THE ANALYSIS OF AC-DC BOOST PFC CONVERTER BASED ON PEAK AND HYSTERESIS CURRENT CONTROL TECHNIQUES

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THE ANALYSIS OF AC-DC BOOST PFC CONVERTER BASED ON PEAK AND HYSTERESIS CURRENT CONTROL TECHNIQUES

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Abstract- This paper presents two current control techniques of an ac-dc boost converter to obtain unity power factor (PF). Single phase high power factor rectification is the most frequently accomplished using a boost converter. This converter reshapes distorted input current waveform to approximate a sinusoidal current that is in phase with the input voltage. There are several current control techniques for achieving a sinusoidal input current waveform with low distortion. Two typical techniques for power factor correction (PFC) are peak current mode control (PCMC) and hysteresis current mode control (HCMC). These control techniques are evaluated based on control strategy, circuit components, and total harmonic distortion of input current. The single phase ac-dc boost converter is operated in continuous conduction mode (CCM). Both control techniques are simulated in Matlab/Simulink program.

Keywords: Power Factor Correction, Boost Converter, Peak Current Mode Control, Hysteresis Current Mode Control.

I. INTRODUCTION

To reduce losses, and decrease weight and size associated with converting ac power to dc power in linear power supply, switch mode power supplies (SMPSs) were introduced. The high nonlinearity of this kind of power electronic systems handicaps itself by providing the utility power system with low PF and high total harmonic distortion (*THD*). These unwanted harmonics are commonly corrected by incorporating PFC technique into the SMPS [1, 2].

The increased severity of power quality in power utility has attracted the attention of power engineers to develop dynamic and adjustable solutions to the power quality problems [3]. Such equipment generally is known as active filters. They are able to compensate current and voltage harmonics, reactive power, regulate terminal voltage. The advantage of active filtering is that it automatically adapts to changes in the utility and load fluctuations. They can compensate for several harmonic orders, and are not affected by major changes in utility characteristics, eliminating the risk of resonance between the filter and utility impedance. Another superiority is that they take up very little space compared with traditional passive filters. The most common used converter is single phase boost topology [4].

The single phase boost converter can operate in continuous conduction mode (CCM), discontinuous conduction mode (DCM), and boundary conduction mode (BCM). These names refer to the continuity of the inductor current within the switching cycle. The boost converter operating in DCM and BCM modes is usually easier to control, but it has higher peak-to-peak current ripple, which causes higher rms value of the inductor current, higher magnetic and conduction losses, and higher switching noise, which leads to increased filtering requirements. Therefore, these modes are restricted to relatively low power levels, while the CCM is used at medium and high power levels. So the boost converter is operated in continuous conduction mode (CCM) [5].

Current control of switching power converters mainly serves two purposes. For converters where the primary control objective is to regulate the output voltage, such as in the case of switching mode power supplies, a current control loop embedded inside the voltage loop simplifies converter dynamics and facilitates the design of the voltage loop. PFC control techniques for single phase boost converter may be classified as current control and voltage control. Current control is the most common control strategy since the primary objective of PFC is to force the input current to trace the shape of line voltage [6]. The PFC current control techniques get their fast development due to requirement to meet the compliance of European standards for the regulation of low frequency current harmonics. The publication of specific international standards, such as IEEE and IEC [7] become one aspect of most important issue to arrange harmonic pollutions. The researchers develop more efficient power electronic systems to comply with these standards.

In this paper, the principle of the ac-dc boost PFC converter description is presented in section II. The current control strategies of peak and hysteresis techniques are compared and presented advantages and disadvantages is described in detail in section III. The simulation results are presented according to the simulation results of Matlab/Simulink program in section IV. The conclusion is given in the last section.

II. SYSTEM CONFIGURATION OF BOOST CONVERTER

There are different topologies used in PFC converters. The topology used in this study, is an ac-dc boost converter. Many applications require an ac-to-dc conversion from the line voltage. In its most simple form, this conversion is performed by means of a bridge rectifier and a bulk capacitor. The bulk capacitor filters the rectified voltage and provides certain energy storage in case of a line failure. But the resultant line current pulsates, causing a low power factor due to its harmonics and its displacement with respect to the line voltage. In many applications, this low quality in the power usage is not acceptable above certain minimum power levels, and the corresponding standards require improved technical solutions. One of topologies most commonly used to deal with this problem is so called single phase boost PFC. The simplified boost PFC circuit is shown in Figure 1.

