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Design and Implementation of Single Phase AC-DC Buck-Boost Converter for Power Factor Correction and Harmonic Elimination

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ABSTRACT

This paper discusses the Power Factor Correction (PFC) for single phase AC-DC Buck-Boost Converter (BBC) operated in Continuous Conduction Mode (CCM) using inductor average current mode control. The proposed control technique employs Proportional-Integral (PI) controller in the outer voltage loop and the Inductor Average Current Mode Control (IACMC) in the inner current loop for PFC BBC. The IACMC has advantages such as robustness when there are large variations in line voltage and output load. The PI controller is developed by using state space average model of BBC. The simulation of the proposed system with its control circuit is implemented in MatLab/Simulink. The simulation results show a nearly unity power factor can be attained and there is almost no change in power factor when the line frequency is at various ranges. Experimental results are provided to show its validity and feasibility.

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1. INTRODUCTION

The several current control techniques have been researched in the literature for boost and cuk single phase PFC rectifiers [1-5]. Among these, Inductor Average Current Mode Control (IACMC) is most widely used in PFC circuits [3]. The important feature of ACMC, as compared with peak current mode control, is that ACMC uses a high gain, wide bandwidth Current Error Amplifier (CEA) to force the average of one current within the converter, typically the inductor current, to follow the demanded current reference with very small error, as a controlled current source. Advantages of ACMC include large noise margin, no requirement for additional slope compensation, easy current limit implementation, excellent voltage and current regulation, simple compensation, good behavior in both continuous and discontinuous inductor current modes, and has inherent input voltage and output voltage feed-forward properties. All this is achieved with only a slight increase in complexity over earlier schemes [2]-[3].

IACMC is typically a two loop control method (inner loop, current; outer loop, voltage) for power electronic converters. Many of these applications have been in the higher switching frequency, lower power segment (up to 10kW, at 20 kHz and above), but this is changing. A 30kW three phase inverter using analog IACMC has been reported [6]. The regulation of output voltage of PFC boost converter using PI controller at the outer loop has been reported [7]-[8].

The simple models of power converters are usually obtained from state-space averaging and linearization techniques; these models may then be used for classical control design [9]-[10]. Therefore in this paper, we propose a PFC BBC to regulate the output voltage/supply current by using both PI controller at the outer loop and the IACMC at inner loop. The state-space average model for BBC is derived at first and used for designing the PI controller. In section II, we discussed the circuit description and mathematical model of PFC BBC. The design of PI controller and IACMC is presented in section III. Simulation results of system are discussed in section IV. The conclusions and future work of system is discussed in section.

2. MATHEMATICAL MODEL OF PFC BBC

A typical topology of PFC BBC is shown in Figure 1, and it is constructed by the uncontrolled diode bridge, followed by a BBC. It consists of AC input supply voltage, inductor L, capacitor C, power switch S (n-channel mosfet), diode D and load resistance R. It allows the output voltage to be higher or lower than the input voltage, based on the duty ratio d. In the circuit there are two storage elements inductor and capacitor. It is customary and convenient to take the inductor current and the capacitor voltage as state variables. Each switching stage can be represented by a corresponding circuit topology. The voltage transfer gain of BBC is

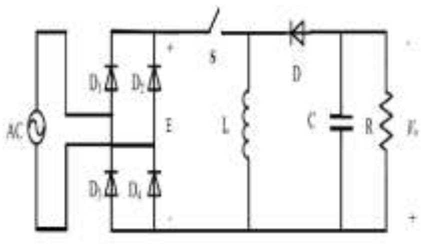

Figure 1. The topology of the PFC BBC circuit

$$\frac{V_o}{E} = -\frac{d}{(1-d)}$$

and it's the corresponding current transfer gain is

$$\frac{I_o}{I_{in}} = -\frac{(1-d)}{d}$$

In the on-duration circuit configuration, the switch is conducting and diode is not conducting. The system state equations describing the on-interval circuit configuration is describing by

$$\frac{di_L}{dt} = \frac{E}{L}$$

$$\frac{dV_C}{dt} = -\frac{1}{RC}V_C$$

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_{Cf} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \text{E} \qquad (1)$$

In the off-duration circuit configuration, the switch is opened and the diode is conducting. The system equations for the off-circuit topology are given as

$$\frac{di_L}{dt} = -\frac{V_C}{L}$$

$$\frac{dV_C}{dt} = \frac{1}{C}i_L - \frac{1}{RC}V_c$$

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_C}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} \qquad (2)$$

By using the state-space averaging model the system model can be written as [9]-[10]

$A = A_{on}\, d + A_{off}\,(1\text{-}d)$
$B = B_{on}\, d + B_{off}\,(1\text{-}d)$

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_C}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1+d}{L} \\ \frac{1-d}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} \frac{d}{L} \\ 0 \end{bmatrix} E$$

3. DESIGN OF PI CONTROLLER AND INDUCTOR AVERAGE CURRENT CONTROLLER

3.1. Design PI Controller Design

The PI controller is designed to ensure the specifying desired nominal operating point for PFC BBC, then regulating it, so that it stays very closer to the nominal operating point in the case of sudden disturbances, set point variations, noise, modeling errors and components variations.

