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Design and Analysis of Robust Current Control of PFC Boost Rectifier

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Abstract

In this paper, the problem of controlling AC-DC full bridge converter is considered. The control objectives are two, the robust current mode control consists of a slow control loop and a fast control loop. The slow one is known as the outer voltage loop and is responsible for regulating the output voltage. The first one is known as the inner current loop and is responsible for programming the input current so that it follows the same sinusoidal waveform as the input voltage. In the current loop, the sensed inductor current is compared with the reference current profile using a current error amplifier. The resulting error signal is then fed into the PWM modulator, where the logical gate drive signal is produced by comparing the current error with a fixed-frequency saw tooth. In this way the inductor current is programmed by the current loop to follow the sinusoidal envelope of the input voltage and a near unity power factor to achieve output voltage regulation. The desired features of an active PFC technique are less than 10 % total harmonic distortion in line current and simple control strategy. The Robust control gives better performance during different line voltage and load. The results are verified through MATLAB/Simulink.

1. Introduction

THE conventional off-line switch-mode ac-to-dc converters draw pulsating ac line current from the utility grid, therefore, they inject high order harmonic components to the utility line. These result in i) Electromagnetic interference (EMI) and line distortion, and ii) Increase of RMS current in the transmission line, and, thus, additional losses. With increasing demand for more power capability and better power quality from the utility line, power factor correction techniques have attracted much more attention.

The advantages are: i) The input current is a smooth waveform, resulting in much less EMI and therefore reduced input filtering requirements, ii) Current stress in the power switches is lower, iii) The inductor current in the boost converter is the input current and is therefore easily programmed and, iv) The dc output voltage is higher than the peak of the input voltage. This high voltage allows the output capacitor to store more energy and to provide longer hold up time. Up to the present, there are two most commonly used power factor correction techniques for the boost type pre-regulator and multi loop multiplier control.

These two schemes make the inductor current to track a reference which is a scaled rectified input voltage. Thus, a close to unity power factor is achieved. However, these two techniques have their own demerits as explained below. As soon as the inductor current i_L reaches i^*, the switch is turned off. In fact, this problem becomes even more difficult to deal with due to the varying input voltage. By adding an external ramp compensation to the sensed inductor current waveform, the current control loop can be stabilized however, considerable distortion is introduced and the circuit becomes complex.

2. Robust control base PFC System Configuration

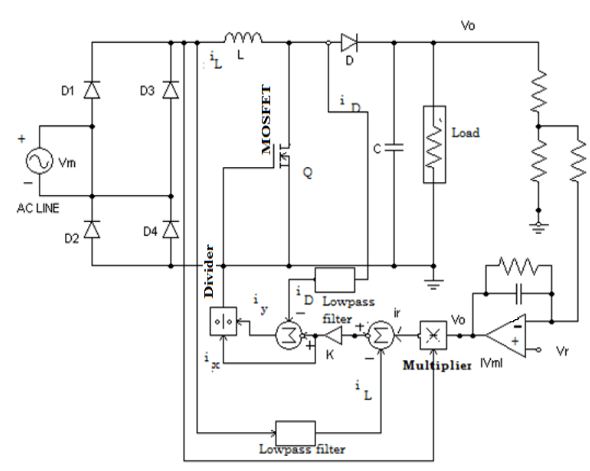

Fig.1. Boost PFC converter with robust control

The proposed dynamically robust current control is to program the inductor current in the boost converter. This method can be formulated from the low frequency averaged equivalent. The equivalent circuit model can be derived from the state space averaging method. In this model, the switch Q is modeled by circuit model. A controlled current source with its value equal to the averaged current flowing through it over one switching cycle, i.e.,

$$i_{sw} = d \cdot i_L \qquad (1)$$

For boost converter, where i_L is the average inductor current and d is the duty ratio. The diode is modelled by a controlled voltage source with its value equal to the averaged voltage across it over one switching cycle, i.e.

