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Design and Implementation of Hyteresis Current Mode Controller for Buck-Boost Converter for Power Factor Correction and Harmonic Elimination

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Abstract: The aspects regarding the improvement of the Power Factor Correction (PFC) for single phase AC-DC Buck-Boost Converter (BBC) using inductor hysteresis current mode control. The major control technique employs Proportional-Integral (PI) controller in the outer voltage loop and the hysteresis Current Mode Control (HCMC) in the inner current loop for PFC BBC. The HCMC was able to respond when there are large variations in line voltage and output load. The PI controller is proposed by using state space average model of BBC. The simulation of the proposed system is implemented in MatLab/Simulink. The simulation results show a nearly unity power factor and there is no change in power factor when the line frequency is at different ranges. Experimental and simulation results are conformed the analysis and verified the feasibility of the proposed converter topology.

Key words: AC-DC Buck-Boost Converter · Hysteresis Mode controller · PI Controller · Power Factor correction

INTRODUCTION

The several current control techniques have been researched in the literature for boost and cuk single phase PFC rectifiers [1-5]. Among these, Hysteresis Current Mode Control (HCMC) is most widely used in PFC circuits [3]. The important feature of HCMC, as compared with peak current mode control, is that HCMC 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 HCMC 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].

HACMC 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 HCMC 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 HCMC 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 HCMC 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 V.

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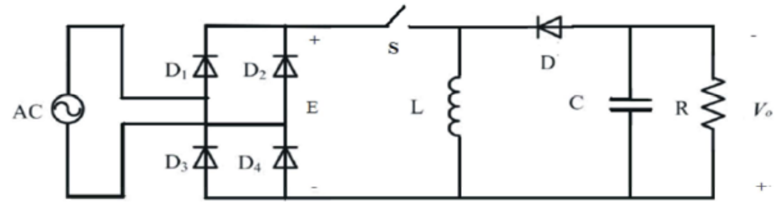

Fig. 1: The topology of the PFC BBC circuit

Circuit Description and Mathematical Model of PFC BBC: A typical topology of PFC BBC is shown in Fig. 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

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

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;

$$\frac{di_L}{dt} = \frac{E}{L} \tag{3.17}$$

$$\frac{dV_C}{dt} = -\frac{1}{RC}V_C \tag{3.18}$$

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_{CF} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} E \tag{1}$$

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;

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

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

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*	*2L*	0.5*L*

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

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

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_C}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1+d}{L} \\ \frac{1-d}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} \frac{d}{L} \\ 0 \end{bmatrix} E \tag{2}$$

Design of PI Controller and Hysteresis Current Controller

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.

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 (2) to obtain S - shaped curve of step 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 Fig. 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 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

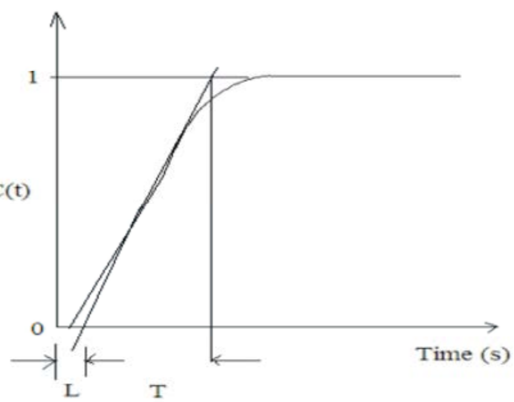

Fig. 2: S- Shaped curve of step response of BBC

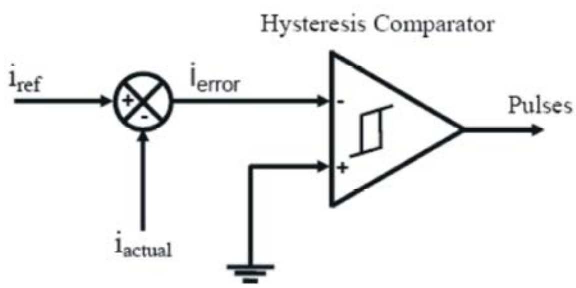

Fig. 3: Block diagram of Hysteresis current controller

Design of Inductor Hysteresis Current Controller: In Fig. 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 Fig. 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]. The advantages of HCMC over the peak and average current controllers as follows,

- Average current tracks the reference current with high degree of accuracy. This is especially important in high power factor converters.
- Slope compensation is not required, but there is a limit to loop gain at switching frequency in order to achieve stability.
- Noise immunity is excellent.

