Design and implementation of analog controller to reduce line current distortion of high input power factor boost rectifier

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Abstract— This paper presents design and implementation of analog controller to obtain high input power factor and low input current distortion in a single phase boost PFC rectifier. The proposed control scheme ensures the reduction in input current distortion at higher voltage loop bandwidth. The dominant second order ripples in the control voltage are eliminated by a simple RC filter stage placed immediately after PI controller. This controller requires minimum additional circuitry. The proposed controller reduces the harmonic distortion to 6-7% at voltage loop bandwidth as high as 50Hz. A 250W single phase rectifier system is designed and simulated on MATLAB/SIMULINK software. A prototype of single phase boost converter rated at 250W, 85V-260V (input rms), 385V (output) is implemented with the UC3854 analog controller to validate the proposed control method.

Index Terms— AC-DC power conversion, Analog controller, Boost rectifier, Input current distortion, Power factor correction, Power quality improvement, Pulse width modulation,

1 Introduction

SINGLE phase pulse width modulated (PWM) rectifiers are used to maintain a high quality input current with unity power factor to satisfy the necessary harmonic standards [1] of the utility. Single phase boost rectifier with high bandwidth voltage loop exhibits fast dynamic response but offers high input current distortion. The high input current distortion pollutes the utility supply which in turn introduces disturbances in other appliances connected to the same supply. Two important dynamics which affect the performance of rectifier are 1) Dips and rises in the input voltage 2) Frequent variations in the load. This forces the switching and magnetic components to subject to higher stresses and results in reduction in efficiency of the rectifier. The efficiency of the rectifier reduces significantly under the low input voltage and the light-load conditions [2].

A conventional control of a single phase boost rectifier system is shown in Fig.1. Low input current distortion and high power factor is achieved by a fast current control loop (8-10 kHz) and a slow voltage loop (10-15Hz) [3]-[7]. The dynamic response and the input current distortion are largely influenced by bandwidth of the voltage control loop. Low bandwidth of the voltage control loop reduces the current distortion but responds slowly to transients. In order to draw a compromise between good current quality and fast dynamic response, various methods have been proposed .

The input current distortion in boost rectifiers is mainly due to the even order harmonics present in the output voltage. Several methods are presented to eliminate harmonics from output voltage before it is processed to form a current reference. The second-harmonic ripple from the output voltage is compensated by using the ripple estimators as given in [8]-[10]. This method requires additional sensing or measurement requirements. In order to eliminate second order as well as higher order harmonics dead zone characteristics of A-D coneverters is used in [11].

Various forms of filters are used in the voltage loop to eliminate dominant low order harmonics from output voltage. A notch filter [12]-[13], having notch frequency set at second-harmonic frequency reduces 2nd order ripples but higher order ripples are not reduced. The comb filter [14] with multiple notches for harmonics of second order and multiples has a complex analog implementation. The work presented in [15] is a simple digital implementation of a running average filter on FPGA platform. This filter allows 2-3% of additional current distortion during line frequency variations as the clock signal has a fixed averaging period.

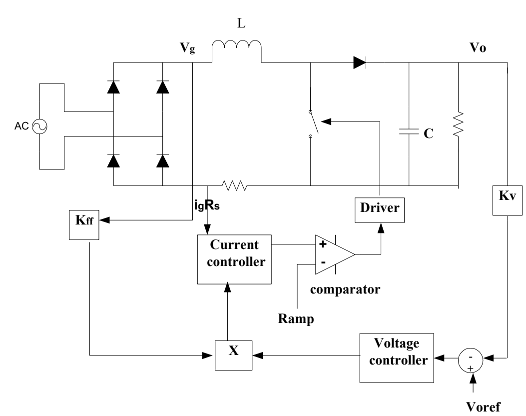


Fig.1 Conventional boost rectifier

In this paper a simple method is proposed to address the challenge of obtaining both low input current distortion and fast dynamic response at a common high bandwidth of the voltage loop (40-50Hz). The proposed filter requires minimum additional circuitry in analog domain. Hence proposed filter has a simple analog and digital implementation. The work presented here proposes a simple RC low pass filter to be introduced as shown in Fig.2 in a high bandwidth voltage loop to filter out the harmonics from PI regulator output before it is further processed. The proposed methodology is implemented using UC3854 PFC controller.

