



Digital Implementations of Float Rectifier cum Boost Charger for Railway Signaling

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ABSTRACT

Railway wayside signaling is a system used to control railway traffic safely, essentially to prevent trains from colliding. Therefore it is required to have a reliable power supply to keep a healthy and sustainable rail network. The methodology to develop the power supply presented in this paper involves study and implementation of power factor correction (PFC) boost-converter integrated with two-switch DC-DC forward-converter for high voltage and high frequency application using individual digital signal processors (DSPs). The proposed method confirms the efficient and reliable operation of the integrated converters with the line side power factor maintained to near unity for various load conditions. This approach not only reduces the size of magnetic components, but also makes it possible to achieve a fully-controlled AC-DC-AC converter when further integrated with single-phase inverter.

Key words: PFC boost converter, two switch DC-DC Forward converter, integration of power stage, FRBC module, single phase H-bridge inverter, with better THD (total harmonic distortion) and power factor

INTRODUCTION

SMPS (Switch mode power supply) are extensively used inside most of electrical and electronic appliances today such as in computers, televisions and audio sets etc. Basically the power factor and harmonics related problem occurs in the power companies, because they cannot compensate for the harmonic current by adding simple LC filter. It presents a non-linear impedance to the mains, as a result of the input circuitry. The input circuitry consists of a full wave diode bridge rectifier followed by capacitor. The capacitor maintains a voltage of approximately the peak voltage of the input sine wave. The current will be drawn from the input only when input voltage exceeds the capacitor peak voltage and the current pulse must contain enough energy to sustain the load until next peak. So the current has very large amplitude and the power factor is very poor and it has very poor THD [1].

Another reason to employ PFC in many of today's power supplies is to comply with regulatory requirements according to (International Electrotechnical Commission Standards) IEC 61000-3-2 [7] and (European standards) EN 61000-3-2 [8] Harmonic Standards. A typical SMPS makes a DC bus using a rectifier circuit followed by large storage capacitor to make the DC voltage almost ripple free.

So the problem with this is that it is a non-linear load and hence the input current is highly distorted so that non-linearity Effect on Electricity Distribution Network [1]. And this problem is eliminated by using Digital implementation. The basic block diagram of FRBC (Float rectifier cum boost charger) module is given in Fig. 1. FRBC (Float rectifier cum boost charger) module consists of closed loop PFC Boost converter and closed loop Two Switch DC-DC Forward converter. And that's output is given to the Single phase inverter.

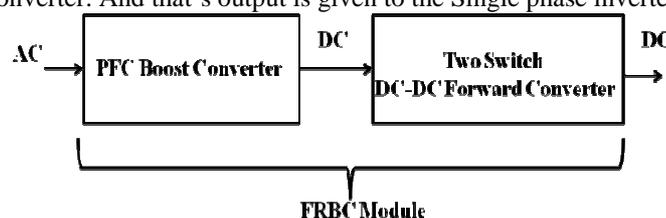
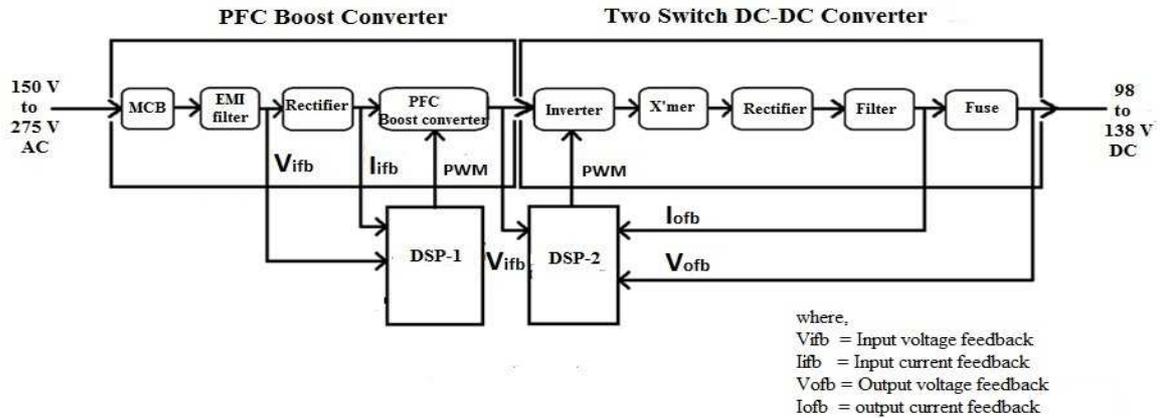


Fig. 1 Basic Block Diagram of Digital Implemented FRBC Module

In this paper design and calculations have been carried out for PFC Boost Converter as well as Two Switch DC-DC Forward Converter. Calculated results are verified through simulation. Here the output of PFC boost converter is given to the two switch DC-DC forward converter as shown in Fig. 2. And PFC boost converter and DC-DC converter are controlled by individual DSP control cards as well as power feedback. The output of DC-DC Converter is given to the Single phase Inverter and to the battery bank.



PFC BOOST CONVERTER

Types of Power Factor Correction Techniques

Here Active PFC is employed so it is very popular in the Industries because power electronic system that controls the amount of power drawn by load in order to maintain the power factor close to unity [1] and the active PFC circuits operate at a higher switching frequency than the line frequency to allow a large reduction in the size and cost of passive filter elements [3].

