boost converter. This paper explains about the control algorithm and boost converter to reduce harmonics [13]. PID control system design, analysis tunning rules has been presented [14] [15]. Boost converter is used as voltage controller in PV system where PID controller is employed for optimal control of DC-DC boost converter has been presented [16]. The controller permits optimal control of boost converter at any load condition without retuning parameters or possibility of failure [17]. The method of extended linearization is used to design the stabilizing non-linear PI controllers that regulate to a constant value either the average output voltage or the average input current DC-DC power converters [18] [19]. A brief look at learning the Arduino microcontroller and some of its applications are presented [20].

In this paper active power factor correction system using PI controller is simulated as well as hardware set-up has been developed in laboratory. Boost converter is being employed for this power factor correction system, PI controller is used for feedback and programming is fed to the microcontroller to generate the pulses which is fed to the MOSFET used through isolation circuit (TLP250) which is used to isolate the power and the control circuit. Various observations were recorded for different input voltages, varying the load where resistive load is taken into consideration.

2. PRINCIPLE AND OPERATION

Voltage and current waveforms in a purely resistive AC circuit are in step (or in phase), changing polarity at the same instant in each cycle and all power is consumed by the load. Power circuit of active power factor correction system consists of AC supply, rectifier, boost converter circuit and resistive load whereas control circuit consists of power factor correction block i.e. PFC controller as shown in Figure 1. A linear load do not change the waveform of the shape of current, but may changes the phase between current and voltage whereas the non-linear loads change the shape of the current waveform from a sine wave to some other form and generates the harmonic currents in addition to the actual (fundamental frequency) AC current. Line current harmonics are introduced due to the non-linear loads that need to be minimized with standardization using active power factor correction system.
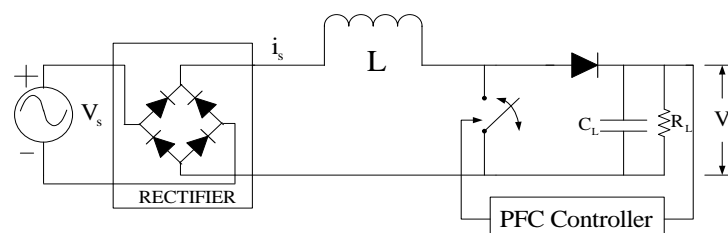

Figure 1. Circuit diagram of DC-DC boost converter with PFC controller

Power semiconductor devices like MOSFETs and IGBTs being used for the active PFC technique that involves in the shaping of the line current. The low and medium power ranging upto few kilowatts (<5 kW) where as MOSFETs are not suitable choice for PFC because of their switching speed, ease of ruggedness and driving. BJTs, IGBTs are used for high voltage medium power applications.

The use of active PFC techniques have the advantage of lower %THD, unity power factor is possible to achieve with %THD of about 3-5%, reduced in weight, size and having cost benefits for higher power levels when compared with the passive PFC techniques. Power circuit and control circuit are explained below with necessary details. The most prominent topology in PFC applications is the boost topology [21] [22], shown in Figure 1 together with a generic controller. Capacitor allows a small ripple of the output voltage V_o thus reduces the input power pulsation.

2.1. Power Circuit

Main block in the power circuit is the boost converter circuit. In general, the boost converter is the simplest way to increase the voltage of a DC supply is which is not possible with the help of the transformers and promises high efficiency. The dc-dc boost converter topology is most widely used for power management and voltage-regulator applications [23][24]. With this feature the usage of heat sinks and cooling agents can be avoided. Working principle of boost converter is explained.

Basic circuit of the boost converter is shown in Figure 1. Here, L is the inductor and R is the resistor which is considered as a load, i_s is the current flow through the circuit. Triggering depends on the duty cycle as the pulse generated by PWM technique triggered by the switch that remains on during t_{on} cycle and off during t_{off} cycle V_s is the DC input voltage supply which is taken from the bridge rectifier that converts AC input voltage into DC output voltage, V_o which is larger than the input V_s.
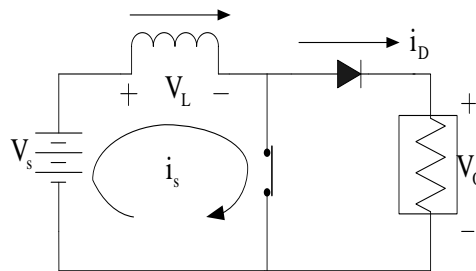