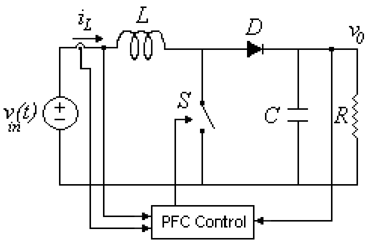

Figure 1. Boost PFC circuit topology

The boost inductor in the boost PFC circuit is in series with the ac power line. This topology inherently accepts a wide input voltage range without an input voltage selector switch. The equivalent circuits of the system are derived based on the "on" and "off" states of the converter switch and shown in Figure 2-a and Figure 2-b, respectively. The mathematical models of the respective equivalent circuits are given in Equations (1), (2) and (3).

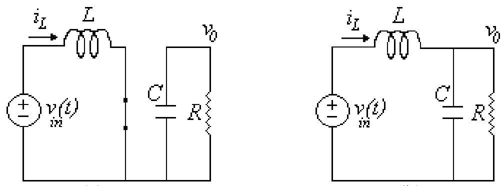

Figure 2. Switching operations of Boost PFC circuit topology
(a) on state switching, (b) off state switching

$$v_{in}(t) = V_m \left|\sin(wt)\right| \tag{1}$$

$$v_{in}(t) = L\frac{di_L(t)}{dt}, \; 0 < t < DT \tag{2}$$

$$v_{in}(t) - v_0 = L\frac{di_L(t)}{dt}, \; DT < t < T \tag{3}$$

The output voltage of a boost PFC circuit should be higher than the peak value of the maximum input voltage. Although this is a simple topology, it must be designed to handle the same power as the main power converter. Only the single-phase boost PFC circuit operating in the continuous inductor current mode is discussed with two different control techniques in this study.

It can be implemented with a controller, making the circuit relatively simple with a minimum number of components. The models corresponding to time intervals of $0 < t < dT_S$ and $dT_S < t < T_S$ are given in Equations (4)-(5), respectively.

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_0}{dt} \end{bmatrix} = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v_{in} + \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{R_L C_0} \end{bmatrix} \begin{bmatrix} i_L \\ v_0 \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_0}{dt} \end{bmatrix} = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v_{in} + \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C_0} & -\frac{1}{R_L C_0} \end{bmatrix} \begin{bmatrix} i_L \\ v_0 \end{bmatrix} \tag{5}$$

where $L=L_a+L_b$, C, T_s and R are the input inductance, output capacitance, switching period and load, respectively.

The voltage conversion ratio is

$$M = v_0 / v_{in} = 1/\left(1-d\right) = 1/d' \tag{6}$$

where d represents the duty-cycle corresponding to on time and d' represents the (1-d) corresponding to the off time of the switches. v_{in} is the rectified input voltage. Using Equations (4)-(5) the state matrices can be given as [8];

$$\bar{X} = \begin{bmatrix} i_L \\ v_o \end{bmatrix}, \; \dot{X} = \begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_o}{dt} \end{bmatrix} \tag{7}$$

$$\bar{A} = \begin{bmatrix} 0 & -\frac{1-d}{L} \\ \frac{1-d}{C} & -\frac{1}{RC} \end{bmatrix}, \; \bar{B} = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}, \; \bar{U} = \left[v_{in}\right] \tag{8}$$

$$\dot{X} = \bar{A}\bar{X} + \bar{B}\bar{U}$$

At steady state operation, the state variables of the bridgeless converter can be written as Equation (9).

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_o}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1-d}{L} \\ \frac{1-d}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ v_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \left[v_{in}\right] \tag{9}$$

The variation of duty cycle in time and the relationship between the voltage conversion ratio and duty-cycle are shown in Figure 3.

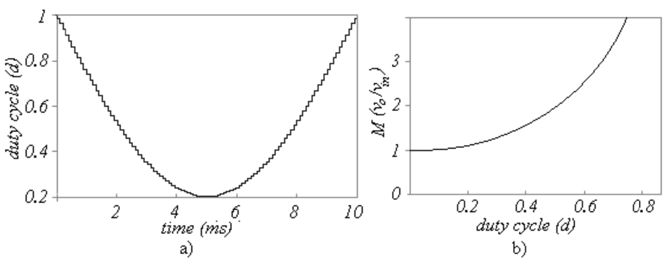

Figure 3. (a) Variation of duty cycle,
(b) Relationship between voltage ratio, M and duty cycle

III. CURRENT MODE CONTROL TECHNIQUES

Over many years, different current control techniques are usually used for controlling the PFC converters. In this section, several known methods of PCMC and HCMC techniques are discussed to enable the input current to be synchronized with the fundamental component of the input voltage. The parameters used in controllers to generate the gate signals of the switches are; input voltage, input current and output voltage. There are two loops in the software. The inner loop is responsible for controlling the shape of the inductor current and the outer loop controls the output voltage and keeps it constant at the pre-defined reference value. In outer loop, the output voltage level is scaled and compared with the given reference.