Basics of PFC Boost Converter

Its reshapes the distorted input waveform to approximate a sinusoidal current that is in phase with the input voltage. This leads to the development of a new area in switch mode power supply design, i.e. the current mode control [9]. Boost converter produces the output voltage more than input voltage. Therefore the MOSFET switch rated is rated for voltage greater than output voltage. The input current is continuous and hence the stress on the switch is less, making it suitable for high power applications [3] and [4]. But the new digital control PFC strategy based on CCMC (continuous current mode control) can be implemented by a low cost DSP with Boost circuit as the power stage [12].

In Fig. 3 the feedback output voltage signal is compared with the reference voltage and the difference between them produces the error signal for the voltage regulator. The instantaneous input voltage is sensed and after multiplication of voltage error and instantaneous input voltage, reference current will be generated. Now this reference current is compared with the instantaneous input current and from that compared signal, the gate pulses has been generated and provided for the switch via the PWM module inside DSP TMS320F28062 [12].

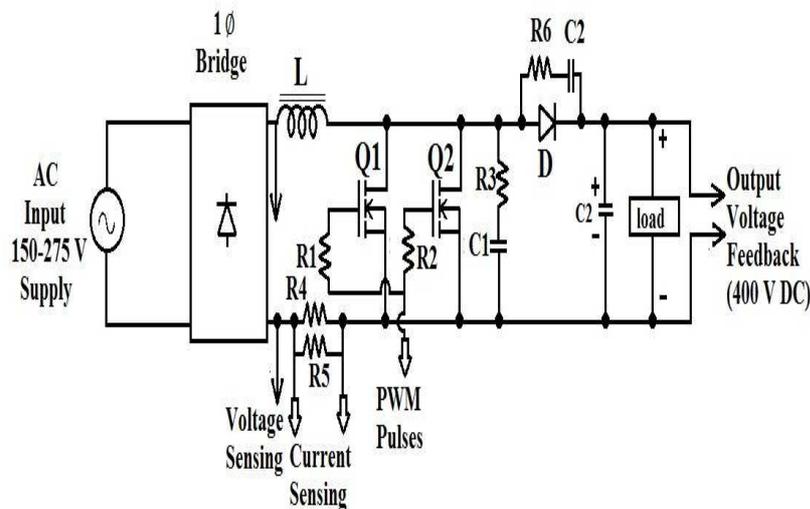


Fig. 3 Schematic diagram of PFC Boost Converter

Table -1 Design Parameters

Parameters	Ratings
RMS Input Voltages	230 V AC
Required DC Output Voltage	400 V DC
Required DC Output Current	6 A DC
DC Output Power	2400 W
Permissible inductor Current Ripple	20 % of $I_{in(max)}$
Output Efficiency	> 0.85
Switching Frequency	70 kHz

Design and Calculations of PFC Boost Converter

The design parameters [6] are as given in the Table -1, The input power of PFC Boost converter is,

$$P_{in} = \frac{P_{out}}{\eta} \tag{1}$$

$$I_{in(RMS)} = \frac{P_{in}}{V_{in(RMS)}} \tag{2}$$

$$I_{in(max)} = \sqrt{2} \times I_{in(RMS)} \tag{3}$$

According to IEC 1000 harmonic distortion specifications, the current ripple is (= 20 % of the $I_{in(max)}$) considered. Therefore the current Δi passing through inductor is to be,

$$I_L = 0.2 \times I_{in(max)} \tag{4}$$

$$I_{in(avg.)} = \frac{2 \times I_{in(max)}}{\pi} \tag{5}$$

$$I_{out(max)} = \frac{P_{out}}{V_{out(max)}} \tag{6}$$

$$D = \frac{V_{out(max)} - V_{in(max)}}{V_{out(max)}} \times 100 \tag{7}$$

Where; Pout = DC output power, Pin = AC input power, η = Input efficiency, Vin (rms) = AC input RMS current
 $I_{in(max)}$ = AC input maximum current, $I_{in(avg)}$ = Average AC input current, I_L = Inductor current
 Δi = Inductor current ripple, $I_{out(max)}$ = Maximum DC output current

The selection of inductor and the capacitor in the Boost topology plays a major role in the output response,

$$L = \frac{V_{in(min)} \times D}{F_{s/w} \times \Delta i} \tag{8}$$

Where; L = Inductance, $F_{s/w}$ = Switching Frequency, Vin (min) = Minimum input voltage, D= Duty cycle
 Here consider 5 % tolerance in output voltages so that the value of the output Capacitor is,

$$C_{out} = \frac{I_{out(max)} \times D}{F_{s/w} \times \Delta V_{out}} \tag{9}$$

Where; ΔV_{out} = Output Voltage ripple, C_{out} = Output capacitance

SIMULATION RESULTS OF PFC BOOST CONVERTER

Table -2 Simulation Parameters

Parameters	Values
Booster Inductor	165 μ H
Output Capacitance	2000 μ F
AC input voltage	230 V
Load Resistance	66.66 Ω
Output voltage sensor gain	0.0049
Rectified voltage sensor gain	1
Rectified current sensor gain	9.5
PWM Switching Frequency	70 kHz

As shown in Fig. 4 and Table-2, the simulation of PFC boost converter is carried out and the result wave forms are obtained which are shown in Fig. 5 & 6.