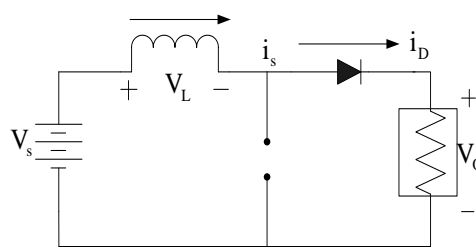Figure 2(a). Circuit diagram of DC-DC boost converter during ON state

Figure 2(b). Circuit diagram of DC-DC boost converter during OFF state

When switch turns on, the current flows through switch thereby increasing the current through the inductor. At the end of time t_{on}, i_s current is stored into the inductor. Above Figure 2(a) shows the boost converter operating in on state. In this state of operation the switch will be in closed state so that V_s will be the source voltage applied across inductor. ON States begins when MOSFET is switched on at t=0 and terminates at t=t_{on}. The inductor current i_s greater than zero and ramp up linearly. The inductor voltage is V_L. Figure 2(b) shows the boost converter operating in off state. In this state of operation the switch will be in open position and inductor starts discharging and aid the supply voltage to boost the voltage. OFF State begins when IGBT's is switched off at t=t_{off} and terminates at t =T_s. The inductor current decreases until the IGBT is turned on during the next cycle again. Voltage across the inductor in this period is (V_s-V_o).

Time integral of the inductor voltage in steady state over one time period must be zero. When the switch is ON the inductor gets charged to its maximum level, because of its flexibility of ON and OFF states it can be switched to OFF state when inductor charges to its maximum capacity.

$$V_S * t_{on} + (V_S - V_0) * t_{off} = 0 \tag{1}$$

$$\frac{V_0}{V_S} = \frac{T_S}{t_{off}} = \frac{1}{(1-D)} \tag{2}$$

where V_s is the input voltage, V_o is the average output voltage, t_{on} is the switching on time of IGBT, t_{off} is the switching off time of IGBT, T_s is the switching period, D is the duty cycle.

2.2. Control Circuit Implementation for PI Controller

The current loop and the compensating current error amplifier for the classical approach of the boost PFC converter operated using PI controller. The feedback loop is essential to maintain the output voltage. In this Figure 3, V_o is given to the Pulse Width Modulator and the output of the PWM is compared with V_{ref} which is given to the controller (PI) and then added with V_s which is given to the system.
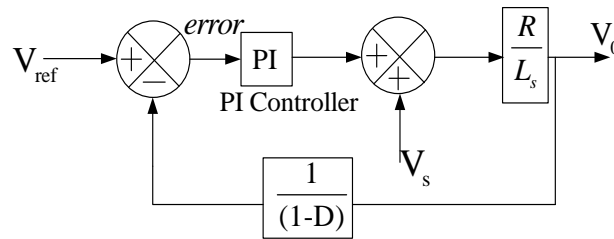

Figure 3. Closed Loop System Boost PFC Converter for PI Controller

The steady state time integral of the inductor voltage for one cycle can be written below since the boost converter operates in two modes:

$$V_{in} = L * \frac{di_s}{dt} \tag{3}$$

Using Laplace Transformation,

$$V_s(s) = sLi_s(s) \tag{4}$$

$$V_o(s) = i_s(s) * R \tag{5}$$

$$V_o(s) = \frac{V_s(s)}{sL} * R$$

$$\frac{V_o(s)}{V_s(s)} = \frac{R}{sL} \tag{6}$$

Equation (6) being basic Laplace Transformation equation of the boost converter.

$$V_o = \left(\frac{R}{sL}\right) * \left[V_s + \left(K_p + \frac{K_i}{s} \right) * \left(V_o - V_{ref} \right) \right] \tag{7}$$

Taking $V_{ref} = 0$,

$$V_o + \left[\left(\frac{R}{sL} \right) * \left(K_p + \frac{K_i}{s} \right) * \left(\frac{1}{1-D} \right) * V_o \right] = V_s * \left(\frac{R}{sL} \right) \tag{8}$$

Transfer function of closed loop system,

$$\frac{V_o}{V_s} = \left(\frac{\frac{R}{sL}}{\left[1 + \left\{ \left(\frac{R}{sL} \right) * \left(K_p + \frac{K_i}{s} \right) * \left(\frac{1}{1-D} \right) \right\} \right]} \right) \tag{9}$$

The K_p and K_i value is calculated by using MATLAB.

