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Analysis on Power Factor Improvement for Switch-Mode Power Supply

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Abstract**—** Input power factor of static power converters is generally low due to angular displacement between input voltage and current plus due to current distortion. On the other hand, static power converters usage is increasing continuously with the increase in use of power supply units to commercial, industrial and residential complex automation and communication systems. Digital control for power factor correction is an important field of study since it can be used to reduce the harmonics in the line current, increase the efficiency of power systems, and reduce customers' utility bills. In this paper, a digitally controlled switched mode PFC (Power Factor Correction) converter is designed, modeled and simulated. The two control modes such as current mode control and PFC mode control, which are used for switched mode converter, aresimulated using the MATLAB/Simulink.

Keywords**—***Digital Control, Power Factor Correction, current Mode Control, PFC Mode Control, MATLAB/SIMULINK.*

I. INTRODUCTION

The block diagram for digital control of a boost PFC converter based on average current mode control is illustrated in Fig.1. In the outer voltage loop, output voltage is sensed and compared with the voltage reference. The error becomes the input to the voltage proportional-integral (PI) controller. The output of this PI controller is the scaling factor for the rectified voltage that is used as one of the inputs to the multiplier. The product of the scalingfactor and the rectified voltage is the current reference, i_{ref}. The inner current loop implements average current mode control to force the average inductor current to follow the reference current.

In digital implementation for average current mode control, multiplication and division operations are implemented by the software. Because all the calculations, including multiplication and division, are executed in every switching period, the implementation requires a high speed digital controller.

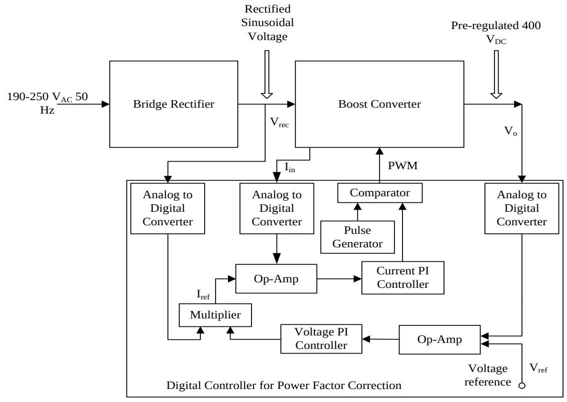

Fig.1 Block diagram of switched mode power supply power factor improvement with digital controller

The processes in a digital control PFC based on average current mode control include: output voltage samples, voltage error calculation, voltage PI controller, reference current controller (including multiplication), current error calculation, current PI controller and duty cycle calculations. Because this process is iteratively running in every switching cycle, a high performance digital controller is needed. In this paper, general purpose DSP ADMC401 from Analog Device is chosen for the implementation.

II. IMPORTANCE OF HARMONIC ELIMINATION

Nowadays, AC lines result more and more polluted, due to the increasingly number of non-linear loads such as power converters and, more in general, switching devices whose commutations increase current harmonics amplitude. Quite simply, harmonics are a source of EMI. EMI can create voltage and current surges. Harmonics can also create losses in power equipment. Harmonics can also lower the power factor of a load. The power factor of a load is proportional to the ratio of the magnitude of the fundamental of the load current to the magnitude of the load current. Increased harmonic content may decrease the magnitude of the fundamental relative to the magnitude of the entire current. As a result, the power factor would decrease.

III. CONTROL METHODS OF POWER FACTOR CORRECTION

The most common closed loop control methods for PWM PFC converters are current mode control and PFC (average current mode) control [4].

A. Current Mode Control

The current mode control is presented in Fig.2. The peak inductor current is proportional to the input voltage. Hence, the inner loop of the current mode control naturally accomplishes the input voltage-feed forward technique. The inner control loop feedbacks an inductor currentsignal. After then, a voltage converted from this current signal is compared to the control voltage [3][4].