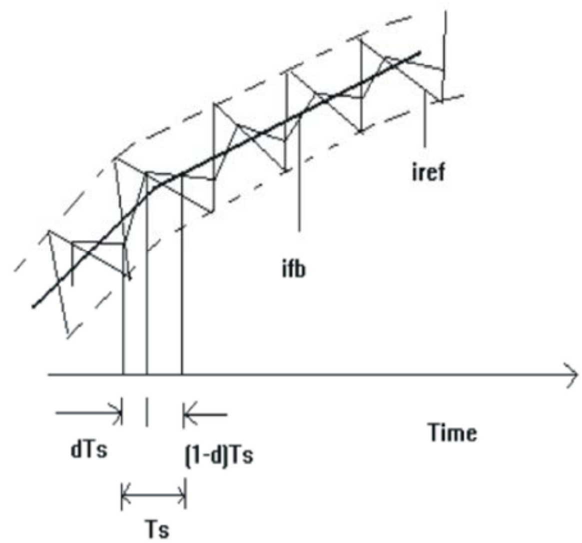

Fig. 4: Waveforms of i_{fb} and i_{ref}.

- The average current mode control can be used to sense and control the current in any circuit branch.
- Switching frequency is fixed.
- Speed of the response is fastest.
- Ripple current is fixed.
- Filter size is usually small.

Design specification of HCC; Ramp function magnitude: 1A, Reference current magnitude: 1.3A, Fed back current magnitude:

Simulation Results: The simulation results of PFC BBC with HCMC and PI controller is presented in this section. The single phase PFC BBC with proposed controllers is shown in Fig. 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 HCMC and PI controller for PFC BBC are evaluated in MatLab/Simulink.

Under constant load operation, the waveform of the output voltage is obtained as shown in Fig. 6. In steady state, the output voltage variation is not more than ±1.5. The input current and voltage waveforms are shown in Fig. 7. The input current waveform is almost in phase with the input voltage. From the harmonic spectrum analysis of input current in Fig. 8, the Total Harmonic Distortion (THD) is almost up to 9.64%.

The zoomed waveform of input current and voltage waveforms are shown in Fig. 9. The input current waveform is almost in phase with the input voltage.