Section II presents the overview, working principle and model of the proposed controller. In section III design and development of the experimental set up is presented. The simulation and experimrntal results are presented in section IV. Section V concludes the paper.

2 Overview Of The Proposed work

2.1 Input Current Distortion in Boost Rectifier

The conventional AC-DC power conversion circuits connected to utility supply absorb distrorted current from the supply. The output voltage of the boost PFC rectifier has ripples at twice the line frequency (100Hz) as described by Eq.(1). The output voltage consists of a constant dc and varying quantity (at 100Hz) components. At a low bandwidth (10-15Hz) of the voltage loop these ripples are effectively attenuated by the PI regulator. But PI regulator continues to carry the ripples to the next stage at higher voltage loop bandwidth (40-50Hz). These ripples are responsible for the input current distortions because this signal is further processed to form a current reference and to generate pulses.

$$v_{out} = \underbrace{v_o(t)}_{dc} + \underbrace{\frac{P_{out}}{2\omega C V_o}\sin(2\omega t)}_{\text{var}\,ying} \qquad (1)$$

The input current waveshaping technique includes two major tasks (i) to reduce the line current distrortion and (ii) increasing the input power factor close to unity. In addition to this, a fast dynamic response is obtained by deigning a high bandwidth voltage loop.

2.2 Proposed Analog Filter

In order to attenuate the ripples at voltage control stage, a simple RC low pass filter shown in Fig.2. is introduced after the PI regulator in the voltage feedback loop. The filter blocks the components of control voltage above the specific cutoff frequency (2f) .This indicates that harmonics at 2f and higher odd multiples of 2f components are effectively blocked by the filter. The cutoff frequency (f_C) given by (3) is set at 2f/4 (10~20Hz) to eliminate second order ripples from regulator output.

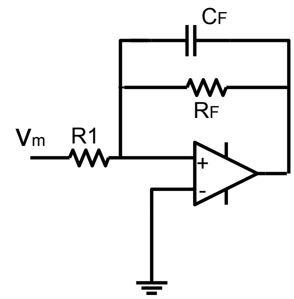


Fig.2 RC filter

$$f_C = \frac{1}{2\pi R_F C_F} \qquad (2)$$

The filter enables to set a high bandwidth of the voltage loop thereby improving the dynamic response of the boost rectifier

2.3 Model of Voltage Loop and Analysis

The small signal model of the boost rectifier is developed to analyse the closed loop performance[16]. The voltage loop model parameters (3)-(6) play a significant role in limiting input current distortion. The model of the voltage loop with proposed controller is shown in Fig.3(a).

The bode plot is shown in fig.3(b) for 50% and 100% load with phase margins of 53^0 and 54^0 respectively. The filter transfer function is given by (5).The filter pole T_f is placed at 20Hz. In order to compensate for pole introduced by the filter in the voltage loop, a lead lag compensator (6) is designed. The compensator zero is placed at T_c=T_f, such that filter pole is cancelled and pole T_p is placed at high frequency.