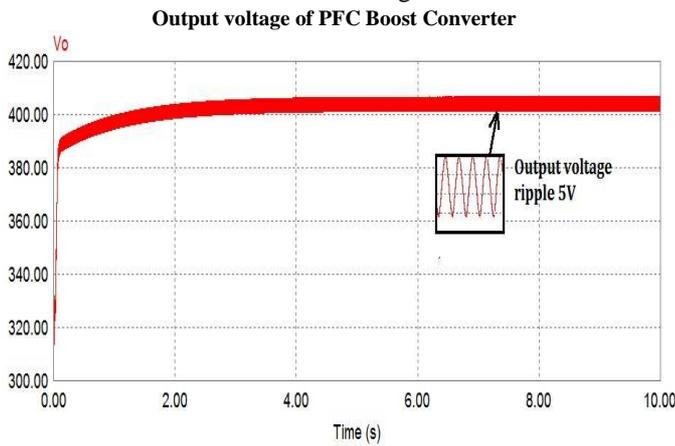


Fig. 5 Output DC Voltage [$V_{o(avg)} : 400 \text{ V}$] [Scale: X axis: 100 V/div. , Y axis: 1 s/div]

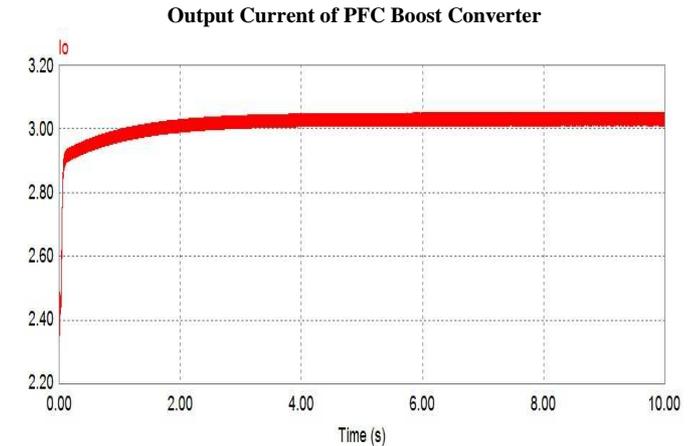


Fig. 6 Output DC Current [$I_{o(avg)} : 20 \text{ A}$] [Scale: X axis: 1.05 A/div. , Y axis: 1 s/div]

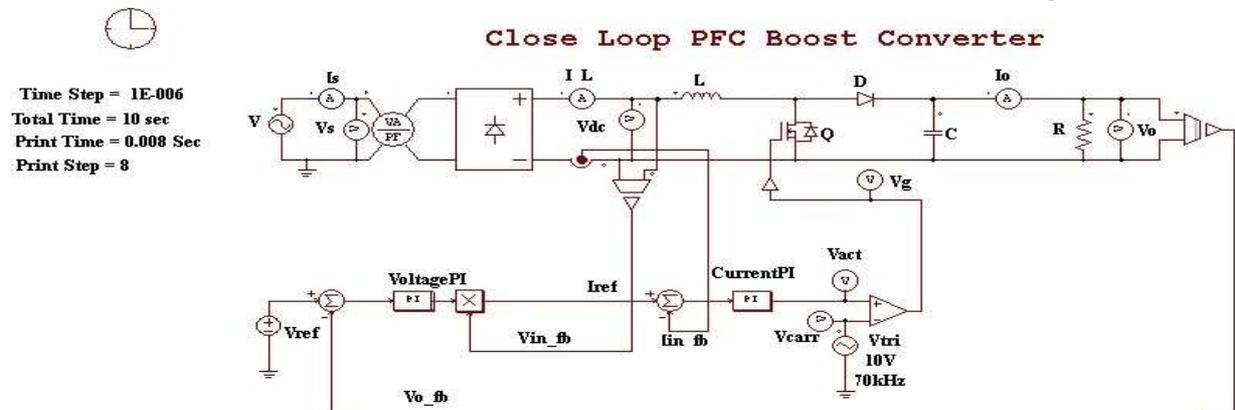


Fig. 4 Close loop simulation diagram of PFC boost converter

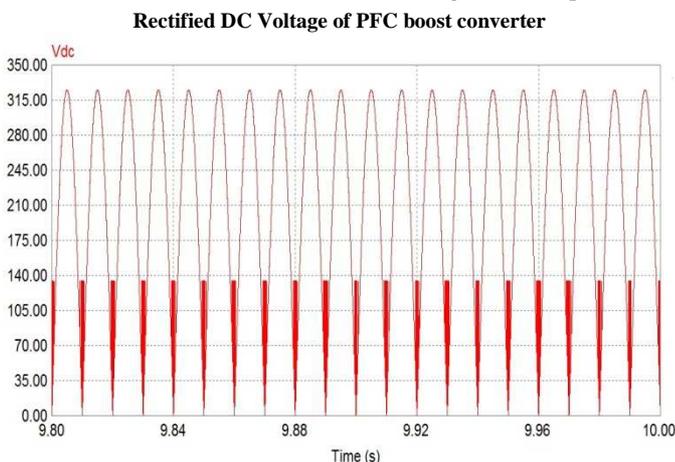


Fig. 7 Rectified DC Voltage [$V_{dc} : 248.5 \text{ V}$] [Scale: X axis: 84 V/ div. , Y axis: 0.01 s/div]

