POWER FACTOR CORRECTION AND THD MINIMIZATION USING INTERLEAVED BOOST CONVERTER IN CONTINUOUS CONDUCTION MODE

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ABSTRACT

A general feature of all DC power supplies and nonlinear loads such as SMPS and computer systems connected to the AC mains is the presence of a diode rectifier terminated on a DC link capacitor. During this convertion, the supply current is pulsating in nature. This leads to the reduction in power factor and distortion in supply current. This necessitates the use of Power Factor Correction circuits for power electronic converters. In this work, high power factor and low harmonic distortion is achieved with the help of Interleaved Boost Converter. The Interleaved Boost Converter is implemented using both analog and digital proportional integral controller. Analog controller uses average current mode control technique with two control loops, namely a high bandwidth inner current control loop to have sinusoidal wave shape for input current and a low bandwidth outer voltage control loop to obtain a regulated output voltage. Digital controller uses Digital Pulse Width Modulation technique for the control system design. Mathematical modelling of Interleaved Boost Converter and stability analysis of the converter is carried out. The proposed Analog and Digital controller helps to obtain a regulated output voltage against disturbances in load. The simulation schematic covering the power and control circuit has been developed using MATLAB/Simulink software and the corresponding results are obtained. It is observed from the results that the THD of input current is reduced effectively and power factor is also improved.

Keywords: two phase interleaved boost converter (IBC), average current mode control, power factor, THD, proportional integral, digital pulse width modulation (PWM).

1. INTRODUCTION

The available AC supply is converted to DC supply using interfacing power electronic switching circuitry. This produces ripple of high magnitude at the output. To reduce the ripple magnitude at the output DC voltage, filter capacitor is added at the output which causes the problem of low power factor and high harmonic distortion. This filter capacitor helps to regulate the output voltage to a constant value, but it draws input current that is out of phase with the supply voltage. This pulsating input current leads to low power factor and high harmonic distortion. Power Factor Correction is incorporated to improve power factor. Among all the converters used for power factor correction, Boost Converter [1] is chosen as continuous source current is drawn from the supply side. Conventional boost converter has ripple in the input current and this ripple can be reduced by using two phase interleaved boost converter [2-3]. Interleaved boost converter helps in eliminating the ripple in the input current almost completely and for this reason, interleaved boost converter is advantageous. Two phase Interleaved Boost Converter contains two parallel connected boost converters that operate in 180 degree phase shift [4].

In switched mode power supplies, various control techniques have been developed to achieve unity power factor. In the beginning, Analog controllers have been widely used in this application due to its excellent performance at low cost. The Analog Controller is presented in [5] that use hysteresis control due to its stability, robustness and dynamic response [6-8]. Both impedance matching application and power factor correction is implemented using hysteresis controller [9-12]. Current controllers with constant frequency-based controllers are preferred for PFC than hysteresis controllers as the EMI filters are easy to design. Cost of analog controllers was high and implementation was difficult, so a single chip with low cost was developed for PFC [13] that involved an external multiplier. In order to avoid the use of external multiplier, one cycle control and nonlinear control [14-16] were developed. In the last decade, Digital controllers are used extensively as computational capability is increased with respect to its Analog counterparts [17-20].

Analog and Digital controllers are used with interleaved boost converter to get a regulated output voltage, input current in phase with the supply voltage that is sinusoidal with good power factor and low THD [21].

The next section gives the details of the interleaved boost converter. In section III, Interleaved Boost Converter is designed. In Section IV, mathematical modeling of two phase Interleaved Boost Converter is derived. State space averaged system modelling is done in section V. Stability is analysed in section VI. Power factor correction by average current mode control is explained in section VII. Section VIII exhibits the digital control of Interleaved Boost Converter. Digital controller is designed using Trapezoidal Rule of Integration in Section IX [22-32]. The performance of the control methods are validated by the simulation results shown in section X. Section XI discusses the conclusion of the work carried.

VOL. 12, NO. 11, JUNE 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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2. INTERLEAVED BOOST CONVERTER

Interleaved Boost Converter consists of N number of boost converters connected in parallel and it is controlled by interleaving technique i.e. phase shifted switching function. Pulse between parallel networks is phase shifted by $\frac{360}{N}$, where N is the number of phases connected in parallel. Inductor size is reduces by phase shift interleaving operation. Two phase Interleaved Boost Converter is used to reduce the component size, to reduce the stresses in devices, to cancel the ripple present in the input current and output voltage and current and to distribute current between parallel paths.