$$V_d = d \cdot V_s \qquad (2)$$

For boost converter, where V_s stands for the input voltage. A block diagram is shown in Fig. 1. The Robust current mode control consists of a slow control loop and a fast control loop. The slow one is known as the outer voltage loop and is responsible for regulating the output voltage. The fast one is known as the inner current loop and is responsible for programming the input current so that it follows the same sinusoidal waveform as the input voltage. In the current loop, the sensed inductor current is compared with the reference current profile using a current error amplifier. The resulting error signal is then fed into the PWM modulator, where the logical gate drive signal is produced by comparing the current error with a fixed-frequency saw tooth. In this way the inductor current is programmed by the current loop to follow the sinusoidal envelope of the input voltage and a near unity power factor to achieve output voltage regulation. To investigate the stability of the current loop, small-signal analysis is performed for dc-to-dc boost converter and boost type ac-to-dc power factor corrector. According to Kirchhoff's law, the inductor current can be expressed as

$$i_L = d i_L + i_d \qquad (3)$$

Where i_L and i_d are the averaged values of inductor current, and diode current respectively. The duty ratio can be expressed as

$$d_P = \frac{i_L - i_d}{i_L} \qquad (4)$$

Equ (4) defines the duty ratio required by the power stage of the boost converter at a specific operating point of i_L and i_d.

$$d_c = \frac{K(i_r - i_L) - i_d}{K(i_r - i_L)} \qquad (5)$$

Where i_r is the reference current, K is the gain of the proportional error amplifier, and d_c denotes the duty ratio generated by the control circuit. In the practical circuit, the output of the control circuit is connected to the gate of the active switch in the power stage of the boost converter, making $d_P = d_c$.

The closed-loop characteristics can be obtained by equating (4) and (5) as

$$\frac{i_L - i_d}{i_L} = \frac{K(i_r - i_L) - i_d}{K(i_r - i_L)} \qquad (6)$$

Equ (6) can be simplified as

$$1 - \frac{i_d}{i_L} = 1 - \frac{i_d}{K(i_r - i_L)} \qquad (7)$$

From equ (7), the average inductor current can be found as

$$i_L = \frac{K}{K+1} i_r \qquad (8)$$

Equ (8) shows that, by the control law (5), the inductor current is forced to be proportional to a reference current and is independent of the supply voltage and the load current. This implies that the inductor current is dynamically immune from the large deviations on supply voltage and output load. Therefore this control law is called dynamically robust current control law. The control law (5) is nonlinear. The duty ratio generated is proportional to the difference of the output of the current error amplifier and the average diode current and is inversely proportional to output of the current error amplifier. Nonlinear control law combined with the inherent nonlinear boost converter has resulted, in this case, in a linear closed loop control system. A divider is required to generate the required duty ratio d_c which is equal to the ratio of i_y and i_x, A simple divider using op-amp and comparator is used to generate the required duty ratio as follows: the duty ratio generator has two inputs, the numerator i_y (corresponding to numerator of (5)) and the denominator i_x, (corresponding to the denominator of (5)). A saw tooth waveform signal whose peak value is proportional to the denominator ix is one input. The numerator i_y is the other input which is compared with the saw tooth waveform and a pulse signal is generated at the output of the constructed divider. This duty ratio of the output pulse signal is proportional to the ratio of i_y and i_x. As discussed above, under the dynamically robust current control, the input current in the dc-to-dc boost converter will only depend on the reference current. In the ac-to-dc boost type power factor corrector using the proposed technique, the reference

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current signal i_r is derived from the rectified input voltage V_{in} scaled by a factor proportional to the error voltage from the output voltage feedback loop V_e. The input current i_{in} which is also the inductor current i_L, will exactly follow the reference current i_r. Consequently, the input current of the ac-to-dc converter i_{in} will be made sinusoidal and in phase with the input voltage V_{in}. As a result, a closed to unity power factor can be achieved. The output voltage of the power factor pre-regulator is regulated by conventional voltage feedback loop. A novel dynamically robust current control technique is proposed in this paper for the boost type power factor pre-regulator. It has the following features:

- Operates at constant switching frequency,
- Good noise immunity,
- The current control loop is stable and easy to synthesize.

Converter is first considered. The small-signal duty-ratio to inductor-current transfer function of the power circuit is derived from state space averaging method.