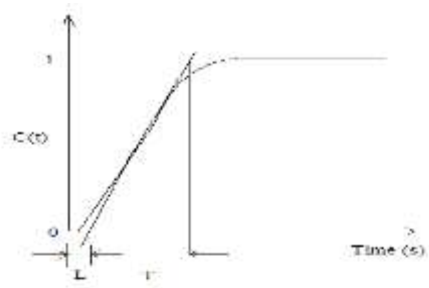

Figure 2. S- Shaped curve of step response of BBC

The PI controller settings proportional gain Zeigler – Nichols tuning method [8]-[9] by applying the step test to (3) to obtain S-shaped curve of step (K_p) and integral time (T_i) are designed using p response of BBC. From the S-shaped curve of step response of BBC may be characterized by two constants, delay time L and time constant T. The delay time and time constant are determined by drawing a tangent line at the inflection point of the S-shaped curve and determining the intersections of the tangent line with the time axis and line output response c(t) as shown in Figure 2. Ziegler and Nichols suggested to set the values of K_p= 0.036 and T_i = 0.016s according to the Table 1.

The PI controller optimal setting values (Kp and T_i) for PFC BBC are obtained by finding the minimum values of integral of square of error (ISE), integral of time of square of error (ITAE) and integral of absolute of error (IAE), which is listed in Table 2. The designed PI controller is used regulate the output voltage of PFC BBC.

Table 1. Ziegler- Nichols Tuning Rules

Type of controller	*Kp*	*Ti*	*Td*
P	*T/L*	∞	0
PI	0.9*T/L*	*L*/0.3	0
PID	1.2T/*L*	2*L*	0.5*L*

Table 2. Simulated Results Of Minimum Values Of ISE, IAE, ITAE And Optimal Setting Values of Kp And Ti

ISE	IAE	ITAE	Kp	Ti (s)
2.377	0.1935	0.001557	0.01205	0.0133

3.2. Design of Inductor Average Current Controller

In Figure 3 shows the PI controller output and full bridge diode rectifier output are applied to multiplier. Now, multiplier multiplies the both signal to form the modulating signal. This modulating signal and ramp function are applied to summer. Its sums the both signal to form reference current. Then reference current is compared to feedback current to form PWM pulse to control the switch S. The output voltage can be varied by changing the duty cycle. In Figure 4 shows the feedback current is compared with reference sinusoidal waveform and is forced to remain between the maximum and minimum values of i_{ref} [3]. Design specification of IACC; Ramp function magnitude: 1A, Reference current magnitude: 1.3A, Fed back current.

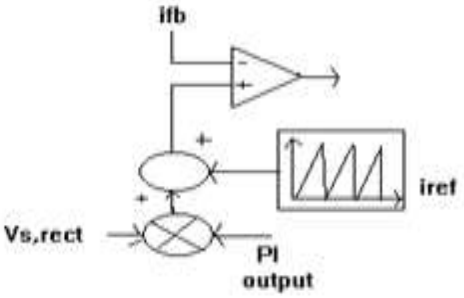

Figure 3. Block diagram of Inductor Average Current Controller

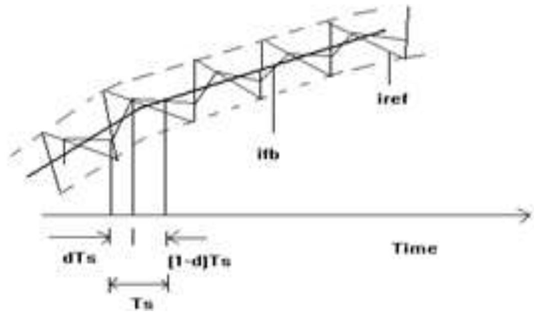

Figure 4. Waveforms of i_{fb} and i_{ref}

4. SIMULATION RESULTS

The simulation results of PFC BBC with IACMC and PI controller is presented in this section. The single phase PFC BBC with proposed controllers is shown in Figure 5. The nominal input voltage is 50Hz with the RMS value 110V, input inductor L_{in} =70μH, inductor L=700mH, capacitor C=760μF, the output load range R=100ohm to 200ohm, the desired output voltage is 200V and the line frequency is 50Hz. The performances of IACMC and PI controller for PFC BBC are evaluated in MatLab/Simulink. In steady state, the output voltage variation is not more than ±1.5.The input current and voltage waveforms are shown in Figure 6. The input current waveform is almost in phase with the input voltage. From the harmonic spectrum analysis of input current in Figure 7, the Total Harmonic Distortion (THD) is almost up to 9.64%.