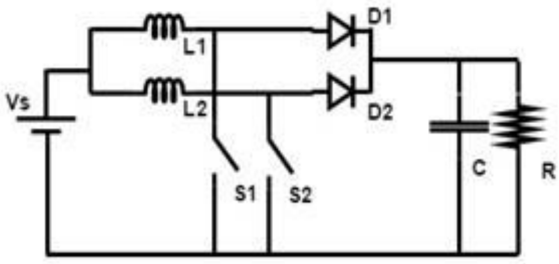

Figure-1. Power circuit diagram of two phase Interleaved Boost Converter.

Sum of both the inductors currents is equal to input current. Two phase interleaved boost converter has two inductors connected in parallel with same inductance value. The energy stored in the inductor is doubled. It can provide same output power level as conventional boost converter for lower value of inductance. Pulse given between parallel networks is phase shifted by 180 degrees.

3. DESIGN OF TWO PHASE INTERLEAVED BOOST CONVERTER

Table-1. Parameters of two phase Interleaved Boost Converter.

Input voltage, V_{in} = 24 V	**Inductor, L = $\frac{V_{in}*D*T_s}{delI_{in}}$ =$1mH$**
Output Voltage, V_o = 48 V	Capacitor C = $(V_0 * D * T_s)/(R_L * del\ V_o)$ = 212µF
Output Power, P_o = 120 W	Output Current, $I_o = \frac{P}{V_o} = \frac{120}{48} = 2.5\ A$
Switching Frequency, f_s = 10 kHz	Resistance, $R = \frac{V_o}{I_{out}} = \frac{48}{2.5} = 19.2\ \Omega$

4. MODELLING OF INTERLEAVED BOOST CONVERTER

State variables are inductor currenti_1, inductor current i_2 and output voltage V_o.

Table-2. Eight running states of Interleaved Boost Converter.

	Switch 1 ON	**Switch 2 ON**	**Diode 1 ON**	**Diode 2 ON**
Switch 1 ON	state 2	state 7	-	state 1
Switch 2 ON	state 7	state 5	state 4	-
Diode 1 ON	-	state 4	state 3	state 8
Diode 2 ON	state 1	-	state 8	state 6

5. STATE SPACE AVERAGE SYSTEM MODEL

The average state matrices are derived separately for each eight state and the average state space model of the proposed system is expressed as

$$\dot{X} = (A_1d_1 + A_2d_2 + A_3d_3 + A_4d_4 + A_5d_5 + A_6d_6 + A_7d_7 + A_8d_8)X + (B_1d_1 + B_2d_2 + B_3d_3 + B_4d_4 + B_5d_5 + B_6d_6 + B_7d_7 + B_8d_8)V_S \quad (1)$$

$$V_O = (C_1d_1 + C_2d_2 + C_3d_3 + C_4d_4 + C_5d_5 + C_6d_6 + C_7d_7 + C_8d_8)X \quad (2)$$

On substituting all the matrix values in the above equation 1and 2, we get the overall combined matrices as

$$A = \begin{bmatrix} 1/L_1 & 0 & (d_3+d_4+d_8)/L_1 \\ 0 & 1/L_2 & (d_1+d_6+d_8)/L_2 \\ (d_3+d_4+d_8)/C & (d_1+d_6+d_8)/C & 1/(RC) \end{bmatrix}$$

$$B = \begin{bmatrix} (d_1+d_2+d_3+d_4+d_7+d_8)/L_1 \\ (d_1+d_4+d_5+d_6+d_7+d_8)/L_2 \\ 0 \end{bmatrix}$$

$$C = [0 \quad 0 \quad 1]$$

6. MODES OF OPERATION

The Two Phase Interleaved Boost converter operates in Continuous Conduction Mode and converters inductor current waveform can have different shape depending on the PWM pulse duty (D).

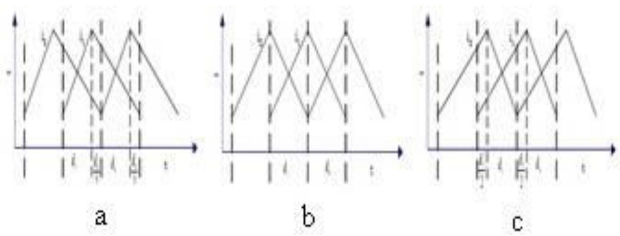

Figure-2. Inductor current waveforms in continuous conduction mode based on duty ratio.
a D<0.5 b D=0.5 c D>0.5

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The whole systems uniform state-space average matrices in continuous conduction mode is given by

$$A = \begin{bmatrix} 0 & -(1-D)/L \\ (1-D)/C & -1/(RC) \end{bmatrix}$$

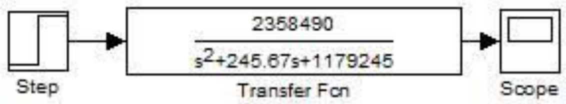
$$B = \begin{bmatrix} 1/L \\ 0 \end{bmatrix} \quad C = \begin{bmatrix} 0 & 1 \end{bmatrix}$$