3. SIMULATION RESULTS AND EXPERIMENTAL SET-UP WITH RESULTS
3.1. Simulation Results

Simulation result comprises of simulation of active power factor correction in MATLAB using PI controller. The results captured are of input current, input voltage and output voltage. A boost converter using PI controller being simulated in MATLAB as shown in Figure 4(a). The simulation results of various parameter such as input current, input voltage and output voltage are shown in Figure 4(b), 4(c), 4(d) respectively.

According to the simulation results, input voltage=230V, output voltage=400V and input current=2.1A are measured. Power factor of the converter is PF=0.993 and THD value is 3.922 % are measured. To reduce the switching losses, the switching frequency is taken as 15 kHz. Input current variation ≤2%.

Duty cycle (α): $\frac{V_s}{V_o} = \frac{1}{1-\alpha}$, α=0.50

Inductor design: The main boost inductor had to be hand wound. The core chosen was a Mag core high flux 58548-A2. It has a 33mm outer diameter and a permeability of 125. The value of inductance required can be calculated by:

$V_s = L\frac{di}{dt}$, L=0.97mH

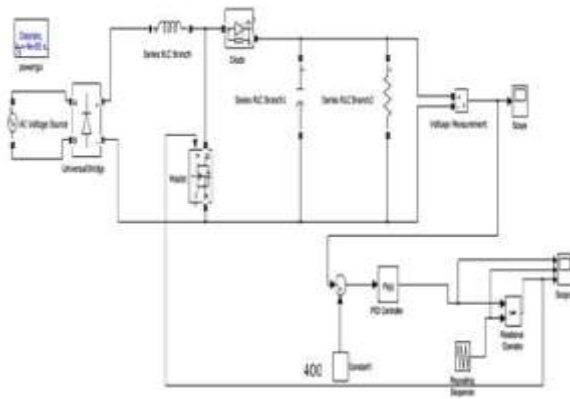A value of L=1mH was used for hardware design purpose.

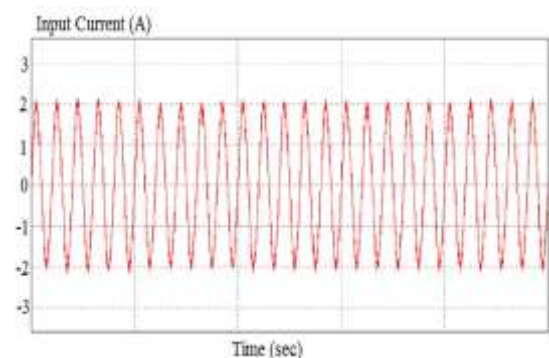Figure 4(a). Simulation circuit for boost converter using PI controller

Figure 4(b). Input current waveform
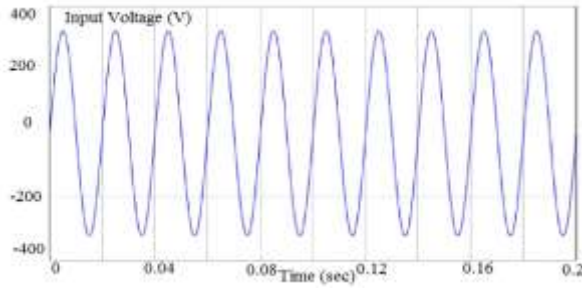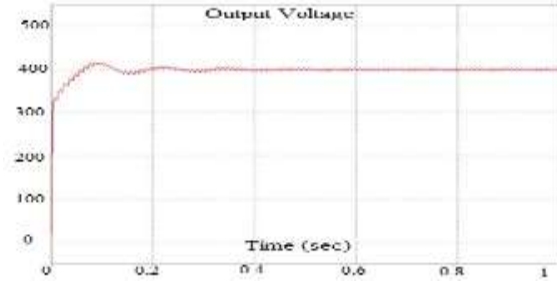
Figure 4(c). Input voltage waveform