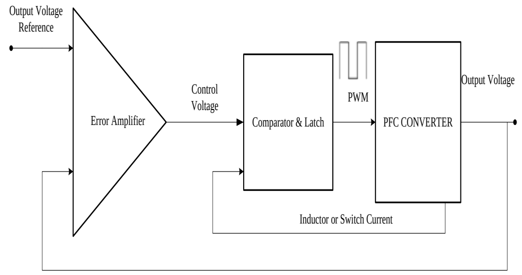

Fig.2 Current mode control scheme [4]

B. PFC Mode Control

The PFC controller generally has two control loops. The first loop is a voltage control loop for regulated output voltage. The second loop is a current control loop for high power factor value and active shaping the input current [3][4].

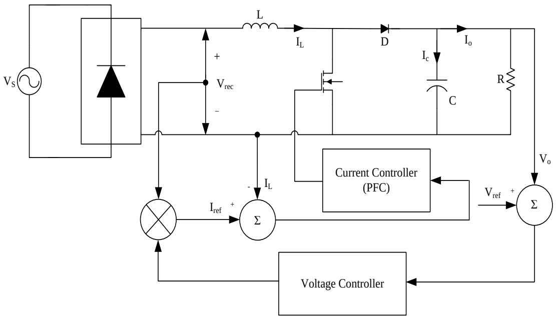

Fig.3Boost converter with PFC mode controller [4]

A PFC mode controller with boost converter is shown in Fig.3. In basic form, a switch controls the boost converter circuit. When the switch is closed, current flows through the inductance. After then, the switch is opened and the current is forced to flow through the diode to the output. Multiple cycles of this switching cause the output capacitor voltage to build due to the charge it stores from the inductor current. The result is a higher output voltage than the source voltage [4]. Generally, voltage and current control of boost converter can be fulfilled via traditional control methods such as PI controller.

IV. DESIGN AND MODELING OF PFC MODE CONVERTER

The circuit diagram of a boost PFC converter with digital controller based on average current mode control is illustrated in Fig.4.

A.Boost PFC Converter Design

A 4 kW boost PFC converter is designed with the following power stage specifications.

- Input voltage = 220 V_{ac} single phase
- Output voltage = 400V
- Output power = 4000 W

η (efficiency of converter) = 0.95

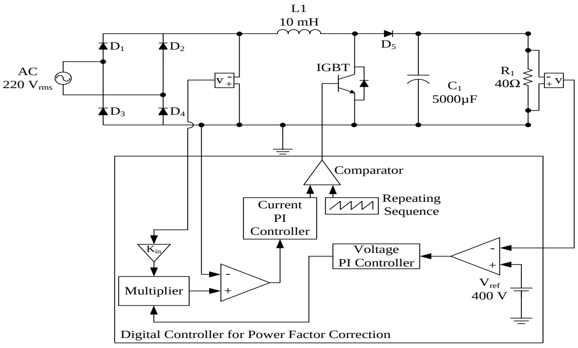

Fig.4Circuit diagram of power factor improvement switching converter with digital PI controller

For boost PFC converter, PF is assumed to be 0.99 or greater. Assuming a nominal efficiency of the converter to be 0.95 [5],

$$P_{IN(MAX)} = \frac{P_{O(MAX)}}{\eta} = \frac{4000W}{0.95} = 4210.53W \quad (1)$$

The maximum rms AC line current is

$$I_{IN(RMS)MAX} = \frac{P_{O(MAX)}}{\eta . V_{IN(RMS)} . PF} = 19.18A \quad (2)$$

where, $V_{IN(RMS)}$=220V, PF=0.998

The peak value of the AC current is

$$I_{IN(PK)MAX} = \frac{\sqrt{2} . P_{IN(MAX)}}{V_{IN(RMS)}} = 27.07A \quad (3)$$

Power switch duty cycle (D) is determined using input rms voltage. The peak input voltage is used for boost inductor calculation [5].

$$V_{IN(PK)} = \sqrt{2} . V_{IN(RMS)} = \sqrt{2} . 220V = 311V \quad (4)$$

$$D = \frac{V_O - V_{IN(RMS)}}{V_O} = \frac{400V - 220V}{400V} = 0.45 \quad (5)$$