Substituting all the values in the above matrices, we get the systems state matrices as

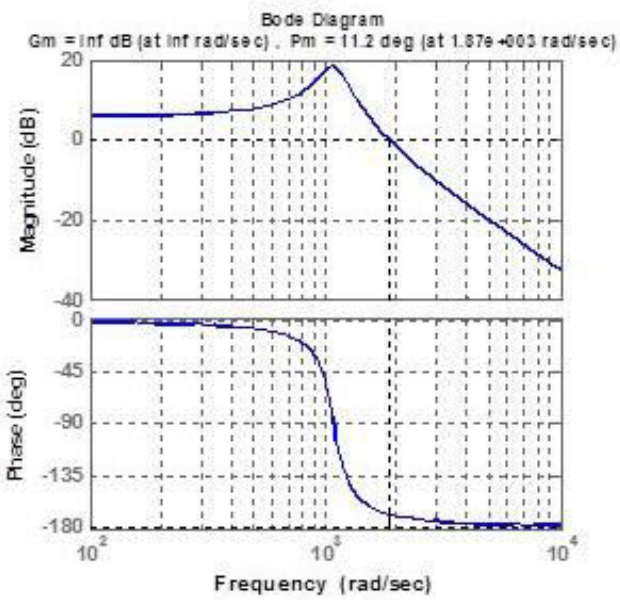
$$A = \begin{bmatrix} 0 & -500 \\ 2358.49 & -245.67 \end{bmatrix} B = \begin{bmatrix} 1000 \\ 0 \end{bmatrix} \quad C = \begin{bmatrix} 0 & 1 \end{bmatrix}$$

The state space average system model is converted to Transfer Function and it is given by

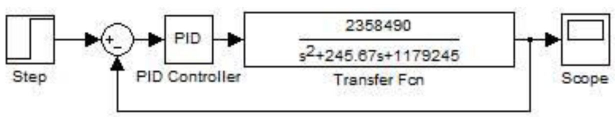
$$G(s) = \frac{235890}{s^2+25.67\,s+1179245} \qquad (3)$$



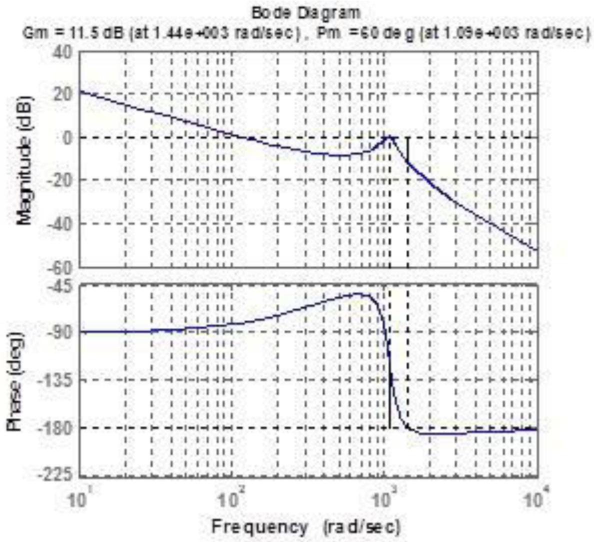
(a)



(b)



(c)



(d)

Figure-3. Stability analysis of two phase Interleaved Boost Converter.
a. Block diagram of open loop control Interleaved Boost Converter.
b. Bode plot of the open loop system
c. Block diagram of the PI controlled Interleaved Boost Converter.
d. Bode plot of the closed loop system.

Bode Plot of Interleaved Boost Converter is drawn as shown in figure 3b and a phase margin of 11.5 degree is obtained. In order to improve the phase margin, proportional integral controller is used. Bode Plot of Interleaved Boost Converter with proportional integral controller is shown in figure 3d and a desired 60 degree phase margin is obtained. The PI controller parameters are obtained as Kp = 0.1009, Ki = 57.39. Ziegler Nicholas closed loop method is used to determine the Kp and Ki values.

7. ANALOG CONTROL OF INTERLEAVED BOOST CONVERTER

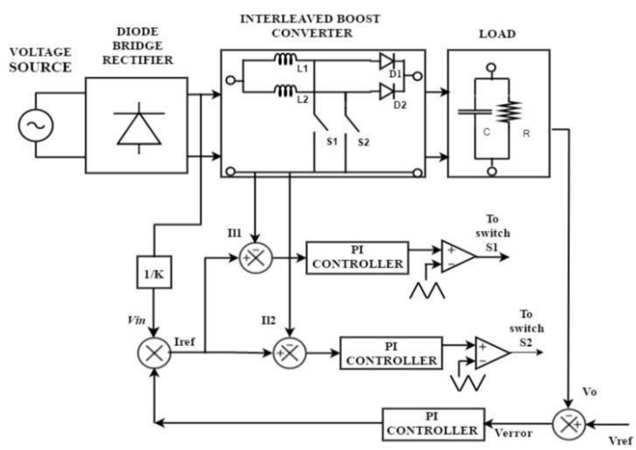


Figure-4. Block diagram of analog control of Interleaved Boost Converter.