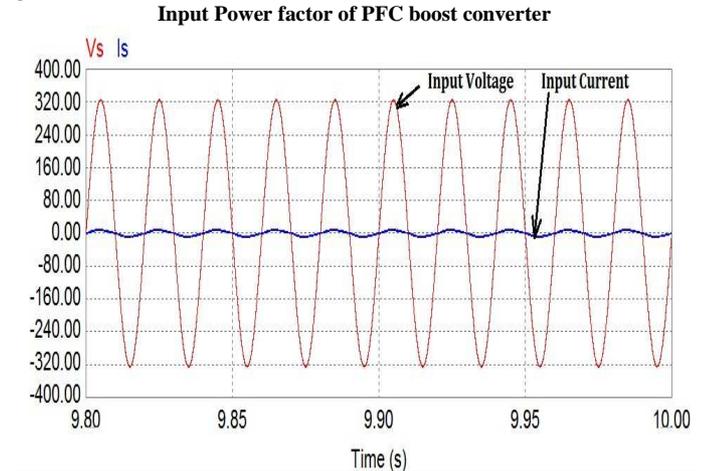


Fig. 8 Input Power factor [PF: 0.995]

Hardware Results of PFC Boost Converter by Digital Control

In the hardware implementation, the main component Values of the Boost circuit are inductor 280 μH , output filter Capacitor 2000 μF .

Table-3 Hardware Parameters

Parameters	Values
Booster Inductor	280 μH
Output Capacitance	2000 μF
AC input voltage	230 V
Load Resistance	50 Ω

Here experimental results are shown in steady state condition and it is shown that the power control works nicely near to unity power factor at nominal voltage (230 V AC) when loads are at 50% and 100% loading condition, the input line current and line voltages are shown in Fig. 9 & 10.

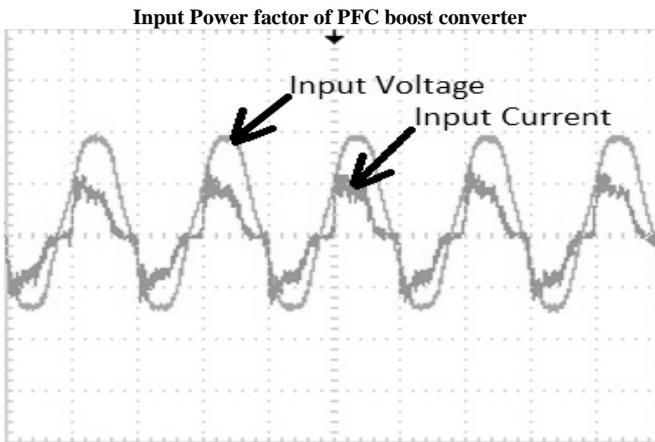


Fig. 9: Input Power factor [PF: 0.918] at 50 % loading condition [3 A] [VRMS: 239 V, IRMS: 3.2 A, Input Power factor: 0.918 [Scale: (Ch-1; Y axis: 100 V / Div)(Ch-2; Y axis:5 A / Div), X axis:5 ms / Div]

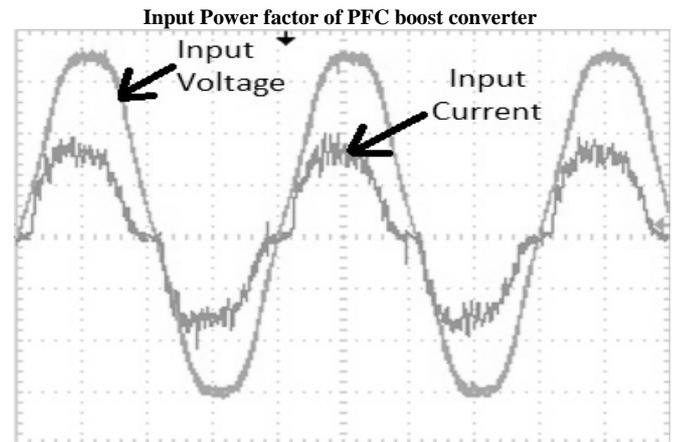


Fig. 10: Input Power factor [PF: 0.963] at 100 % loading condition [6 A] [VRMS: 239 V, IRMS: 8.6 A, Input Power factor: 0.963 [Scale: (Ch-1; Y axis: 100 V / Div) (Ch-2; Y axis: 5 A / Div), X axis: 5 ms / Div]

TWO SWITCH DC-DC FORWARD CONVERTER

Basics of Two Switch DC-DC Forward Converter

Single-switch forward converter is widely used due to the advantage of simple structure and low cost. But there is a disadvantage of high voltage stress of switch, in order to overcome that disadvantage by using two switches DC-DC forward converter [12].

In Fig. 11 shown the two switches DC-DC forward converter, here it could be divided into three modes such as energy transfer stage, transformer reset stage and dead time stage. In energy transfer Stage, both primary switches are turned on; energy is transferred from input to output. In transformer-reset stage, two primary diodes will conduct and apply reversed input voltage to the transformer winding to reset the transformer. When transformer is totally reset, converter will come into dead time stage with no current in the primary side while secondary side is freewheeling [11].