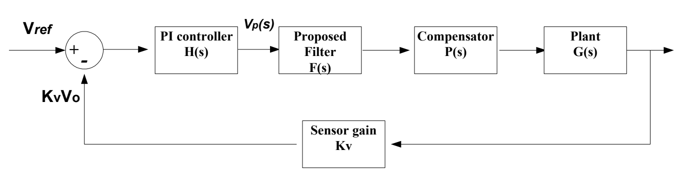


Fig.3 Voltage loop Model

$$H(s) = \frac{K_v}{1 + sT_v} \qquad (3)$$

$$G(s) = \frac{1}{2}\frac{V_s}{V_o}\frac{(R_o/2)}{1 + s(R_o/2)C_0} \qquad (4)$$

$$F(s) = \frac{K_f}{(1+T_f s)} \quad (5)$$

$$P(s) = K_i \frac{(1+T_C s)}{(1+T_p s)} \quad (6)$$

R_o is load resistance, C_o is output capacitance
K_v and T_v are PI controller parameters.
K_f and T_f are Filter parameters
T_c and T_p are compensator parameters

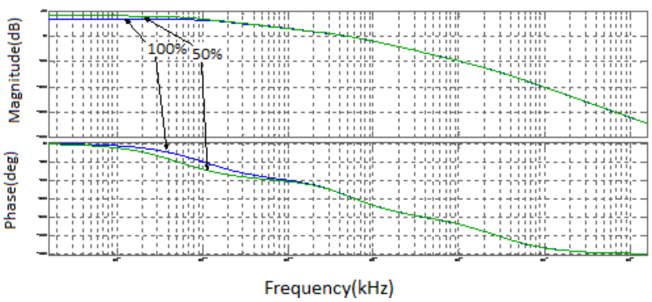


Fig.4 Frquecy domain plot of voltage loop with filter

3 EXPERIEMENTAL SETUP

A 250W, 85V-260Vrms input voltage, 385V output, single phase boost rectifier prototype is designed [17] and implemented with the proposed controller .The operation of the controller is verified on MATLAB/SIMULINK software. The control scheme is tested and verified on hardware prototype.

3.1 Design

The design specifications of the single phase universal input voltage boost rectifier are presented in Table I. The Inductor and output capacitor values are obtained by,

$$L = \frac{V_{in} D}{\Delta i_L f_s} \quad (7)$$

$$C_o = \frac{2 P_o t_h}{V_o^2 - V_{o\min}^2} \quad (8)$$

D is duty ratio, Δi_L is ripple current, f_s is switching frequency

The control scheme is implemented using UC3854 analog controller as shown in Fig.5. The components of the voltage control loop are designed based on following expressions.

TABLE 1
DESIGN PARAMETERS OF BOOST RECTIFIER

Parameter	Specification	Parameter	Specification
Output Power (P_o)	250W	Current sense gain (R_s)	0.25Ω
Load Voltage(V_o)	385V	Inductor (L)	8mH
Input Voltage(V_{in})RMS	85-265V	Output Capacitor(C_o)	470uF
Line frequency (f)	50Hz	Switch (S_1) (MOSFET)	IRFP460
Switching frequency (f_s)	10kHz	Diode(D1) (Ultra fast)	MUR1660
Output voltage sensor gain (K_v)	0.02	Diode Bridge	DFB2060

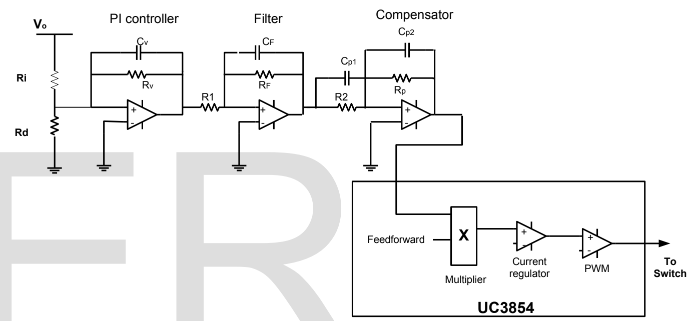


Fig.5 Proposed controller implementation

PI controller parameters (set at 50Hz) are given by,

$$K_v = \frac{R_v}{R_i}, T_v = R_v C_v \quad (9)$$

The values of RC Filter parameters (set at 10-20Hz) are computed using,

$$K_f = \frac{R_f}{R_1}, T_f = R_f C_f \quad (10)$$

The lead- lag Compensator parameters are given by,

$$K_i = \frac{C_{p1}}{C_{p2}}, T_c = R_2 C_{p1}, T_p = R_p C_{p2} \quad (11)$$

A series combination of PI regulator H(s), filter F(s) and compensator P(s) is implemented externally using LM324 op-amp. The output of this stage connected fed to current reference input of the (Pin7 of UC3854) multiplier. R_i and R_d form a voltage divider for output voltage sensing. The experimental setup is as shown in Fig.6.The boost PFC Board and load arrangements are shown.