For Analog Control of Interleaved Boost Converter, Average Current Mode Control technique is used as shown in Figure-4. The controller consists of two loops, namely, outer voltage control loop and inner current control loop. The main objective is that the wave shape of source current should be sinusoidal, while a regulated voltage is obtained at the output. The outer voltage control loop is used to regulate the output voltage to a constant value. In this loop, the reference voltage and actual voltage are compared to obtain current reference I_L^* for the inner current control loop. Inner current control loop is used to maintain the sinusoidal wave shape of the input current. Sine reference is required for this purpose. This sine reference is generated by multiplying I_L^* with |sinωt| that is got from the rectified source voltage. Thus, I_L^*sinωt acts as the reference current for the inner current control loop. This reference current is compared with the actual rectified source currents I_{L1} and I_{L2}separately for both the phases in the current controller, and generates the required control outputs. These control outputs are compared with the high frequency ramp signals that are phase shifted by180^0. The comparison of these signals generates the required pulses to drive the switches. Thus, the pulses obtained have 180^0 phase shift between them.

8. DIGITAL CONTROL OF TWO PHASE INTERLEAVED BOOST CONVERTER

The overall block diagram is shown in figure 5. The digital control is used for the generation of pulses by controlling both output voltage and input current. The feedback control is used to get regulated output voltage. Thesampled voltage erroris given to the Digital compensator. The output of this digital compensator is multiplied with sine template and then compared with the sensed inductor current signals. The current error is processed in the digital compensator block and the resulting signal is compared with the carrier signal in the digital PWM block which gives pulses to the switches.

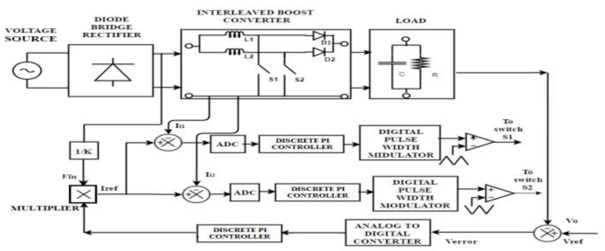


Figure-5. Overall block diagram of digital control of Interleaved Boost Converter.

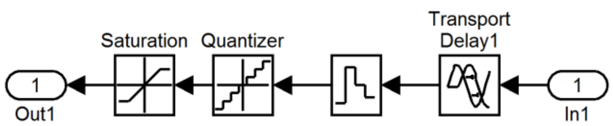


Figure-6. Analog to digital converter.

Sampling technique is used to obtain a discrete time signal from continuous time signal which is done by Analog to Digital converter as shown in Figure-6.

The discrete proportional integral controller is designed by using Trapezoidal Rule of Integration and the block diagram is shown in Figure-7.

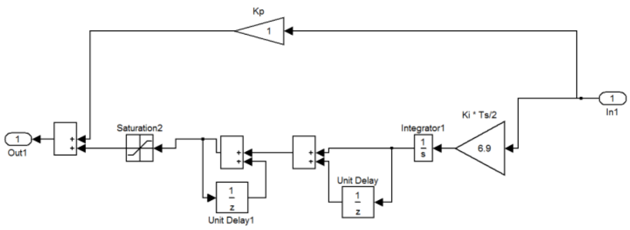


Figure-7. Block diagram of discrete proportional integral controller.

Difference equation model of this controller by using this rule is given by

$$P(Z) = K_P X(Z) + \frac{K_P}{T_I} * \frac{T_S^*}{2} * \left(\frac{1 + Z^{-1}}{1 - Z^{-1}}\right) X(Z) \qquad (4)$$

$$P_1(k) = K_P\, X(k); \qquad (5)$$

$$P_2(k) = \frac{K_I T_S^*}{2}\big(X(k) + X(k-1)\big) + P_2(k-1) \qquad (6)$$

Where X (Z) – Controller Input, P (Z) – Controller Output, K_p − Proportional gain, T_i − Integral time and $K_i = \frac{K_p}{T_i}$ − Integral gain, T_S- sample duration.