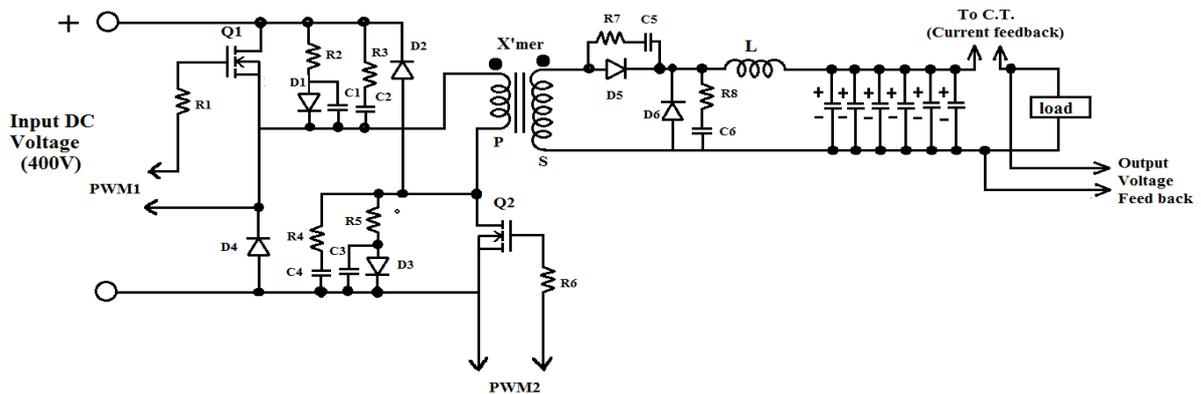


Fig.11 Schematic diagram of Two Switch DC-DC forward converter

Design and Calculations of Two switch DC-DC Forward Converter [5]

The design parameters [6] are as given in the Table -4,

Table- 4 Design Parameters

Parameters	Ratings
Output voltage	110 V
Output current	20 A
Output power	2200 kW
Permissible Output current ripple	20 % of I_o
Switching frequency	50 kHz
Input voltage	400 V
Input efficiency	> 90 %

Design of High Frequency Transformer [10]

Secondary Output power $P_o = (V_o + V_{rl} + V_d) \times I_o$ (10)

Where; V_{rl} = Resistive Drop in the Inductor [$\approx 10\%$ of V_o], V_d = Output Diode drop [≈ 1.5 V in worst case]

Area of Product $A_p = \frac{\sqrt{D_{max}} \times P_o \times \left(1 + \frac{1}{\eta}\right)}{K_w \times J \times B_m \times F_{s/w}}$ (11)

Where; K_w = Window Utilization Factor [≈ 0.3 to 0.4],

B_m = Max. Allowable flux density [≈ 0.2 T to 0.3 T]

J = Current Density,

A_c = Area of core

Window area $A_w = \frac{A_p}{A_c}$ (12)

Primary turns $N_1 = \frac{V_{i(max)} \times D_{min}}{A_c \times B_m \times F_{s/w}}$ (13)

Turns ratio $n = \frac{V_o \times V_{rl} \times V_d}{V_{i(min)} \times D_{max}}$ (14)

Secondary turns $N_2 = n \times N_1$ (15)

Where; RMS secondary current $I_2 = I_o \times \sqrt{D_{max}}$ (16)

RMS secondary current $I_1 = n \times I_2$ (17)

Primary inductance $L_1 = \frac{\mu_o \times \mu_r \times A_c \times N_1^2}{l_m}$ (18)

Magnetizing current $I_{mag} = \frac{D_{max} \times V_{i(min)}}{F_{s/w} \times L_1}$ (19)

Area of primary conductor $a_p = \frac{I_1}{J}$ (20)

Area of secondary conductor $a_s = \frac{I_2}{J}$ (21)

Design of Output Inductor [10]

Output inductance $L = \frac{V_o \times (1 - D_{max})}{\Delta i \times F_{s/w}}$ (22)

Peak current of inductor (23)

Area of product $A_p = \frac{2E}{K_w \times K_c \times J \times B_m}$ (24)

Where; E = Energy dissipation in inductor

HARDWARE IMPLEMENTATION OF TWO SWITCH DC-DC FORWARD CONVERTER BY DIGITAL CONTROL

DC-DC forward converter is implemented by using DSP TMS320F28062 controller. Here its input voltage of DC-DC converter is 400 V, 6 A DC from the PFC Boost Converter and its hardware results are shown in Fig. 12-15.

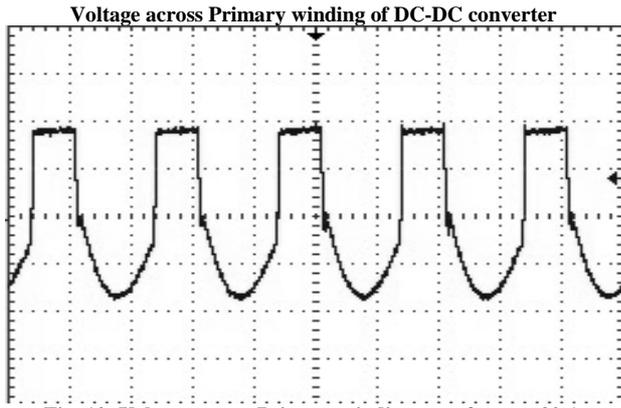


Fig. 12: Voltage across Primary winding waveform at 20 A [Vpri: 395 V, Io: 20A] [Scale; Y axis: 200 V / Div, X axis: 5 μ s / Div]

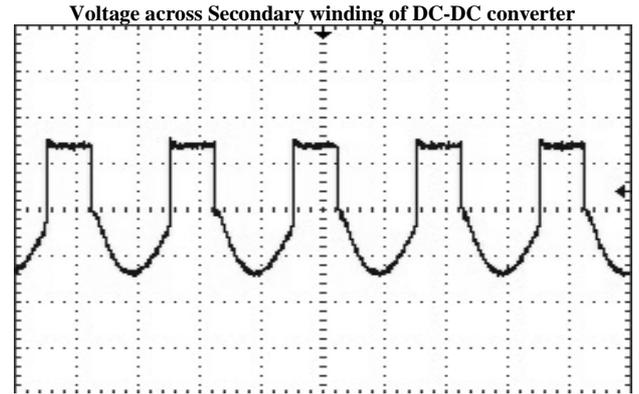


Fig. 13: Voltage across Secondary winding waveform at 20 A [Vsec: 110.2 V, Io: 20 A] [Scale; Y axis: 200 V / Div, X axis: 5 μ s / Div]