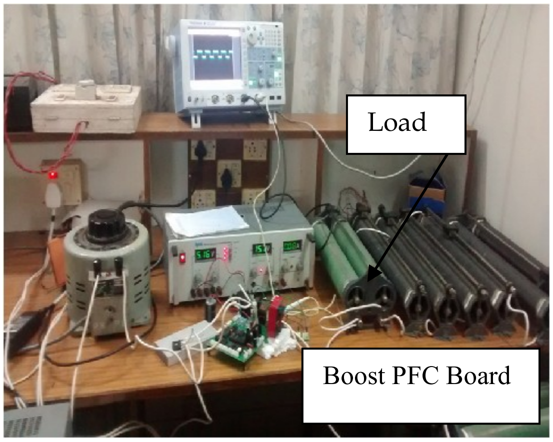


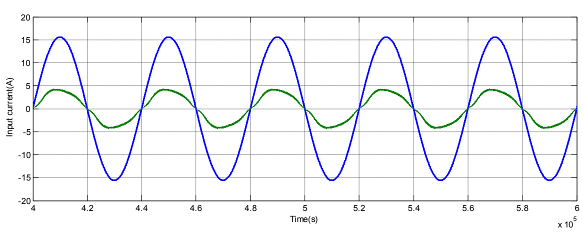
Fig.6. Experimental setup

4 Simulation and Experimental Results

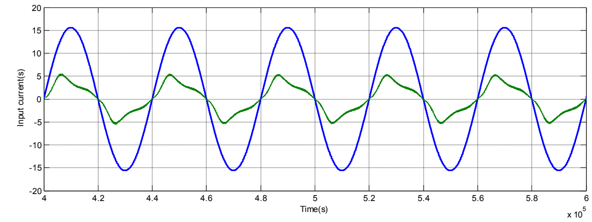
The control concept is validated by simulation study on MATLAB/SIMULINK software. An Experimental prototype of 250W boost rectifier is designed and developed to test and verify the operation.

4.1 Simulation results

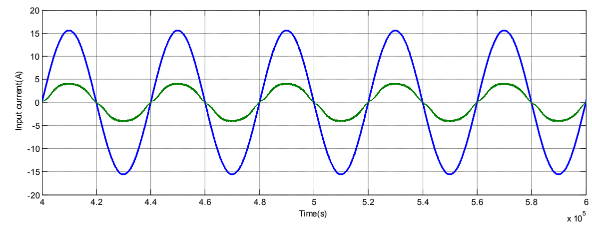
The operation of conventional controller and proposed controllers are tested and verified using simulation. The Fig. and Fig. shows that the conventional controller offers a input current distortion of 7% and 23.9% at voltage loop bandwidth of 10Hz and 50 Hz respectively. The proposed controller offers the current distortion of 5.2% at a bandwidth of 50Hz.



(a)

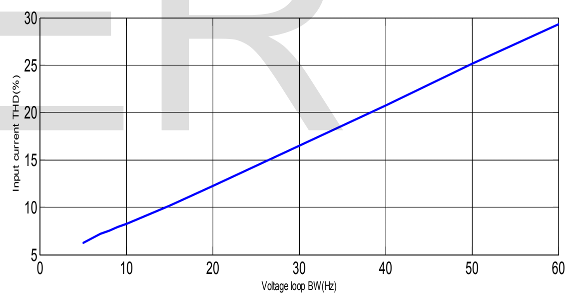


(b)