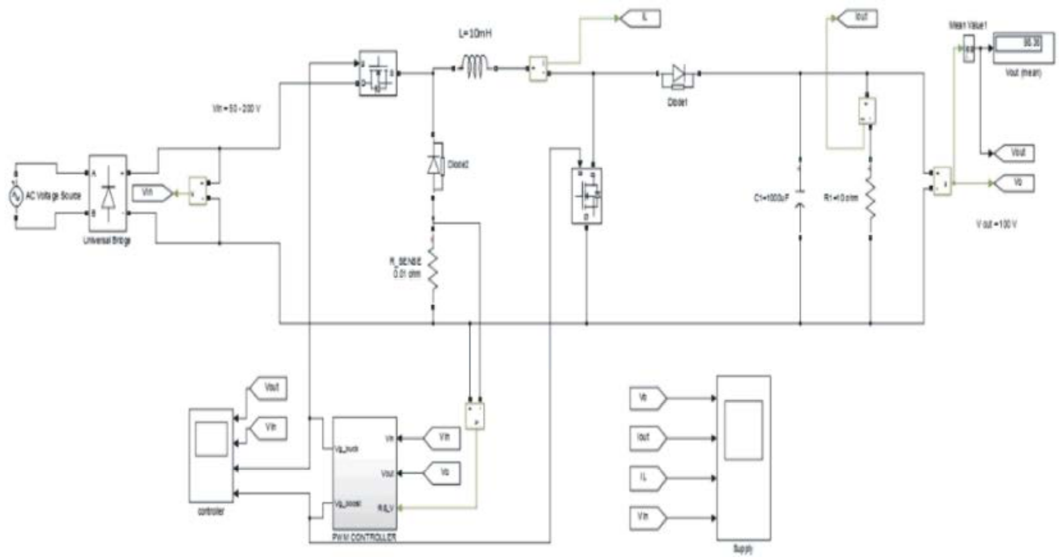

Fig. 5: PFC BBC with Hysteresis current and PI controllers

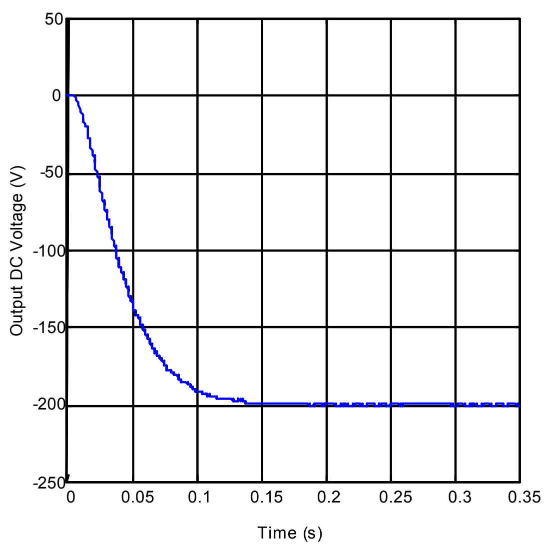

Fig. 6: Waveform of the output voltage with constant load R=100 ohm

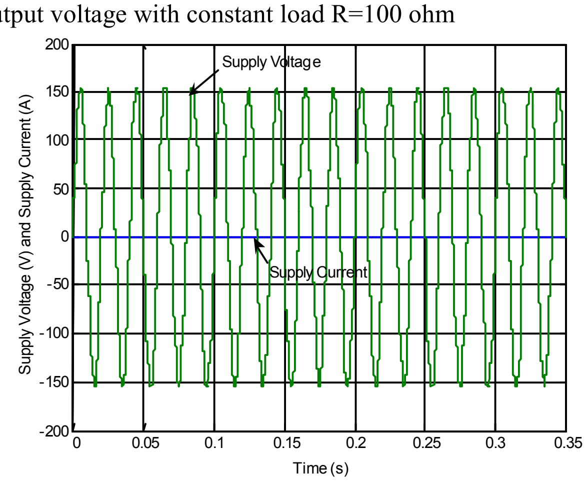

Fig. 7: Waveforms of the supply voltage and supply current when R=100 ohm

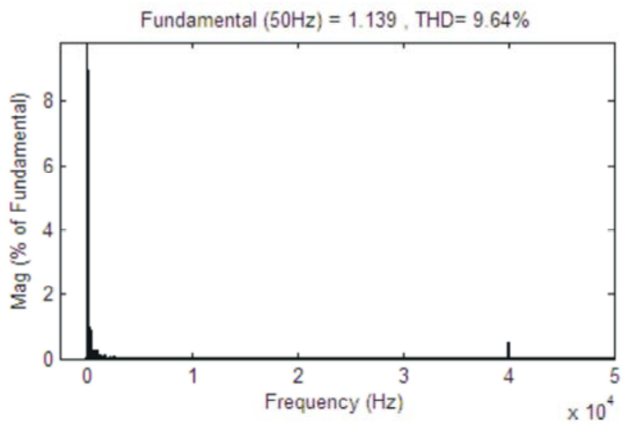

Fig. 8: Frequency domain analysis of input current when R=100 ohm