Figure 4(d). Output voltage waveform

Capacitor design:

$$i_c = C\frac{dv}{dt}$$

A value of C= 450µF was used for hardware design purpose. The specifications of the converters are provided in Table 1 for open loop and Table 2 for closed loop respectively as shown below:

Table 1. Specifications for the open loop converter

Output power	20W
Vin range	10V
Line frequency	50Hz
Output voltage	20V

Table 2. Specifications for the close loop converter

Output power	20W
Vin range	7-18V
Line frequency	50Hz
Output voltage	20V

3.2. Experimental Set-Up with Hardware Results

Hardware results comprises of hardware design of opto-isolator circuit (TLP 250), captured image of firing pulse fed to the MOSFET from microcontroller through TLP circuit, set-up for boost converter at resistive load for fixed input voltage, at resistive load for different input voltage, set-up for boost converter at variable load at fixed input, input current and voltage waveform at different switching frequency.

3.2.1. TLP Circuit

Opto-isolator circuit is made for isolation of the power circuit and the control circuit as well as to provide the pulse generated from microcontroller to the MOSFET. Figure 5(a) shows the TLP circuit design for providing pulse to MOSFET. TLP requires a DC supply being provided by battery and AC supply provided by transformer is rectified using simple bridge rectifier circuit, the output voltage is then filtered and fed to the dc-dc boost converter. The TLP output pulse fed to MOSFET is captured in Digital storage oscilloscope (DSO) as shown in Figure 5(b) at f=15kHz.
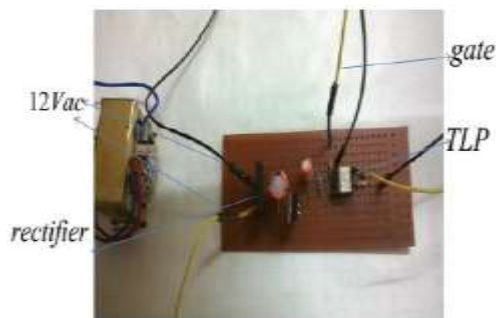

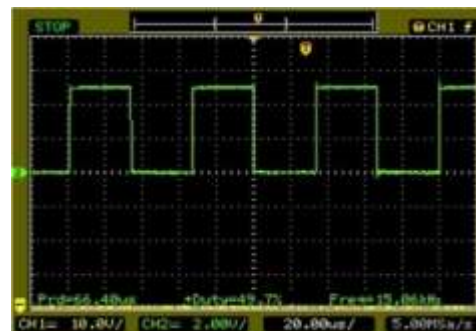Figure 5(a). TLP circuit design for providing pulse to MOSFET

Figure 5(b). TLP output pulse fed to MOSFET

3.2.2. Set-Up for Boost Converter with Input and Output Voltage

Hardware set-up of boost converter with resistive load has been shown in Figure 6. Multimeter showing the input and output voltage of the active power factor correction system. Programming is to be written in "C" coding and the output pulse from micro-controller is fed to the MOSFET of the boost converter through TLP that is being used to isolate the power and control circuit.
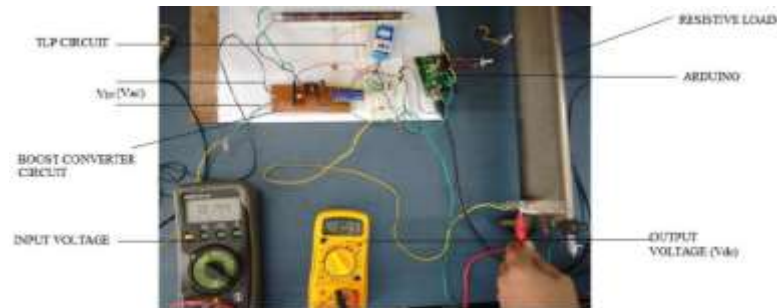

Figure 6. Experimental set-up of boost converter indicating the input and output voltage in multimeter with resistive load