Ripple current (ΔI_L) is assumed to 20% of peak input current [5].

$$\Delta I_L = 0.2 \times I_{IN(PK)MAX} \quad (6)$$

$$\Delta I_L = 0.2 \times 27.07A = 5.41A$$

$$I_{L(PK)MAX} = I_{IN(PK)MAX} + \frac{\Delta I_L}{2} = 29.78A \quad (7)$$

Assuming switching frequency is 20 kHz, the boost inductor is [5]

$$L_{BST} = \frac{8 \times V_{IN(PK)} \times D}{f_{SW} \times \Delta I_L} = 10.34mH \quad (8)$$

So the boost inductor is chosen to be 10mH.

Output capacitor design in PFC converters is typically based on hold up time requirements. For such applications, hold-up time (Δt) can be taken to be around 30ms. Taking minimum input rms voltage to be 190V (13% deviation), minimum output capacitance is given below [5].

$$C_{OUT} \geq \frac{\frac{1}{2} . P_O . \Delta t}{V_{IN(RMS)}^{\ 2} - V_{IN(RMS)MIN}^{\ 2}} = 4878\,\mu F \quad (9)$$

Hence the output capacitance can be taken to be 5000µF. The boost converter design is complete with L=10mH and C=5000µF.

B. Current Controller Design

The current loop with digital controller is illustrated in Fig.5 [6].

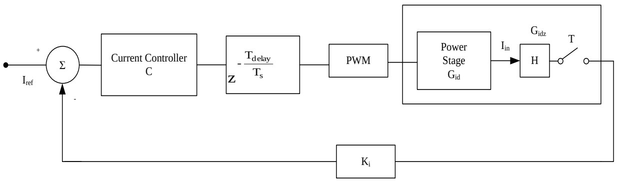

Fig.5 Current loop with digital compensator [6]

In Fig.5, the value K_i is the current feedback gain. The design target is so that, the phase margin is set to 45° and for a faithful tracking of the semi sinusoidal waveform, the bandwidth is 8 kHz [6]. The value of 45° for the phase margin is a benchmark value for stability of the digital controller. The current controller is given in equation (10).

$$C(z) = K_p \frac{(z - \xi)}{z - 1} \quad (10)$$

The current loop gain is given as follows [6].

$$T_C(z) = G_{idz}(z) . C(z) . K_i . z^{-\frac{T_{delay}}{T_s}} \quad (11)$$

$$= \frac{V_{out} . T_s}{L\,(z - 1)} . \frac{K_p (z - \xi)}{z - 1} . K_i . z^{-\frac{T_{delay}}{T_s}} \quad (12)$$

The two design targets, magnitude of the current loop gain and phase margin are used to determine two unknown variables, gain K_p and zero ξ, as shown below.

$$\begin{cases} \left|T_C(e^{j\omega_c T_s})\right| = 1 \\ \angle T_C(e^{j\omega_c T_s}) = -180° + 45° \end{cases} \quad (13)$$

where $\omega_c=2\pi f_c=2\pi*8$krad/sec, $V_{out}=400$V, L=10mH, K_i (current feedback gain)=0.0725, $T_{delay}=10\mu s$ and $T_s=50\mu s$. Solving equation (13),

$$\begin{cases} K_p = 50 \\ \xi = 0.8 \end{cases} \quad (14)$$

Hence, the controller transfer function is given in equation (15). Changing this into continuous s-domain (using d2c function of MATLAB), equation (16) is resulted.

$$C(z) = \frac{50(z-0.8)}{z-1} \quad (15)$$

$$C(s) = \frac{50s+100}{s} \quad (16)$$

Hence a PI current controller is designed with gains $K_p=50$ and $K_i=100$ based on design target.

C. Voltage Controller Design

The voltage loop is shown in Fig.6 [6].The discrete transfer function of the voltage controller is given in equation (17).