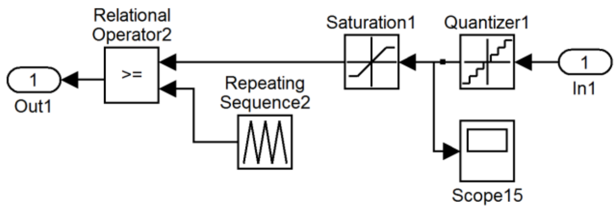


Figure-8. Digital pulse width modulation.

The Proportional Integral Controller output is compared with the high frequency ramp signal to get the pulses for the switch as shown in Figure-8.

9. DESIGN OF DIGITAL CONTROLLER

The digital controller is designed in the two steps discussed here. In the first step, the Analog Controller is designed in the continuous time domain. The Analog Controller behavior is approximated to the Digital Controller in second step. This approximation changes the continuous domain to discrete domain. In this domain, the error signal is being reduced and the exact output voltage is traced.

The Proportional Integral Differential controller in the continuous time domain with u(t) as control output and error as e is expressed as

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$$u(t) = K_p[e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{de(t)}{dt}] \quad (7)$$

The Kp, Td and Ti values are obtained by tuning based on present, past and future error respectively [12]. PID controller's Laplace transform is given by

$$U(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right)E(s) \quad (8)$$

The tuning parameters are properly chosen for a controller that can adapt to a particular converter to achieve better behavior of the system. The range of K_P is found by using Routh-array technique. Ziegler Nichols tuning rule method is used to obtain the values of T_i and T_d.

Transfer function of the Two Phase Interleaved Boost Converter is expressed as

$$G(s) = \frac{235890}{s^2 + 25.67\,s + 1179245} \quad (9)$$

This transfer function is of the general form

$$G(s) = \frac{1}{s^2+2\xi\omega\,s+\omega^2} \quad (10)$$

$\omega^2 = 1179245;$
$\omega = 1085.93;$

Critical period, $P_{cr} = \frac{2\pi}{\omega} = 5.7859 * 10^{-3};$ (11)

$T_i = 0.5 * P_{cr} = 2.8929$ ms; (12)

$T_d = 0.125 * \text{Pcr} = 7.2324 * 10^{-4}$s (13)

$K_p = 0.01$; (14)

$K_i = \frac{K_p}{T_i} = 3.4567$; (15)

$K_d = K_p * T_d = 7.2324 * 10^{-6}$ (16)

Transfer function of Proportional Integral Differential controller is given by,

$$G(s) = K_p + \frac{K_i}{s} + K_d\,s \quad (17)$$

Thus, the Analog Proportional Integral Differential controller equation is given by

$$= \frac{7.2324*10^{-6}*(s^2+1382.667\,s+477946.4631)}{s} \quad (18)$$

The equation is in the continuous time domain and Trapezoidal method is used to transfer it into discrete-time domain.

Let the integral value of e (t) be q (t).
Then the value of integral at t = (n+1) T = value at nT + area from nT to (n+1) T

$$Q[(n+1)T] = u(nT) + \int_{nT}^{(n+1)T} e(t)\,dt \quad (19)$$

$$Q[(n+1)T] = q(nT) + \left(\frac{T}{2}\right)\{e[(n+1)T] + e(nT)\} \quad (20)$$

By taking Z-Transform of the above equation and rearranging the above equation gives the transfer function of the discrete integrator as

$$\frac{Q(z)}{E(z)} = \frac{T}{2}\left(\frac{z+1}{z-1}\right). \quad (21)$$

q (nT) is the derivative of e(t) at t=nT,

$$q(nT) = \frac{e(nT)-e[(n-1)T]}{T} \quad (22)$$

Taking Z transform of the above equation, we get the transfer function of the discrete differentiator as

$$\frac{Q(z)}{E(z)} = \frac{z-1}{Tz}. \quad (23)$$

The Combined Transfer Function of Proportional Integral Discrete controller is expressed as

$$K_p + K_i\left(\frac{T}{2}\right)\left(\frac{Z+1}{Z-1}\right) + \mathrm{K_d}\left(\frac{\mathrm{Z}-1}{\mathrm{TZ}}\right) \quad (24)$$

On substituting all the values, transfer function is

$$\frac{(Z-0.9363)(Z-0.9363)}{Z(Z-1)} \quad (25)$$

which is of the form $\frac{(Z-a)(Z-b)}{Z(Z-1)}$.

For a system to be stable, the value of a and b must lie inside a circle of radius 1. The value of a = b = 0.9363 and this lies inside a circle of radius 1 and hence stability is achieved.