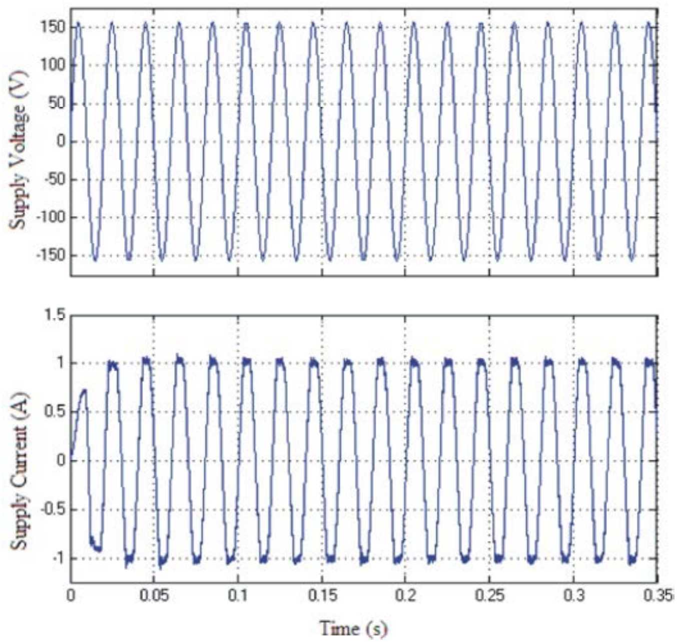

Fig. 9: Zoomed waveforms of the supply voltage and supply current when R=100 ohm

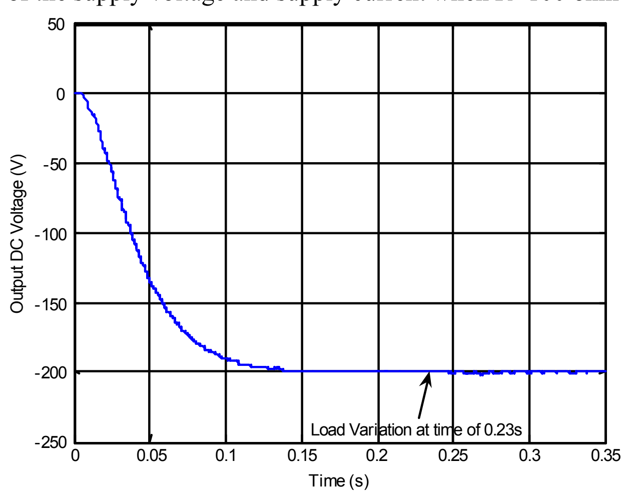

Fig. 10: Waveform of output voltage with load change from 100 ohm to 200 ohm at 0.23s

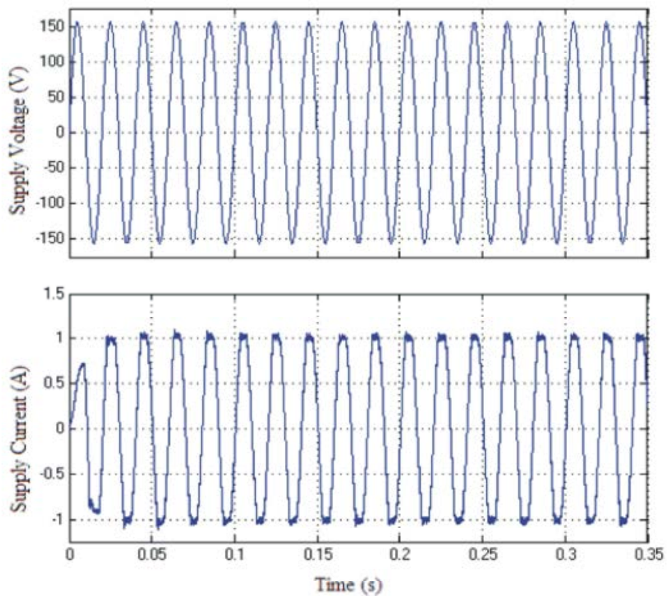

Fig. 11: Waveforms of input current and voltage with load change from 100 ohm to 200 ohm at 15s