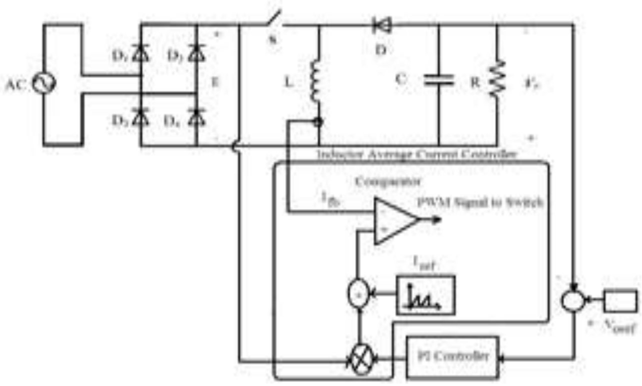

Figure 5. PFC BBC with inductor average current and PI controllers

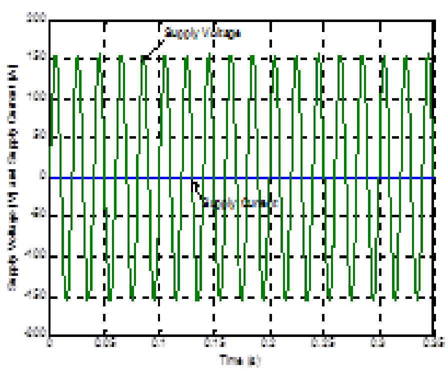

Figure 6. Waveforms of the supply voltage and supply current when R=100 ohm

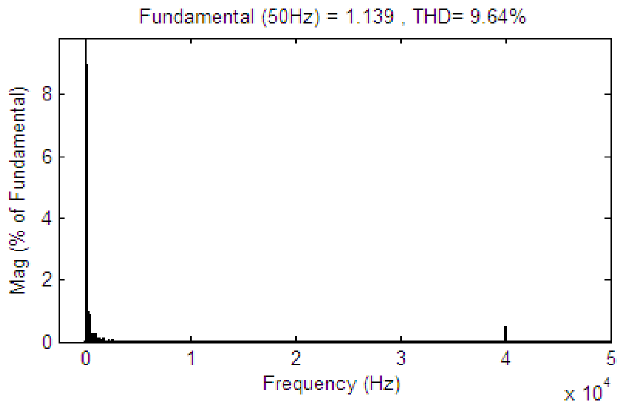

Figure 7. Frequency domain analysis of input current when R=100 ohm

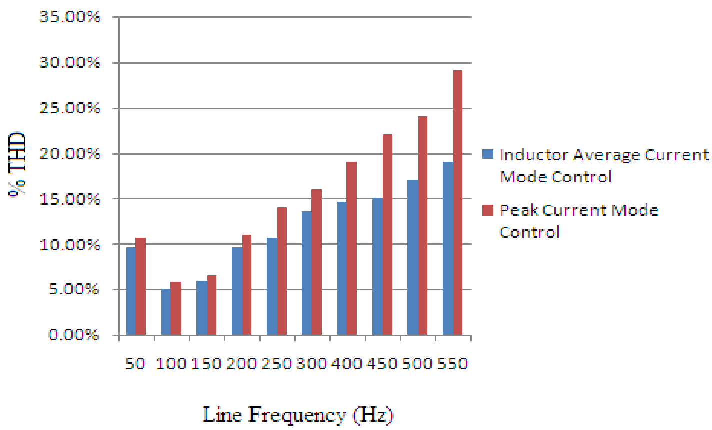

Figure 8. THD comparisons under different line frequencies

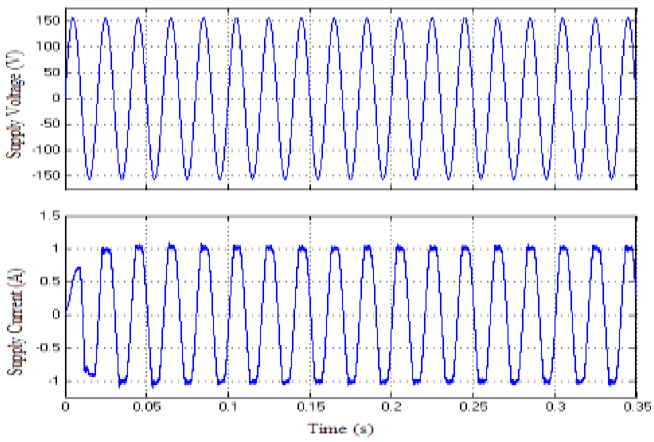

Figure 9. Zoomed waveforms of the supply voltage and supply current when R=100 ohm

The performance of the IACMC and that of the peak current mode controller are compared when the line frequency is changing from 50Hz to 550Hz. Figure 12 shows that THD change little using quasi IACMC, the PF stays at about 96.48%, but THD increase much with the line frequency using the peak current mode controller, the worst PF decreases to 91%.