10. SIMULATION RESULTS

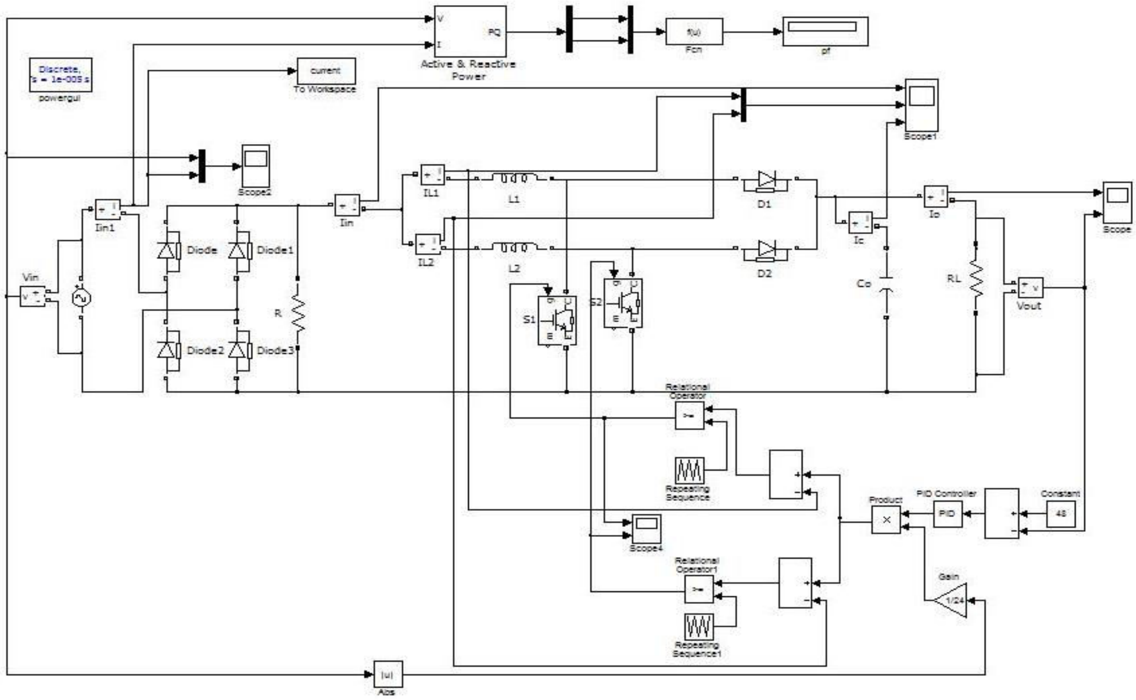


Figure-9. MATLAB/Simulink model of average current mode controlled Interleaved Boost Converter.