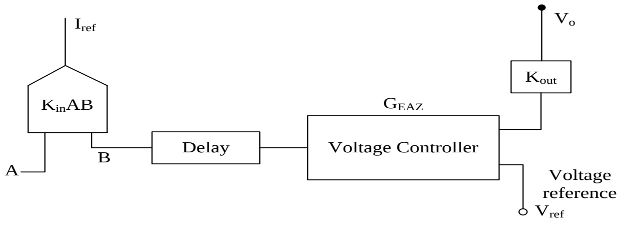

Fig.6 Outer voltage loop [6]

The voltage open loop gain is given in equation (18) [6].

$$G_{EAZ}(z) = \frac{K_p(z-\xi)}{z-1} \quad (17)$$

$$T_v = G_{vz} \cdot K_{out} \cdot G_{EAZ} \cdot z^{-\frac{T_{delay}}{T_s}} \quad (18)$$

The two design targets, the magnitude of the current loop gain and phase margin are used to determine two unknown variables gain K_p and zero ξ as shown below [6].

$$\begin{cases} \angle T_v(e^{-j\omega_c T_s}) = -180° + 45° \\ \left|T_v(e^{-j\omega_c T_s})\right| = 1 \end{cases} \quad (19)$$

where $T_{delay}=10\mu s$, $T_s=50\mu s$, $K_{out}=0.002$ (output voltage sensing gain), $C=5000\mu F$. The voltage controller parameters are found to be as given in equation (20). The voltage controller is given in equation (21).

$$\begin{cases} K_p = 0.002 \\ \xi = -99 \end{cases} \quad (20)$$

$$G_{EAZ}(z) = \frac{0.002(z+99)}{z-1} \quad (21)$$

Changing this discrete function into continuous s-domain (using d2c MATLAB function), the following result is obtained.

$$G_{EA}(s) = \frac{0.002s+2}{s} \quad (22)$$

Hence a PI voltage controller is designed with gains $K_p=0.002$ and $K_i=2$ based on design targets.

V. SIMULATION OF DIGITALLY CONTROLLED PFC CONVERTER WITH MATLAB/SIMULINK

The simulation tests and results of the MATLAB/SIMULINK of power factor corrector for two control schemes are described.

A. MATLAB/SIMULINK for Current Mode Control

The current mode controller for boost PFC converter is simulated using MATLAB/Simulink.

The circuit parameters are given below:

$V_{s(peak)}=311$V, $V_{s(rms)}=220$V, f(line)=50Hz, L=10mH, C=5000μF, R-load=40Ω, $V_{out}=400$V, $P_{out}=4000$W.

For voltage controller $K_p=0.2$ and $K_i=20$. For current controller $K_p=5$ and $K_i=1000$.

Fig.7 and Fig.8 shows the MATLAB/Simulink model of boost converter and the current mode controller respectively. The subsystem diagram for power factor measurement is shown in Fig.9.

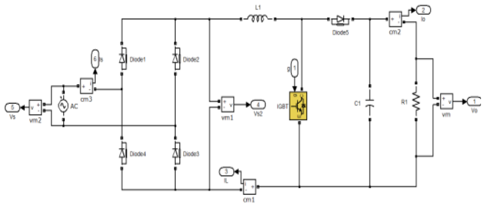

Fig.7 MATLAB model of boost converter

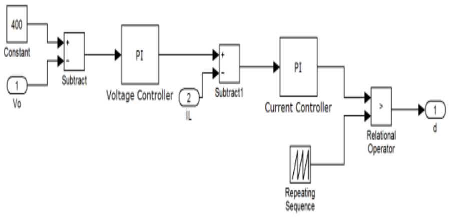

Fig.8 MATLAB model of current mode controller

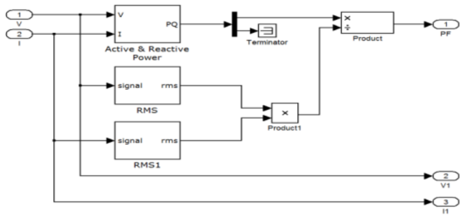

Fig.9 Subsystem for power factor measurement

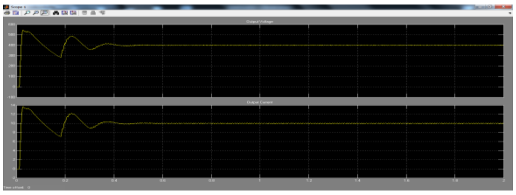

Fig 10. Output voltage and output current of the current mode controlledconverter