The error obtained from this comparison makes the input of the PI controller. Output of this particular controller is the scaling factor and is used to obtain the current reference. The reference current, i_{ref}, is obtained by multiplying a rectified input voltage by the output of the voltage controller. In inner loop, the inductor current is compared with the reference current. The error of this comparison is processed by the different current controllers to be used to generate the gate signals of the switches.

A. Peak Current Mode Control Technique

Peak Current Control mode is a well established control technique in power conversions. More recently, it has been applied widely in PFC pre-regulator converters. In this control configuration, the inductor current, i_L is chosen as the programming variable and is compared to the reference current, i_{ref} in order to generate the switching signal for switch S. The switch is turned on at constant frequency by a clock signal (50 kHz), and is turned off when sum of the positive ramp of the inductor current and a compensating ramp reaches the reference current. Specifically, while the switch is on, the inductor current climbs up, and as it reaches i_{ref}, the switches are turned off, thereby causing the inductor current to ramp down until the next clock comes. The block diagram of the peak current controller is shown in Figure 4.

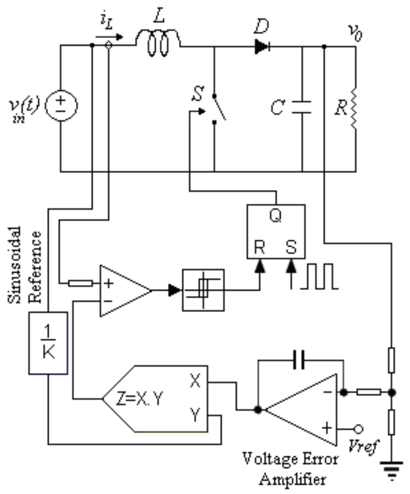

Figure 4. Single phase Boost PFC converter using peak current mode control technique

Advantages and disadvantages of the PCMC are summarized as [9-11]:

Advantages:

- Constant switching frequency,
- For industrial controller chips, only the switch current must be sensed and this can be accomplished by a current transformer, thus avoiding the losses due to the sensing resistor.
- No need for current error amplifier and its compensation network,
- Possibility of a true switch current limiting.

Disadvantages:

- Presence of sub-harmonic oscillations at duty cycles greater than 50%, so a compensation ramp is needed,
- Input current distortion which increases at peak line voltages and light loads
- Control more sensitive to commutation noises.

B. Hysteresis Current Mode Control Technique

HCMC technique has the constant on-time and the constant off-time control, in which only one current command is used to limit either the minimum input current or the maximum input current [12-14]. The circuit and HCMC technique diagram is given in Figure 5.

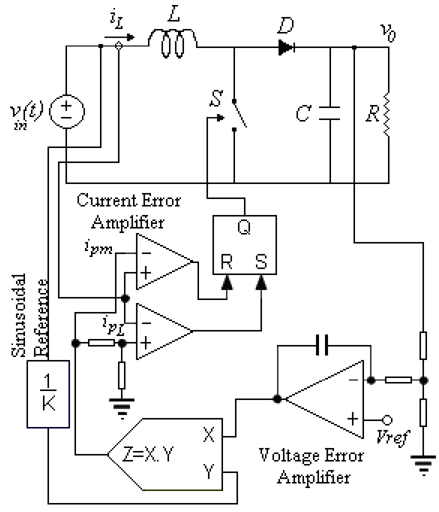

Figure 5. Single phase Boost PFC converter using hysteresis current mode control technique

Hysteresis comparators are used to impose hysteresis band around the reference current. The hysteresis control scheme provides excellent dynamic performance because it acts quickly. Also, an inherent peak current limiting capability is provided. This type of control in which two sinusoidal current references i_{pm}, i_{pL} is generated corresponding to maximum and minimum boundary limits. To achieve smaller ripple in the input current, a narrow hysteresis band must be desired. However, the narrower the hysteresis band, the higher the switching frequency. It is also possible to improve the hysteresis control in a constant frequency operation, but usually this will increase the complexity of the control circuit. Therefore, the hysteresis band should be optimized based on circuit components such as switching devices and magnetic components. Moreover, the switching frequency varies with the change of line voltage. According to this control technique, the switch is turned on when the inductor current decreases below the lower reference (i_{pL}) and is turned off when the inductor current increases above the upper reference (i_{pm}), giving rise to a variable frequency control. Also with this control technique the converter works in CCM. HCMC technique has advantages and disadvantages according to the control strategy. They are given such as:

Advantages

- No need to compensation ramp

Disadvantages

- Variable switching frequency
- Need inductance current sampling
- Control is sensitive to the noises
- Need current error amplifier [11-14]

Line current waveforms of PCMC and HCMC technique are given in Figure 6.