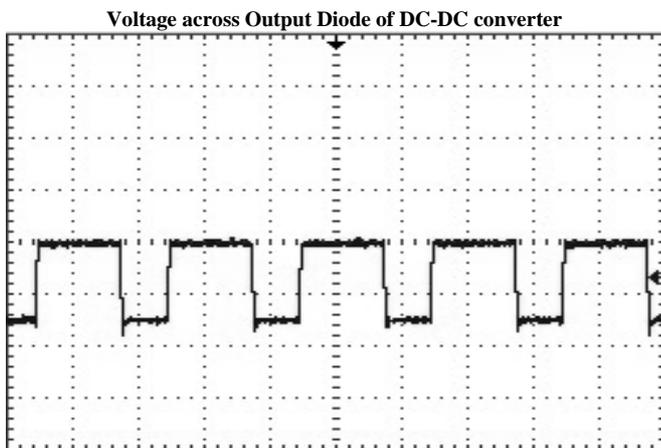


Fig. 14: Voltage across Output Diode (D6) at 20 A [V_{D6}: 110.2 V, Io: 20A] [Scale; Y axis: 200 V / Div, X axis: 5 μ s / Div]

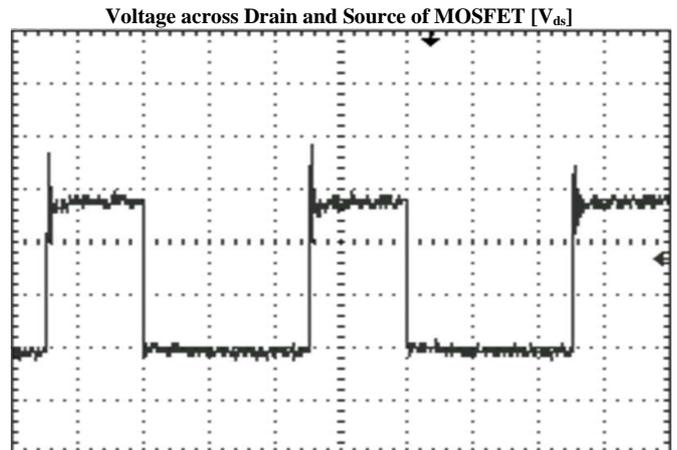


Fig. 15: Voltage across Drain and Source at 20 A [V_{ds}: 110.2 V, Io: 20 A, [Scale; Y axis: 100 V / Div, X axis: 5 μ s / Div]

INTEGRATION OF PFC BOOST CONVERTER WITH DC-DC TWO SWITCH FORWARD CONVERTER

Initially Electrical parameters such as V_o , I_o and V_{in} from the Power card by using of sensors and then after ADCs, GPIOs and interrupts of the DSP will be initialized.

Flow chart of PFC Boost converter Integrated with Two switches DC-DC Converter

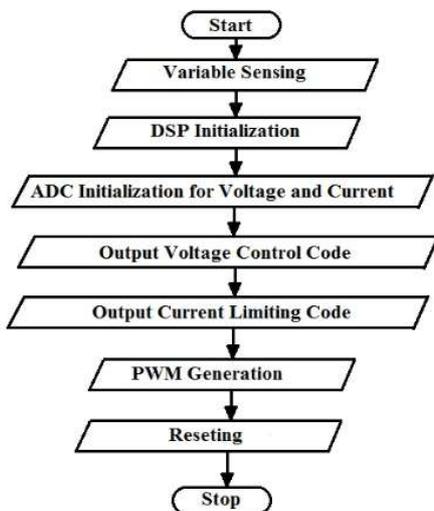


Table -5 Design Parameters Integrated with Two switch DC-DC Converter using Digital control

Parameters	Ratings
RMS Input Voltages range	150-275 V AC
Required DC Output Voltage	110 V
Required DC Output Current	20 A
DC Output Power	2200 W
Permissible inductor Current Ripple	20 % of $I_{in(max)}$
Output Efficiency	> 0.85

Table -6 Load Regulation

$V_{in}(V)$	$I_{in}(A)$	$V_o(V)$	$I_o(A)$	(I/P)PF	%THD _I
240	1.6	110.2	5	0.918	--
239	3.2	110.2	10	0.963	8.58
237	8.6	110.2	15	0.981	7.07
235	11.4	110.2	20	0.989	6.57

Hardware Implementation of PFC Boost Converter
At 25 % load of Full load 20 A

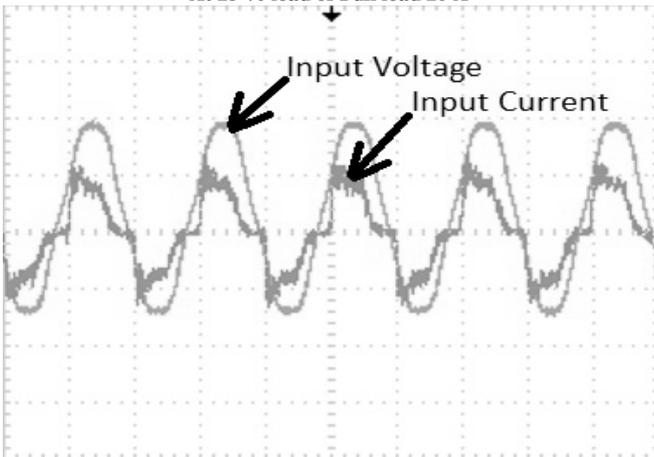


Fig. 16 Input voltage and Input current waveform at 5 A [Vrms: 240V, Irms: 1.6 A] Input Power factor: 0.918 [Scale: (Ch-1; Y axis: 200 V / Div) (Ch-2; Y axis:5 A / Div), X axis:10 ms / Div]