3. Modelling of robust current mode control

To investigate the stability of the current loop, small-signal analysis is performed for dc-to-dc boost converter and boost type ac-to-dc power factor corrector. The small-signal duty-ratio to inductor-current transfer function of the power circuit is derived from state space averaging method .It is approximated as at the specified operating point of input voltage V_S, output voltage V_o, and inductor current i_L.

$$G_{id} = \frac{V_o}{sL} \qquad (9)$$

The control law described in (5), is linear zed at the specified operating point the same as that defined in (9). The small-signal inductor-current to duty-ratio transfer function is approximated as

$$G_{di} = \frac{K\left(\frac{V_o}{R}\right)}{I_L^2} \qquad (10)$$

The current loop transfer function is expressed as

$$T_i(s) = \frac{K\left(\frac{V_o^2}{R}\right)}{sLI_L^2} \qquad (11)$$

Assuming the dc-to-dc boost converter is lossless, the following equations are valid.

$$P_o = \frac{V_o^2}{R} \qquad (12)$$

$$P_{in} = I_L^2 R_{in} \qquad (13)$$

$$P_{in} = P_o \qquad (14)$$

Where P_{in}, P_0, R, and R_{in} are the input power, output power, equivalent dc output resistance, and equivalent dc input resistance, respectively. Substitute (12),(13), and (14) into(11). The equation (11) can be approximated as where the K is the proportional gain of the current error amplifier, L is the value of the inductor in the power circuit, and R_{in} is equivalent dc input resistance of the power circuit.

$$T_i(s) = \frac{KR_{in}}{sL} \qquad (15)$$

Obviously, this is a first-order system. Therefore, the closed current loop system is inherently stable for the dc-to-dc boost converter. For the boost type power factor corrector under the proposed current control, the low-frequency portion of inductor current i_L is proportional to the fully rectified input ac line voltage V_{in} and has the following relation.

$$i_L = \frac{|v_{in}|}{R_e} \qquad (16)$$

Where R_e is defined as the emulated input resistance to the ac-to-dc bridge rectifier. Similar to the steps discussed above for boost dc-to-dc converter, the small signal current loop transfer function for boost power factor corrector is approximated as

$$T_i(s) = \frac{KR_c}{sL} \qquad (17)$$

This first-order system is stable. The crossover frequency of this current loop can be expressed as

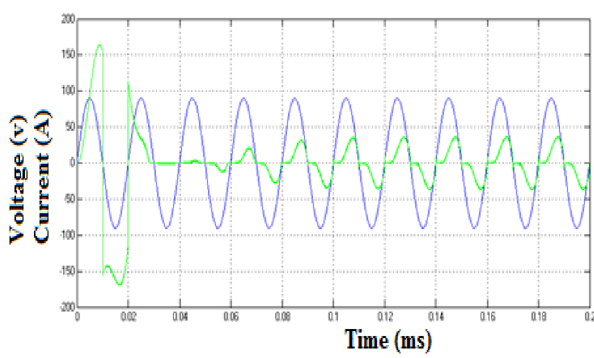
$$f_{ci} = \frac{KR_c}{2\pi L} \qquad (18)$$

A comparison between the proposed dynamically robust current control and the presently popular average current mode control is made.

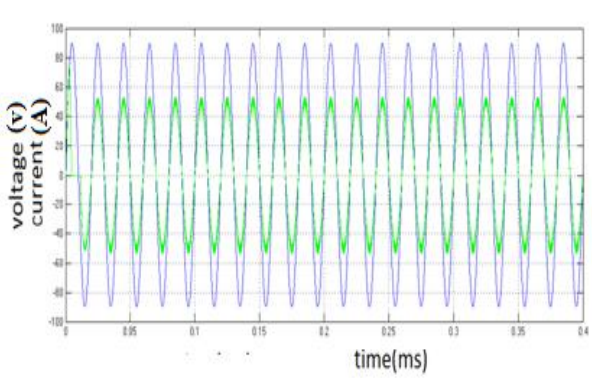
4. Results and Discussion

The steady state and dynamical performances of the proposed dynamically robust current control are studied by computer simulations. The dc-to-dc boost converter is first considered. The simulations are carried out for dc input voltage and dc reference current. The response of the control system to the large indicates that when the dc input voltage has large step changes, the average inductor current remains essentially un disturbances in the output load is also studied by simulation.

These simulated results demonstrate that the input current which is also the inductor current remains unchanged during large step changes in input voltage or output load resistance. The input current is only determined by the reference current. The relationship is confirmed by the simulation. The proposed dynamically robust current control loop remains dynamically stable under large deviations in supply voltage or output load. Hence, robust control technique improves the parameters like, Power Factor and input current and THD reduces.