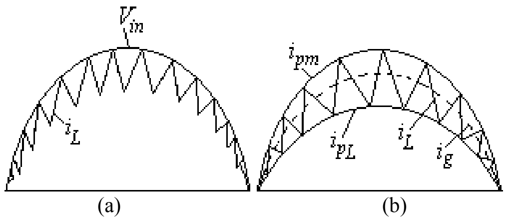

Figure 6. Line current waveforms, (a) Peak current mode control technique, (b) Hysteresis current mode control technique

IV. SIMULATION RESULTS

Many software programs used in the simulation of power electronics circuits. Some studies have been done to produce educational tools including graphical interface. There are some commercially programs that are able to simulate power electronics circuits. Using the schematic editors of some programs such as PowerSim, Pspice, Orcad, Matlab/Simulink, it is possible to carry out the simulation of the electronic circuits. In this study, Matlab/Simulink program for power electronics education is used for effective education and training. This program includes all branches of electrical and electronics engineering [15-18].

Single phase boost PFC converter topology and control diagram is prepared in Matlab/Simulink program. CCM has chosen due to the DCM input technique requires no input current control, but has less power handling capability while CCM has multi loop control and has more power handling capability according to the control simplicity and power handling capability. To reduce weight and size of the single phase boost PFC converter, higher switching frequency is desired, so the PCMC technique is chosen for stable switching frequency. To have good dynamic response, wider bandwidth is desired, however to achieve high PF storage capacitor and output capacitor has used.

The single phase boost PFC converter is simulated using PCMC and HCMC techniques. Simulation conditions are follows in Table 1.

Table 1. Simulation parameters

P	600 W
V_0	400 V
V_{in}	$220V_{rms}$ / 50Hz
Switching frequency - f_s	50 kHz
Inductance value - L	1 mH
Output Capacitor - C	500µF

This scheme makes the inductor current to bring a reference, which is a scaled sinusoidal input voltage. There are three sampling signals; input voltage, input current and output voltage waveforms.

Figure 7 shows the input voltage, inductor current and output voltage respectively for the case that the system is controlled by PCMC technique.

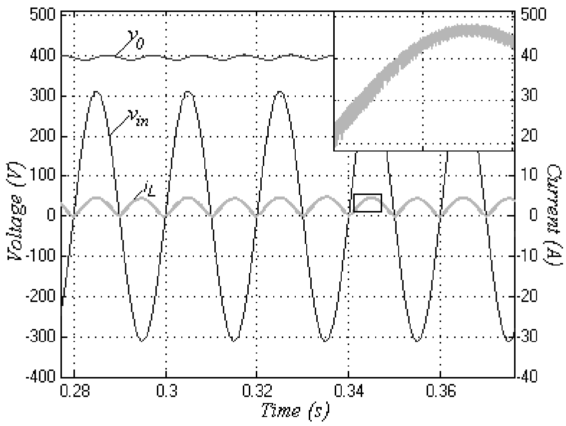

Figure 7. Input voltage, inductor current and output voltage waveforms of peak current mode control technique

In Figure 7, the input current *THD* value is 3.08% for the case that the system is controlled by PCMC technique. It is understood from the Figure 7 that the input current waveform has a little harmonics, and follows the input voltage waveform in same phase.

It is seen in Figure 8 that *THD* value of input current is low. The switching frequency is stable at PCMC technique.

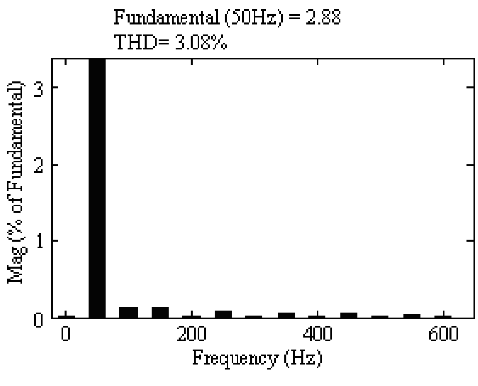

Figure 8. *THD* analysis of input current of peak current mode control technique

Figure 9 shows the input voltage, inductor current and output voltage respectively for the case that the system is controlled by HCMC technique.