5. EXPERIMENTAL RESULTS

The specification of experimental model is same as the simulation model specification. The nominal input voltage is 50Hz with the RMS value 110V, input inductor L_{in} =70µH/15A (Ferrite Core), inductor L=700mH/15A (Ferrite Core), capacitor C=760Mf/440V (Electrolytic type), the output load range R=100ohm to 200ohm, the desired output voltage is 200V, the line frequency is 50Hz, SIRFN 540 (MOSFET) and FR306 (Diode).

Figure 11 shows the input voltage and current with load change from 100 ohm to 200 ohm. From this waveforms it is clearly identified that, there is no fluctuation in input current and voltage using the proposed control scheme. Figure 12 shows the analog implementation of IACMC with components details. Low voltage range of output is obtained by using potential divider circuit. Using this low dc voltage which is compared with reference dc voltage (LM324). The PI controller was implemented using LM324, capacitor and feedback resistance. PI controller output and rectified output signals are multiplied by using multiplierAD633.

After the multiplied output signal and ramp signal (NE 555) is summed. The output signal of this operational amplifier, which act as reference current for feedback inductor current. Both signals are compared using LM311 and generate the PWM pulse. MCT 2E and transistors which is act as an opto-coupler and driver circuit for the power MOSFET.

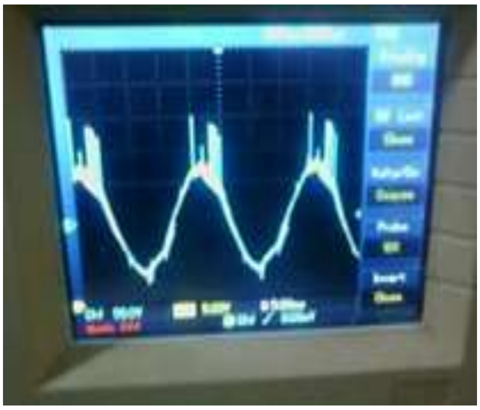

Figure 11. Waveforms of input current with load change from 100 ohm to 200 ohm

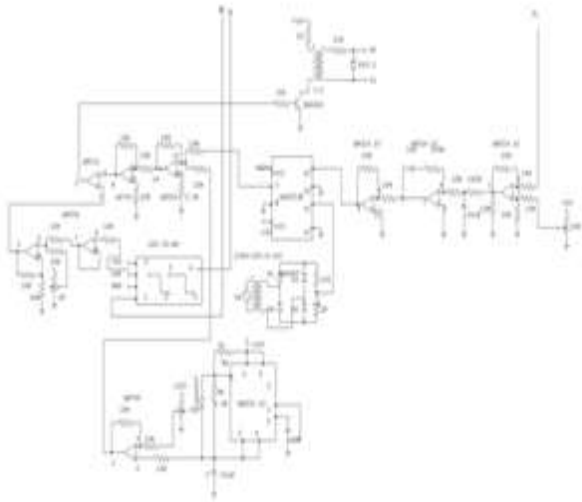

Figure 12. Analog Implementation of IACMC

6. CONCLUSIONS

1. The design of proposed controllers for PFC BBC has been successfully demonstrated and implemented in real time.
2. The IACMC is used at inner loop to regulate the input current and harmonics, which has the advantages over the peak current and hysteresis current controllers such as the robustness when there are large variations in line voltage and output load.
3. The PI controller is implemented at outer loop, which produce the excellent performance of output voltage regulation for BBC under different conditions.
4. The PI controller settings proportional gain (K_p) and integral time (T_i) are designed using Zeigler Nichols tuning method [8]-[9] by applying the step test to (3) to obtain S-shaped curve of step response of BBC.
5. Moreover, this IACMC is advantageous compared to peak current mode controller in the application when the line frequency is changing largely.
6. The proposed technique offers definite benefits over the conventional boost converter and it is easy to understand, is easy to implement, and draws sinusoidal input current from AC source for any DC output voltage condition.

7. The simulation and experimental results confirmed the theoretical analysis and thus verified the feasibility of the proposed convertor topology.
8. The Simulations results shows a nearly unity power factor when the line frequency is at various ranges and the experimental results also verified the feasibility of the work.
9. Figure 12 shows that THD change little using quasi IACMC, the PF stays at about 96.48%, but THD Increase much with the line frequency using the peak current mode controller, the worst PF Decreases to 91%.

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