(a)



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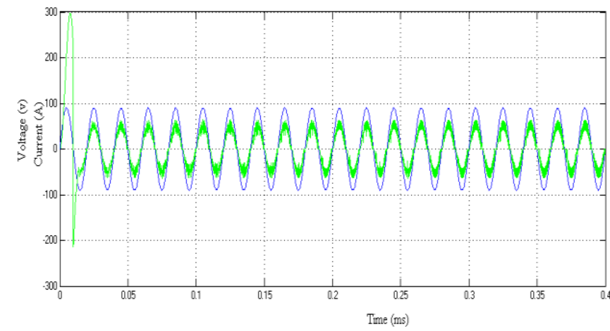
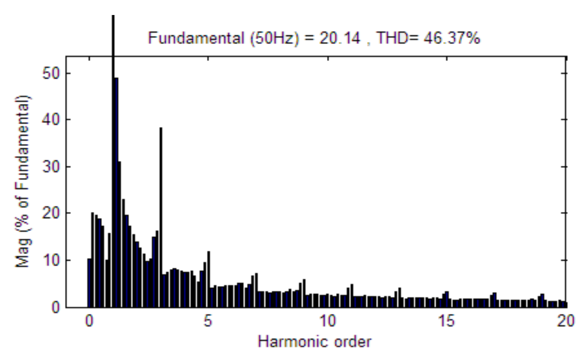


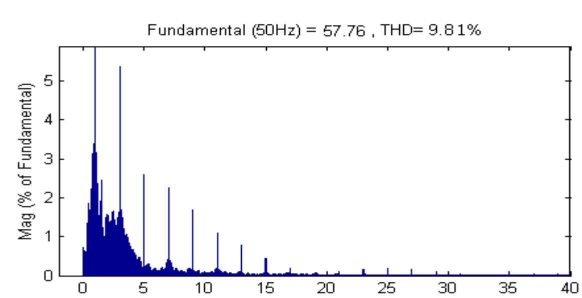
(c)

Fig.2. Simulated waveforms for input voltage in phase with line current (a) Without control technique (b) PI control (c) Robust controller at line voltage 90V.

Fig.2 (a) shows the response of open loop PFC boost converter input voltage in phase with line current,Fig.2 (b) shows the response of PI control PFC boost converter input voltage in phase with line current and Fig.2. (c) Shows the response of robust control PFC boost converter input voltage in phase with line current. Comparing all the three techniques robust control PFC boost converter is optimum one and power factor of the boost converter is improved to near unity (0.9994).



(a)



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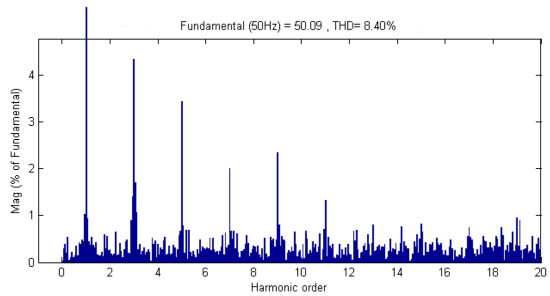

(c)

Fig.3. Simulated waveforms for THD (%) (a) Without control technique (b) PI control (c) Robust controller at line voltage 90V.

Fig.3. (a) shows the response of open loop PFC boost converter THD (%), fig.3. (b) Shows the response of PI control PFC boost converter THD (%) and fig.3. (c) Shows the response of robust control PFC boost converter THD (%). Comparing all the three techniques robust control PFC boost converter is optimum one and the THD (%) of the robust controller is improved to 8.4%.

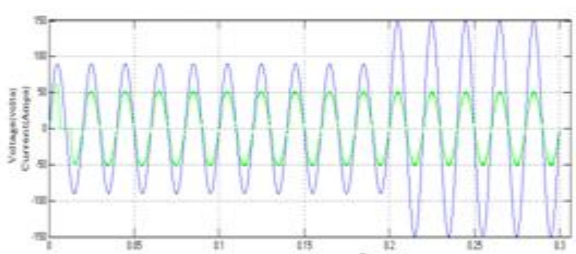

Fig.4.a. Simulated waveforms for input voltage in phase with line current of PI control at different line voltages.

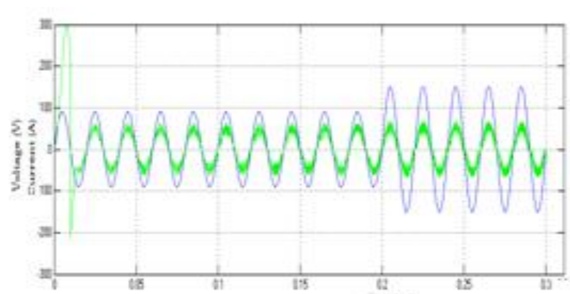

Fig.4.b. Simulated waveforms for input voltage in phase with line current of robust control at different line voltages.