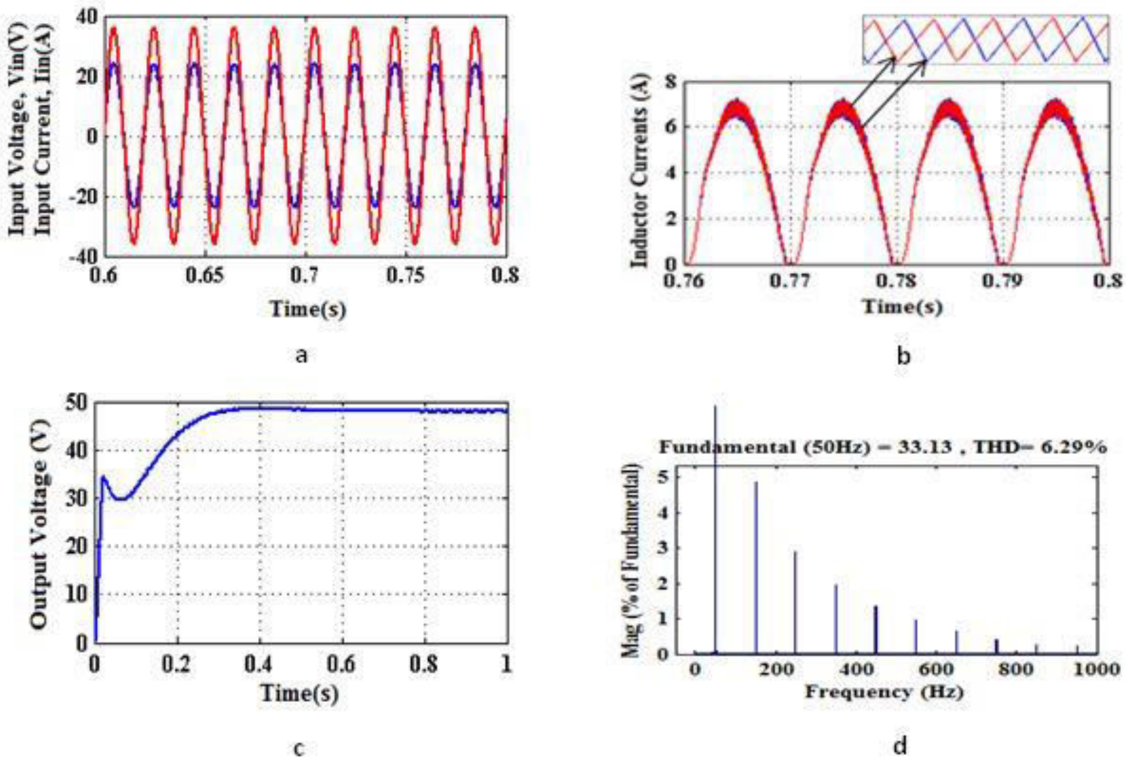


Figure-10. Simulation results of analog controlled of Interleaved Boost Converter. a. Input current and voltage in phase with each other, b. Inductor current waveforms shifted by 180^0, c. Regulated output voltage, d. Total harmonic distortion.

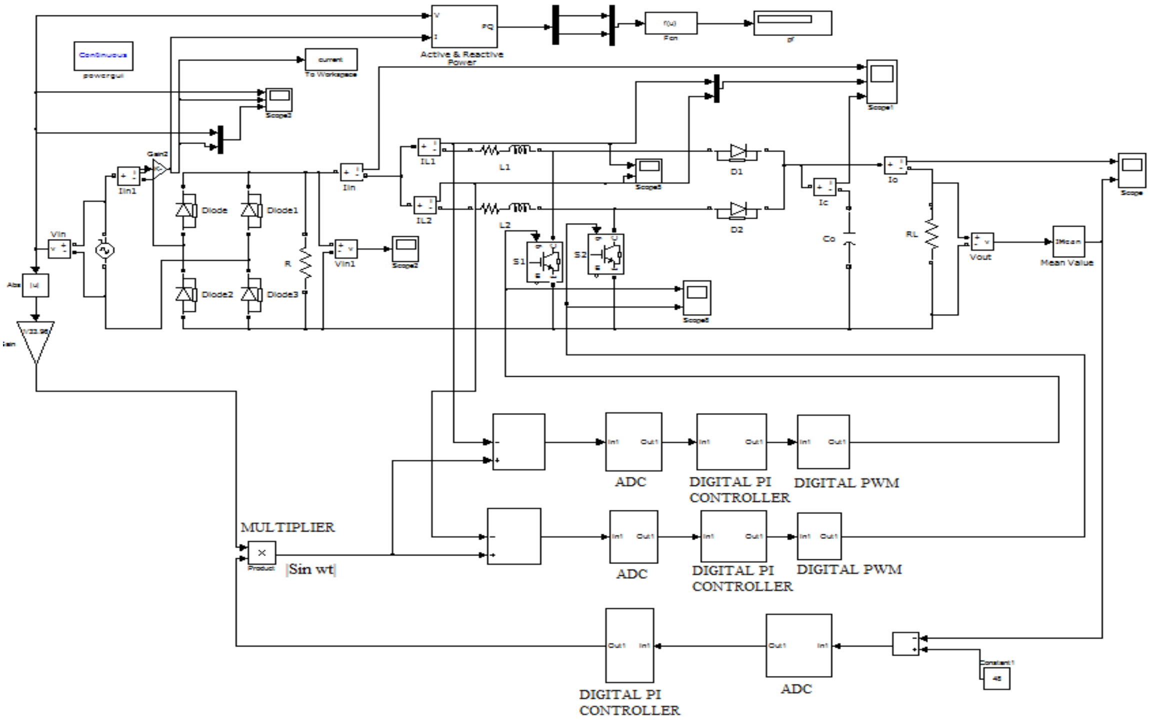


Figure-11. MATLAB/Simulink model of digitally controlled Interleaved Boost Converter.