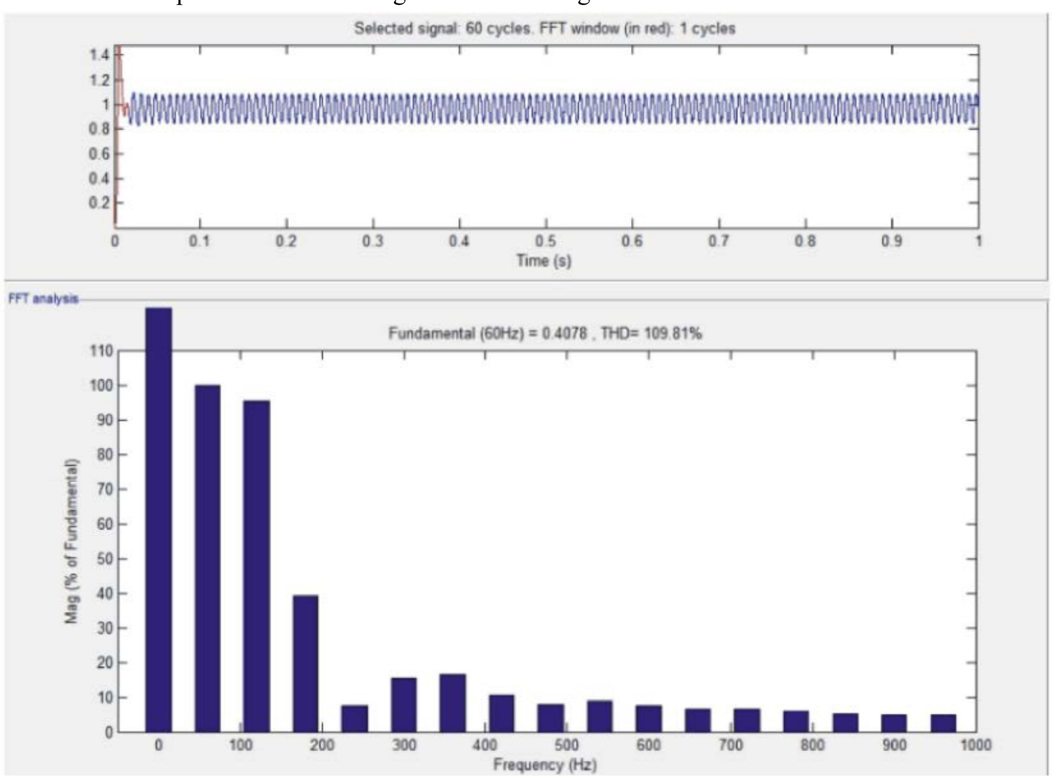

Fig. 12: Variations of THD value with frequency

From this figure it clearly found that, the power factor nearly unity. When the load changes from 100 ohm to 200 ohm at 0.23s, the waveform of the output voltage is shown in Fig. 10, the transient output voltage varies less than 1V and it can attain stable within 0.01s, but the ripple is low when the load is larger with designed PI controller. The waveforms of the input current and voltage are shown in Fig. 11. It can seen that the response of the input current is attains stable within two switching cycles under load variations with designed HCMC.

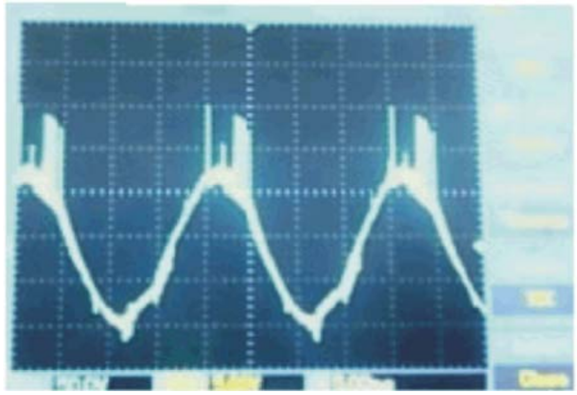

Fig. 13: Waveforms of input voltage with load change from 100 ohm to 200 ohm

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Fig. 14: Waveforms of input current with load change from 100 ohm to 200 ohm

Fig. 15: Waveforms of out current and voltage with load change from 100 ohm to 200 ohm

The performance of the HCMC and that of the peak current mode controller are compared when the line frequency is changing from 50Hz to 550Hz. Fig. 12 shows that THD change little using quasi HCMC, 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%.