Fig.4.b. shows that the simulated waveforms for input voltage in phase with line current of Robust control at different line voltages.

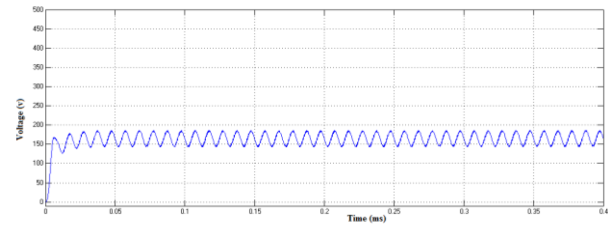

Fig.5. Output waveform of the robust control technique.

Fig.5. Shows that the output waveform of the Robust control technique. Comparing all the three techniques robust control PFC boost converter is optimum one, the output voltage is regulated.

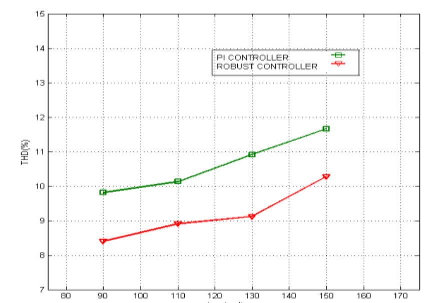

Fig.6. Waveforms for variation of input voltage THD (%) for different control techniques.

Fig.6. Shows the analysis of the variation of input voltage vs input current THD (%) for PI controller and robust controller. In this figure shows the input voltage increases and the power factor decreases. In this waveform Robust control technique improves the input current THD (%) that is 8.4% as shown in the table1.

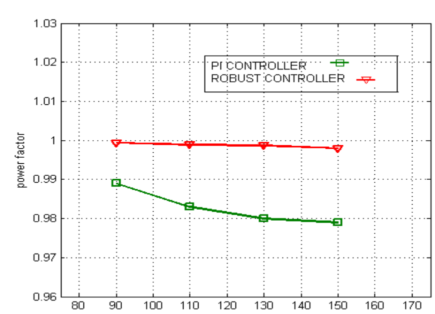

Fig.7. waveforms for variation of input voltage vs Power factor for different control techniques. Fig.7. shows the analysis of the variation of input voltage vs power factor for PI controller and robust controller. In this figure shows the input voltage increases and the power factor decreases. In these waveforms robust control

technique improves the power factor near unity (0.9994) as shown in the table1.

Table.1. Comparison of %THDs and power factor with different line voltage

PFC Without Control Technique			PFC With Average Control Technique			PFC With Robust Control Technique		
Input Voltage	Current THD (%)	Power Factor	Input Voltage	Current THD (%)	Power Factor	Input Voltage	Current THD(%)	Power Factor
150	53.37	0.567	150	11.66	0.979	150	10.28	0.998
130	50.02	0.592	130	10.92	0.980	130	9.12	0.9987
110	48.67	0.624	110	10.13	0.983	110	8.91	0.9989
90	**46.37**	**0.670**	**90**	**9.81**	**0.989**	**90**	**8.4**	**0.9994**

Conclusion

The dynamically robust current control technique can program the input current of the boost converter. It can be concluded that robust controller has a better dynamic response compared to a conventional PI controller. As a result, the average inductor current is proportional to the reference current and is only decided by the reference current. In a boost power factor pre-regulator, when the reference current is derived from the fully rectified input voltage, the input current will accurately track the input voltage. Small-signal analysis for Robust control technique reveals that the close-loop current control system is a first-order system and is stable. Computer simulation is performed to test the operation of the control scheme for both the boost converter and boost power factor pre-regulator. The simulated results show that the closed loop current control system remains dynamically stable when there is large disturbances in supply voltage or output load. The simulated results are verified through MATLAB\Simulink demonstrating the feasibility of the control technique. A power factor of 0.9994 and a THD of 8.4% are measured.

Appendix

Specification Parameters

Input Voltage: (90-150) V rms
Output Voltage: 400V
Boost Inductor: 0.4mH
Boost Capacitor: 1200uF
Load Resistance: 72 ohms
Output Load: 500W

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