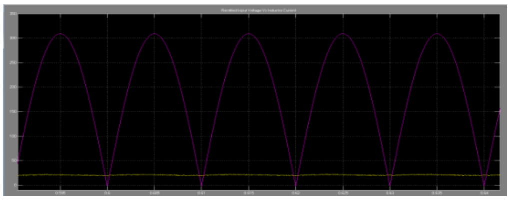

Fig.11 Rectified input voltage (upper) and inductor current (lower) of the current mode controlled converter

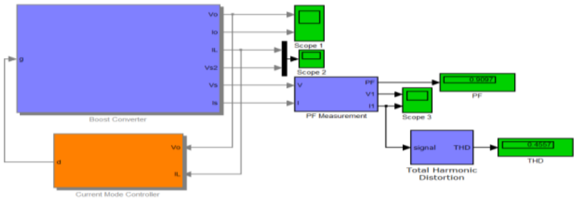

Fig.12 PF measurement of 0.9097 and THD measurement of 0.4557

The output voltage and output current are obtained as desired. Output voltage is controlled to 400V level. The output power is 4kW as desired. Inductor current is not in phase with input voltage waveform when current mode controller is used.

B. MATLAB/SIMULINK for PFC Mode Control

The PFC mode controller for boost PFC converter is simulated using MATLAB/Simulink.

The circuit parameters are given below.

V_s(peak)=311V, V_s(rms)=220V, f(line)=50Hz, L=10mH, C=5000µF, R-load=40Ω, V_{out}=400V, P_{out}=4000W.

For voltage PI controller K_p=0.002 and K_i=2 as determined in Equation (22). For current PI controller K_p=50 and K_i=100 as obtained from Equation (16). These values of K_p and K_i are determined previously in the design stage of the current loop and voltage loop compensator.Fig.13 shows the MATLAB simulink model of PFC mode controller respectively.

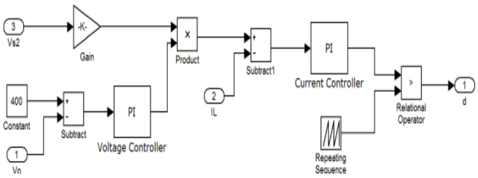

Fig.13 MATLAB model of PFC mode (average current mode) controller

Fig.14 shows the output voltage and the output current respectively. Fig.15 shows the rectified input voltage and the inductor (input) current.

Fig.14 Output voltage and output current of PFC mode controlled converter

As shown in Fig.16, near unity power factor (PF) is obtained by using the designed PFC controller. Output voltage and output current are obtained as desired. Output voltage is controlled to the 400V level. Output power is 4kW as desired. Inductor current is in phase with input voltage waveform and it has the best semi-sinusoidal shape as compared to that obtained by using the current mode control.

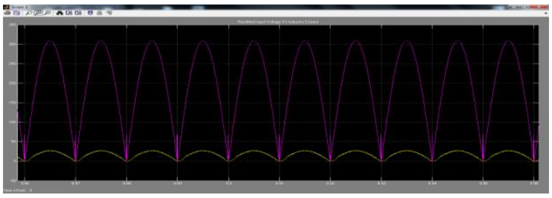

Fig.15 Rectified input voltage (upper) and inductor current (lower) of PFC mode controlled converter