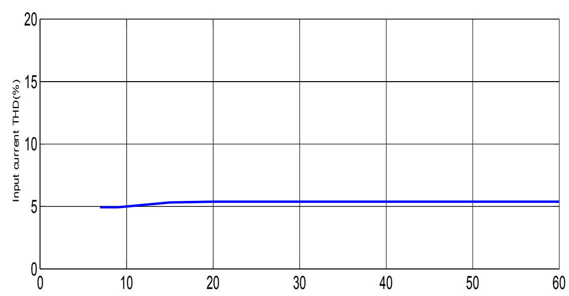


(c)

Fig.7 Input voltage (scaled) and Input current waveforms For voltage loop bandwidth of (a) conventional controller with 10Hz (b) conventional controller with 50Hz (c) Proposed controller with 50 Hz

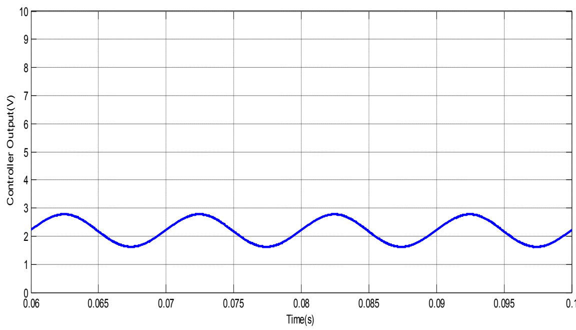


(a)

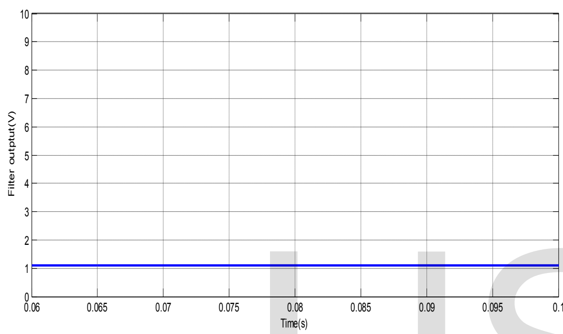


(b)

Fig.8 Simulation results of voltage loop bandwidth Vs Input current THD (a) without proposed control (b) with proposed control



(a)



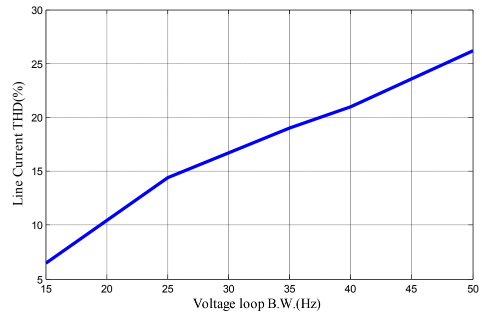
(b)

Fig.9 The RC filter waveforms (a) Input signal from PI controller (b) Output signal

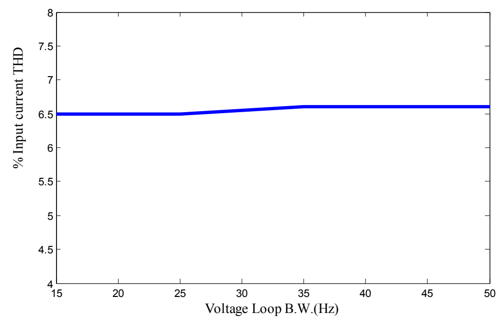
The simulation results of input current distortion at a range of voltage loop bandwidth are shown in Fig. The current distortion is recorded for a bandwidth ranging fron 10Hz to 60Hz.

4.1 Experimental results

The experimental results of the boost rectifier performance are presented in this section. The Fig.10(a) and Fig.10(b) shows the variation of input current distortion with voltage control loop bandwidth for convention controller and proposed controller respectively. The proposed analog controller is exhibits satisfactory results at various load conditions. The input current distortion and input power factor of the boost rectifier withn proposed control scheme at various load conditions are shown in Fig.11(a) and Fig.11(b) respectively. The input power factor is as high as 0.99 is recorded using the proposed controller.