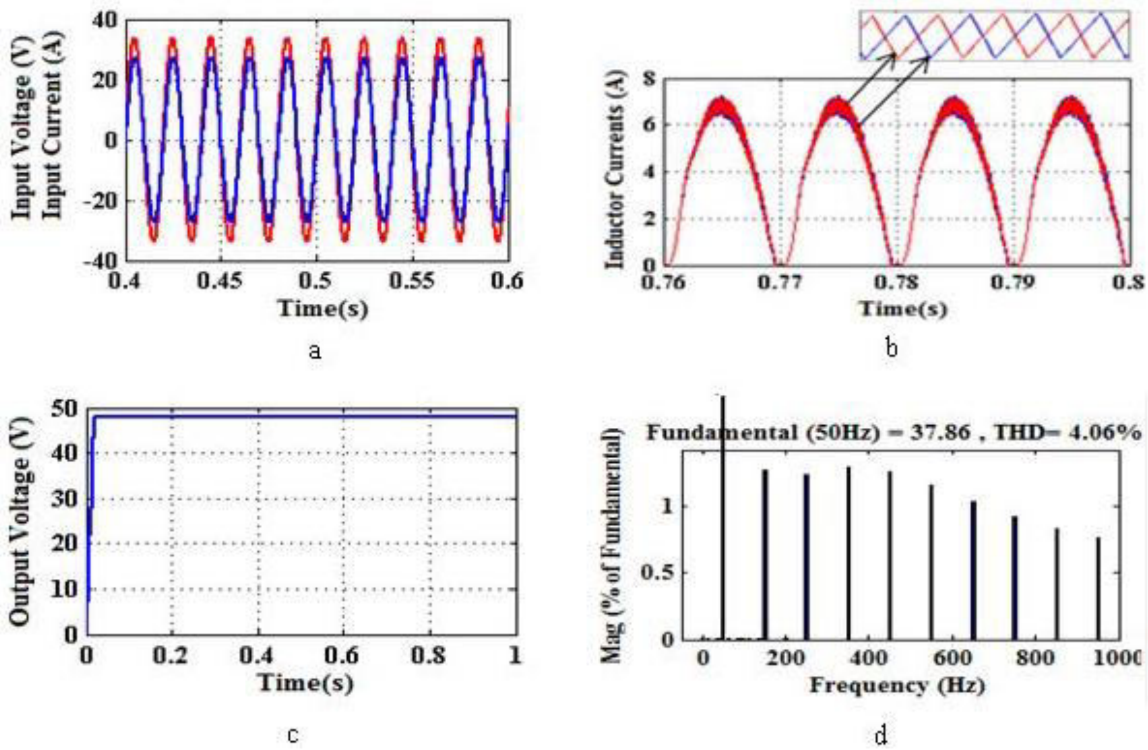
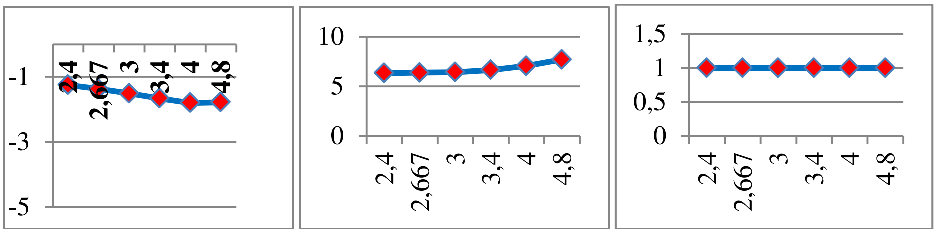
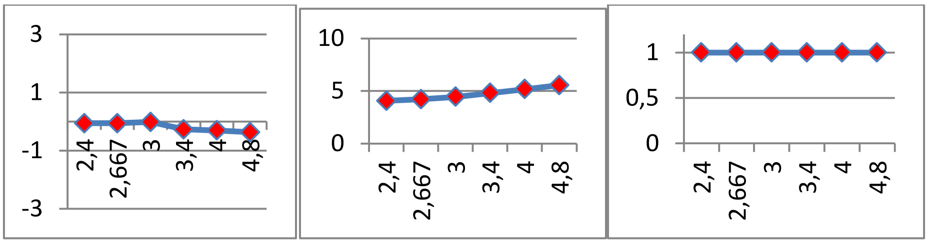


Figure-12. Simulation results of digitally controlled Interleaved Boost Converter. a. Input current and voltage in phase with each other, b. Inductor current waveforms shifted by 180^0, c. Regulated output voltage, d. Total harmonic distortion.



a b c

Figure-13. Performance analysis of analog control of Interleaved Boost Converter
a. Voltage regulation, b. Total harmonic distortion, c. Power factor.



a b c

Figure-14. Performance analysis of digital control of Interleaved Boost Converter
a. Voltage regulation, b. Total harmonic distortion, c. Power factor.

11. CONCLUSIONS

The modelling and control of two phase Interleaved Boost converter is established in this work. The analog and digital controllers are used to draw sinusoidal current in phase with the supply voltage and the outer voltage controller is used to regulate the output voltage to a constant value.

Transfer function is derived for continuous conduction mode. Bode plot is drawn for both open loop and closed loop. The desired 60° phase margin is obtained. Power factor of nearly unity is achieved. Total Harmonic Distortion is less and fast dynamic response is obtained with the help of digital controllerwhen compared to analog controller.

MATLAB/Simulink is used for implementing the circuit. The distortion power factor is nearly unity indicating that the total harmonic distortion is within the IEEE 519 limits. Output voltage is regulated to a constant value and sinusoidal input current in phase with the supply voltage is drawn.

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