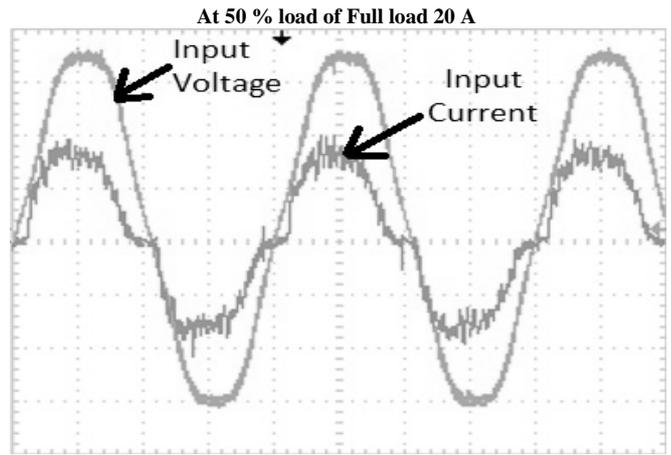


Fig. 17 Input voltage and Input current waveform at 10 A [Vrms: 239 V, Irms: 3.2A] Input Power factor: 0.963 [Scale: (Ch-1; Y axis: 100 V / Div)(Ch-2; Y axis:5 A / Div), X axis:5 ms / Div]

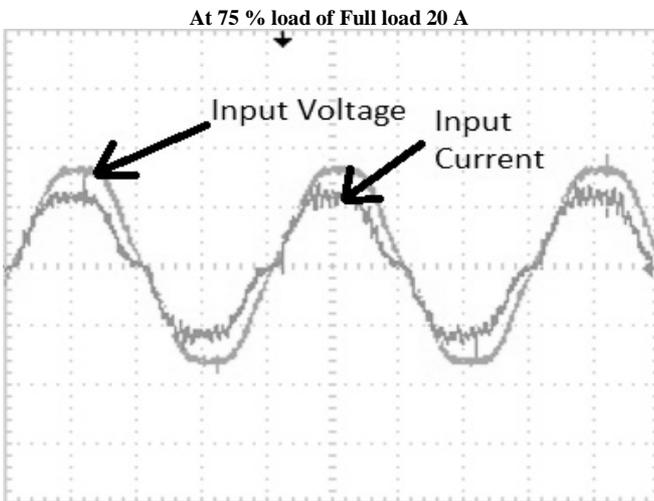


Fig. 19: Input voltage and Input current waveform at 15 A [Vrms: 238 V, Irms: 8.6A] Input Power factor: 0.981 [Scale: (Ch-1; Y axis: 200 V / Div)(Ch-2; Y axis:10 A / Div), X axis:5 ms / Div]

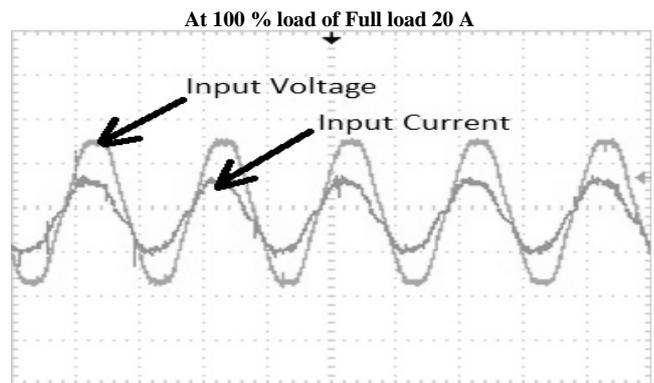


Fig. 21: Input voltage and Input current waveform at 20 A [Vrms: 235V, Irms: 11.4A] Input Power factor: 0.989 [Scale: (Ch-1; Y axis: 200 V / Div) (Ch-2; Y axis: 20 A / Div), X axis: 10 ms / Div]

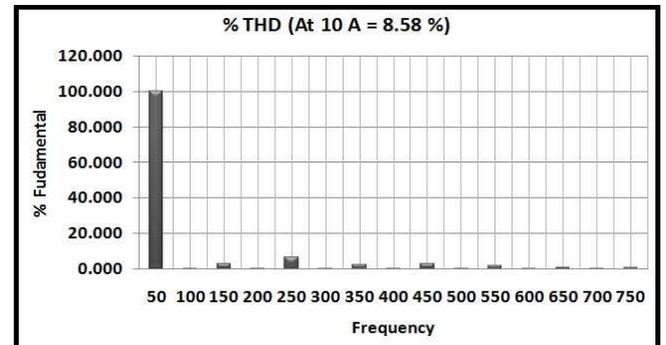


Fig. 18: % Input current THD at 10 A [%THD₁ = 8.58]