3.2.3. Constant Output Voltage for Various Input Voltage

DC Battery is used to provide power supply to the TLP and the single phase auto-transformer as shown below is used to give supply to the power circuit. Handmade inductor is designed for boost converter. Mag core high flux 58548-A2 was chosen having 33mm outer diameter and a permeability of 125. Various output voltages are recorded at various input DC voltages taking resistive load into consideration as shown in Figure 7(a), 7(b), 7(c), 7(d) at a fixed value of rheostat.
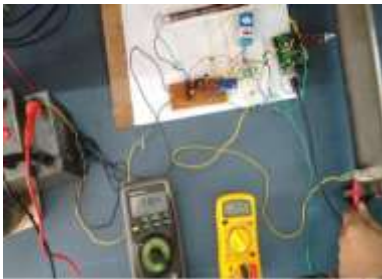

| Figure 7(a) | Figure 7(b) | Figure 7(c) |

Figure 7(d)

Figure 7. Shows almost constant output voltage at different values of input voltages i.e.
7(a) Vs=9.164V and Vo=20.5V, 7(b). Vs=9.164V and Vo=20.5V
7(c) Vs=9.164V and Vo=20.5V 7(d) Vs=9.164V and Vo=20.5V

3.2.4. Constant Output Voltage for Variable Load

Constant output voltage were recorded at different value resistive load as shown in Figure 8(a), 8(b) at 55ohm and 95ohm respectively. In Figure 8(a) Vs=12.066V and Vo=19.2V at R (resistive load)=55 ohm whereas Figure 8(b) shows Vs=12.165V and Vo=20.4V at R (resistive load)=95 ohm.

Figure 8(a)   Figure 8(b)

Figure 8. Shows almost constant output voltage at different values load i.e. 8(a). Vs=12.066V and Vo=19.2V at R (resistive load)=55 ohm, 8(b). Vs=12.165V and Vo=20.4V at R (resistive load)=95 ohm.

3.2.5. Input Current and Voltage Waveform at Different Switching Frequency

At various frequency i.e. at 15kHz and 6.7kHz, the input current and input voltage waveforms are recorded in Figure 9(a) and Figure 9(b) respectively.
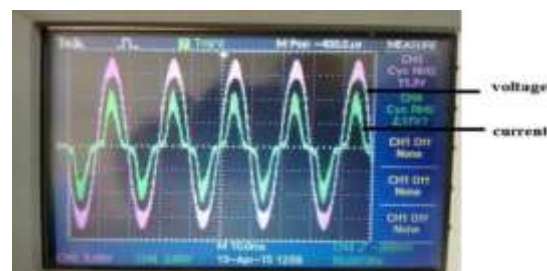

Figure 9(a).   Figure 9(b).

Figure 9. Input current and voltage waveform at different switching frequency at 9(a) 15 kHz 9(b) 6.7 kHz.

4. CONCLUSION

The effective use of grid power can be only achieved with the minimization of line current harmonics meeting the required standardization. The power factor correction is a method of removing the undesirable effects of electric loads thus obtaining unity power factor. This PFC technique is categorized into active PFC and passive PFC method depends on the selection of electric element to filter out the harmonics using the low frequency filter components. In this method, output voltage is un-controllable, therefore active switches are used for active PFC approach to obtain controllable output voltage to achieve a better line current shape. DC-DC converter is thus employed and being operated at high frequency to shape the line current waveform as sinusoidal as possible.

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Bidyut Mahato received his M.E and B.Tech degree from Birla Institute of Technology, Mesra, Ranchi and Guru Nanak Institute of Technology in 2014 and 2011 respectively. Since 2014, he is working towards the Ph.D degree from Indian School of Mines, Dhanbad in the department of Electrical Engineering. His main research interest includes Power factor correction, Phase controlled rectifiers, Multilevel inverters, Converter, AC Drives and Hybrid Electric Vehicles.

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Kartick Chandra Jana received his M.Tech and Ph.D degree from NIT Durgapur and Jadavpur University in 2003 and 2013 respectively. He is currently serving as Assistant Professor in Indian School of Mines, Dhanbad from June 2012. He has been working in Birla Institute of Technology, Mesra from July 2003 till May 2012. His research is in area of Modelling and Design of Multilevel Inverter, Real-time control of power electronics devices, Design and Implementation of efficient power converters.