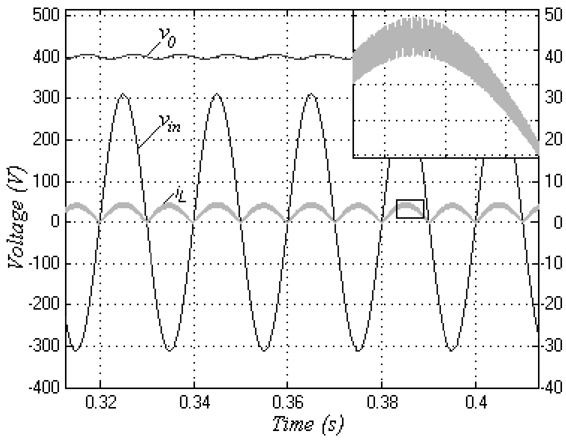

Figure 9. Input voltage, inductor current and output voltage waveforms of hysteresis current mode control technique

That is understood from the Figure 9, the input current waveform has harmonics, and follows the input voltage waveform in same phase too. Figure 10 shows the value of input current *THD* for the HCMC technique. Its value is 4.28%. It is seen in Figure 10 that *THD* value is high. The swithing frequency is unstable at HCMC technique.

Using the PCMC technique the *THD* of the input current is very low with respect to that of input current of the HCMC technique.

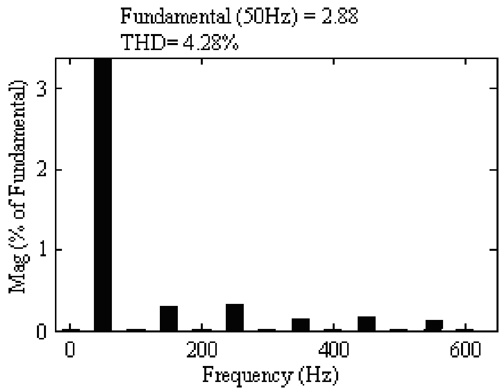

Figure 10. *THD* analysis of input current of hysteresis current mode control technique

As seen from Figures 7-10, the input current ripple of the *PCC* technique is less than that for hysteresis current control technique. Though there is no significant difference among power factors corresponding to other control techniques (*PF*=0.99), their *THD* values are different. It can be improved by increasing the switching frequency or using large inductors.

Simulation studies were carried out for the output powers from 100 to 600 W using the parameters in Table 2. The comparisons of input current *THD* values obtained with different output power levels for different control techniques are given in Table 2.

Table 2. Input current *THD* values of control techniques for different output power levels

Output Power [W]	Peak Current Control	Hysteresis Current Control
	Input Current [*THD*%]	Input Current [*THD*%]
100	6.55	7.46
200	5.44	5.94
300	5.16	5.47
400	4.34	4.69
500	3.97	4.47
600	3.08	4.28

V. CONCLUSIONS

In this study, two known current control techniques of single phase boost PFC converter were simulated and the results obtained from the simulations are compared for deeper understanding the control techniques of PFC topology. These control techniques are peak current mode control and hysteresis current mode control. The simulation study of the converter was carried out using Matlab/Simulink program. The advantages, dis-advantages, control strategy and *THD* values of input current are highlighted in simulation studies for each control technique. Simulation results show that though the PFC value for these control techniques is nearly the same, there are some differences in the *THD* values. It is clear that the peak current mode control technique is less sensitive for noise than the hysteresis current mode control, and its switching frequency is fixed compared with the switching frequency of the hysteresis current mode control technique where is variable. Due to the variable switching frequency, the *THD* value of hysteresis current mode control technique is higher than that of peak current mode control technique.

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BIOGRAPHIES

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Ires Iskender received the B.Sc. in Electrical Engineering from Gazi University, Ankara, Turkey in 1989. He received M.Sc. and Ph.D. degrees in Electrical Engineering from Middle East Technical University, Ankara, Turkey in 1991 and 1996, respectively. From 1989 to 1996 he worked as a research assistant in the Electrical and Electronics Engineering Department of Middle East Technical University. Since 1997 he has been with the Department of Electrical Engineering, Gazi University, where he is currently an associate professor. His interests include renewable energy sources, energy conversion systems, power electronics and electrical machines.