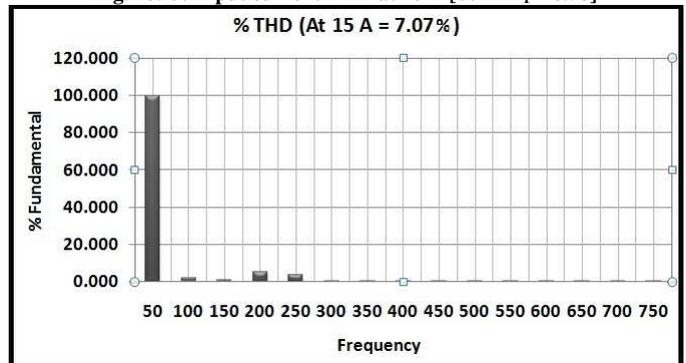


Fig. 20: % Input current THD at 15 A [%THD₁ = 7.07]

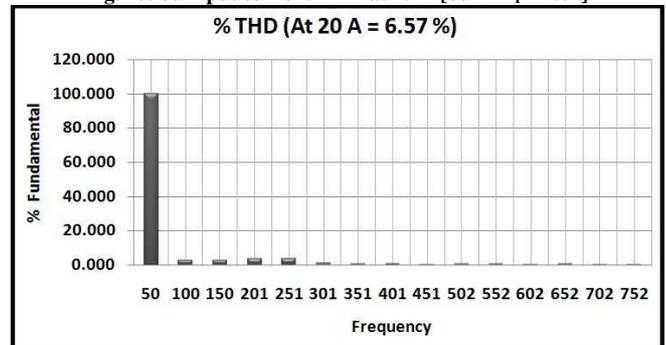


Fig. 22: Input voltage and Input current waveform at 20 A

Load Regulation of PFC Boost converter Integrated with Two Switches DC-DC Converter [6]

From Table-6, it can be seen that when the load resistance value gradually increased in step of 25%, 50%, 75% and 100% load, output voltage is remain constant at 110.2 V and input power factor is improved near to unity with better % Input current THD which is fulfilled the specifications.

Line Regulation of PFC Boost converter Integrated with Two Switch DC-DC Converter [6]

From Table-7, it can be seen that when the supply input voltage gradually increased in step of 150 V, 230 V and 275 V with 25%, 50%, 75% and 100% loading condition, output voltage is remained constant at 110.4 V and input power factor is improved with better % Input current THD which is fulfilled the specifications.

Table -7 Line Regulation

I_o (A)	V_{in} (V)	I_{in} (A)	V_o (V)	(I/P)PF	%THD _i	% η_o
5	150	4.7	110.4	0.945	N/A	82.85
	230	3.2	110.4	0.898	N/A	83.51
	275	2.8	110.4	0.857	N/A	83.65
10	150	8.0	110.4	0.967	8.44	95.14
	230	5.8	110.4	0.948	9.20	87.29
	275	4.8	110.4	0.900	9.37	92.92
15	150	11.8	110.4	0.988	8.50	94.69
	230	8.4	110.4	0.967	9.00	88.63
	275	7.3	110.4	0.923	9.42	89.37
20	150	16.2	110.4	0.989	8.60	91.87
	230	11.0	110.4	0.977	8.90	89.32
	275	8.93	110.4	0.965	9.14	93.17

Filter Design

If surrounding heavy inductive load switching exist then magnetic interference would be come in to the input supply and it will generate noise in the supply system and input current as well as voltage may get non sinusoidal wave form so that to suppress the electromagnetic interference and radio frequency interference noise in the input supply so there is required to connect a low pass filter between the input supply and PFC boost converter input. Here Passive low pass harmonic filter will be used to reduce voltage harmonics and current distortion.

This filter may be of L type or LC type or LCL type filter. The L type filters provide an attenuation of -20 dB/decade for all the range of frequencies. The switching frequency of inverter needs to be high in case of L filter for effective attenuation of high order harmonics [13].

So as the switching frequency increases, the switching losses will increase. The resonance frequency of the LC filters changes with the change in input impedance so it is not recommended where electromagnetic interference is quite high [12].

The key advantages of LCL filter are:

- Attenuation of -60dB/decade of the frequencies in excess of the resonance frequency.
- It is possible to go with relatively low switching frequency for the given harmonic attenuation.

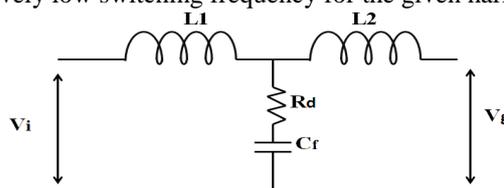


Fig. 23: Basic block schematic of LCL type filter

The main LCL circuit connection is shown in Fig. 23. Where V_i is the input AC voltage; L_1 is the input AC supply side inductor and L_2 is the PFC booster side inductor; C_f is the filter capacitor and R_d is the damping resistor.

CONCLUSION

For a single-stage power factor correction Boost converter and a Two Switch DC-DC forward type converter a design process have been carried out and the hardware results have been achieved as per calculation. And the power factor correction converter is used to shape the line current to resemble the line voltage waveform and there is achieved nearly unity power factor. On the other hand, dc-dc converter is used to provide regulated load voltages with the galvanic isolations from the input side.

A two switch DC-DC forward converter with active clamp was analyzed in this paper. The active clamp circuit is used to demagnetize the transformer after every ON period of the MOSFETs. The active clamp circuit also acts as a snubber circuit for the MOSFETs and it's able to recycle the magnetizing and leakage energy. Here several tests have been carried out such like Efficiency test, Transient Test, Temperature Rise test and Heat-Run test and with the integration of FRBC module and Inverter is successfully working with good efficiency and better harmonic spectrum.

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