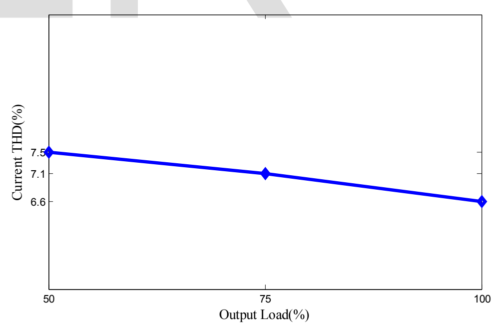


(a)

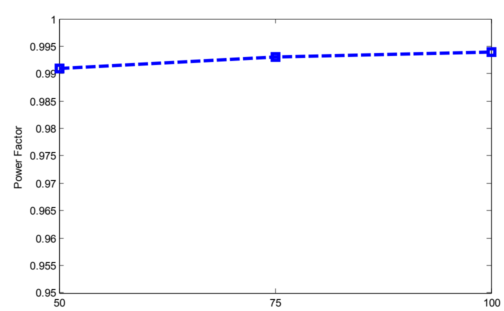


(b)

Fig.10 Voltage loop bandwidth Vs Input current THD (Experimental) (a) without proposed control (b) with proposed control



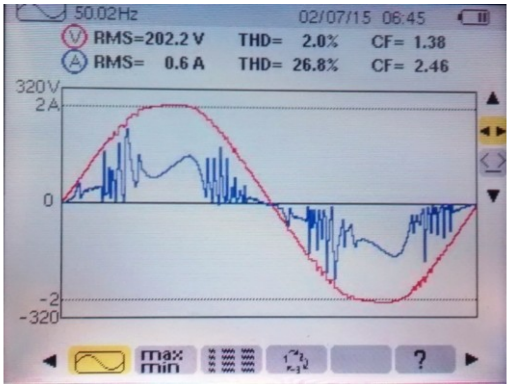
(a)



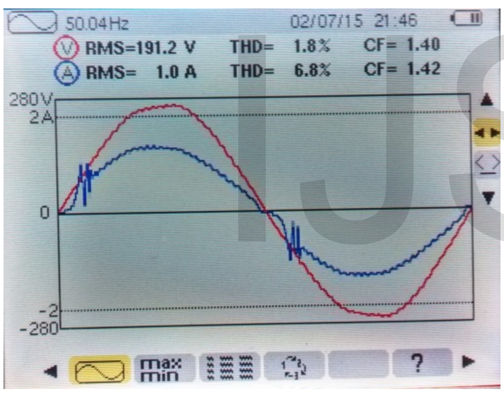
(b)

Fig.12 (a) Input current distortion (b) Input Power factor at various load conditions

The input voltageand input current waveforms of the boost rectifier with proposed controller at a voltage loop bandwidth of 50Hz is shown in Fig. 13(a) and Fig.13 (b). The Fig.13(a) shows the input waveforms with conventional control and Fig.13(b) shows the waveforms with propised control.



(a)



(b)

Fig.13 Input voltage and Input current waveforms at voltage loop bandwidth of 50Hz (a) with conventional control (b) with proposed control

5 Conclusion

The method proposed in this paper enables the rectifier to operate at higher bandwidth of voltage loop. The high voltage bandwidth enables faster dynamic response at low current. The controller is simple in implementation and economic. It improves input current quality of single phase boost rectifier. The boost rectifier with proposed control scheme shows significant reduction in current distortion. The RC filter is simplest in implementation in both analog and digital domain. The delay introduced by the filter in the loop is compensated by suitable compensator design. The controller requires minimum additional circuitry. The control scheme can be extended to NLC (Nonliear carrier control) or PSM (Predictive switching modulator) control [18]-[19] concepts which eliminate the use of input voltage sensor.

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