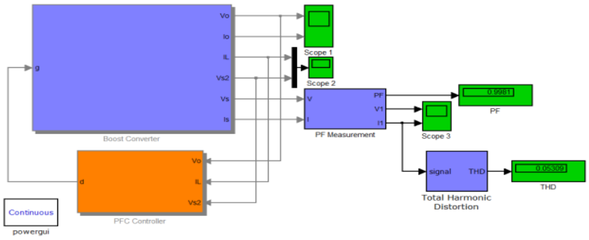

Fig.16 PF measurement of 0.998 and THD measurement of 0.053

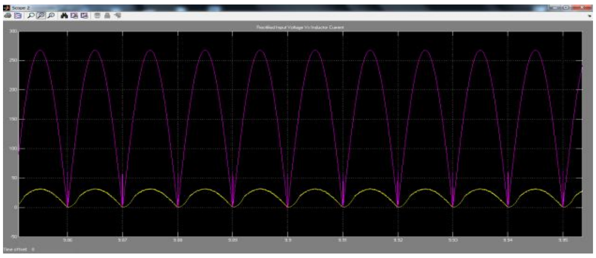

Fig.17 Rectified input voltage (upper) and inductor current (lower) for $V_{in(peak)}$ = 270V

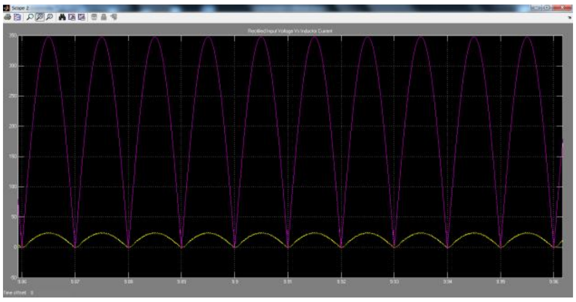

Fig.18 Rectified input voltage (upper) and inductor current (lower) for $V_{in(peak)}$ = 350V

Once the PFC controller is designed, it should be checked that it works properly even if there is deviation in the input voltage and the load. Fig.17 shows the simulation result when the peak input voltage is changed from 311V to 270V, that is about 15% of input voltage variation. Similarly, Fig.18 shows the simulation results when the peak input voltage is changed to 350V (about 15% of variation).

Fig.19 shows the simulation results when the load is changed from 40Ω to 20Ω which is around 50% of load variation. These simulation results show that the designed PFC controller works properly for these input voltage and load variations (deviations).

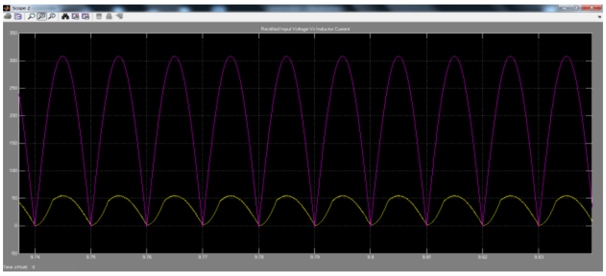

Fig.19 Rectified input voltage (upper) and inductor current (lower) for R (load) = 20Ω

The main target of the PFC controller is to make the input current (inductor current) in phase with the input voltage, and as seen from the simulation results, this task is accomplished with PF = 0. 9981 (unity PF).The designed PFC controller (with voltage PI controller K_p=0.002 and K_i=2, current PI controller K_p=50 and K_i=100) works well for 15% input voltage variation, and for 50% load variation. The PFC controller renders an input current in phase with input voltage more effectively than current mode controller.

CONCLUSIONS

In this paper, a digitally controlled switched mode PFC converter has been designed, modeled and simulated. Of the two control modes, PFC mode controller implementation is the target of this study. From the simulation results, it can be deduced that the PFC mode controller for the switched mode converters has the best performance.

One of the ways of evaluating the performance of a digital controller is to determine how the controller responds to input voltage variation and load variation. It has been found that the PFC mode controller performs well even if there is an input voltage variation up to 15% and load variation up to 10% load. The results of the simulation show that the required level of output voltage and output power are obtained with the power factor being improved to near unity. For the 100% load, the PFC mode controller achieves a near unity input power factor with PF of 0.998 and current mode controller has a lower power factor of 0.910. It is found that the lowest Total Harmonic Distortion and the highest Power Factor are obtained using the PFC mode control. Since a near unity PF is the main objective, based on these criteria the PFC mode control is the best control mode as compared to current mode of control.

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