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).

Figs. 13 and 14 show the input voltage and current with load change from 100 ohm to 200 Figs. 13 and 14 show the input voltage and current with load change from

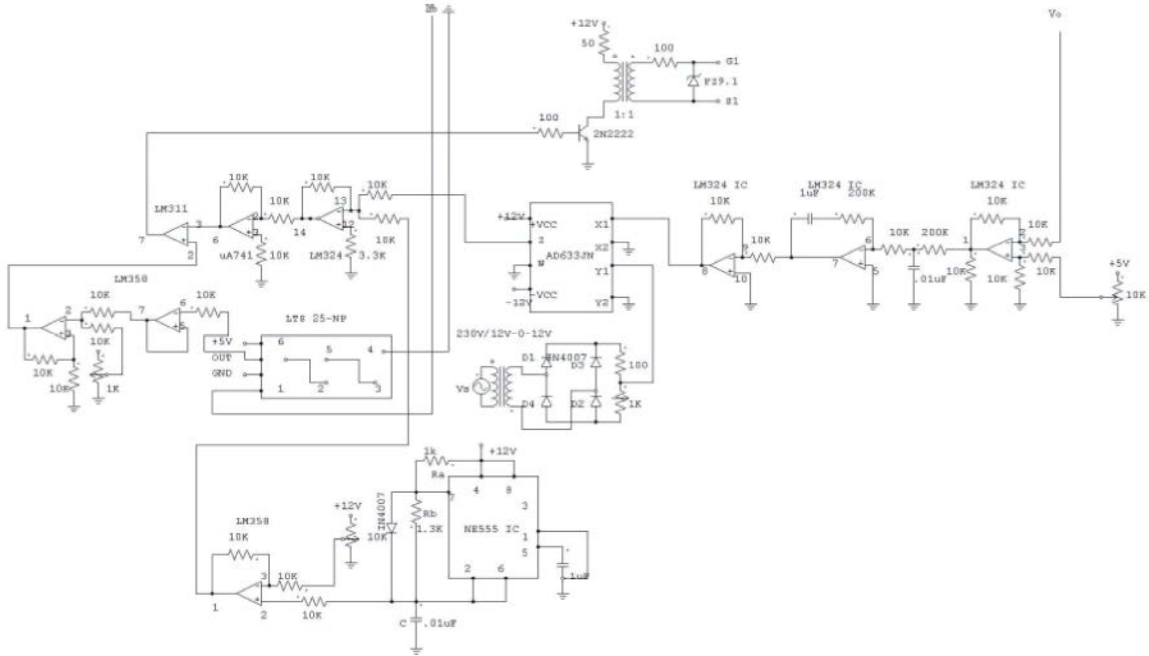

Fig. 16: Analog implementation of HCM

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.

Fig. 15 shows the output voltage and current with load change from 100 ohm to 200 ohm. From these waveforms it is clearly identified that, there is no deviation in output current and voltage using the proposed control scheme. Fig. 16 shows the analog implementation of HCMC 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 multiplier AD 633. 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 anddrivercircuit for the power MOSFET.

CONCLUSION

The design of proposed controllers for PFC BBC has been successfully demonstrated and implemented in real time. The HCMC is used at inner loop to regulate the input current and harmonics, which has the advantages over the peak current and average current controllers such as the robustness when there are large variations in line voltage and output load. The PI controller is implemented at outer loop, which produce the excellent performance of output voltage regulation for BBC under different conditions. Moreover, this HCMC is advantageous compared to peak current mode controller in the application when the line frequency is changing largely. in addition, the proposed technique offers definite befits 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. The simulation and experimental results confirmed the theoretical analysis and thus verified the feasibility of the proposed convertor topology.

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