ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 4, April 2016

Current Controlled Single-Phase Interleaved Boost Converter with Power Factor Correction

R.Rashmi[1], A.Lembhe[2], P.A Kharade[3], M.D Uplane[4]

Research Scholar, Department of Instrumentation Science, SPPU, Pune, India[1]

PG Student, Department of EEE, VJTI, Matunga, Mumbai, India[2]

Associate Professor, Department of E&Tc, Bharti Vidyapeeth College of Engineering, Navi Mumbai,India[3]

Professor, Department of Instrumentation Science, SPPU, Pune, India[4]

ABSTRACT: Design and implementation of boost and Interleave Boost Converter ((IBC) with Proportional and Integral (PI) average current control method for Power Factor Correction (PFC) is presented. The Power Factor (PF) is increased significantly with reduction in total harmonic distortion (THD), current ripple and voltage ripple by integrating the IB converter into the full bridge diode rectifier. The proposed PI average current control method is based on sensing of the input current which can easily be accomplished by using unidirectional current transformer. The full bridge Boost and IB converter with pulse width modulation based on multiplier circuit is analysed as it enhances the voltage gain with reduction in voltage stress of semiconductors in the boost and IBC rectifier circuit. Hence High efficiency is achieved with low voltage rated MOSFETs and diodes. Control characteristics and performance of the IB converter is analysed using state space model and verified by a measurement result from a 1500W model. Operation of the converter with variable switching frequency (25 KHz -100 KHz) and variable load (50 Ω -200Ω) is reported.

KEYWORDS: AC-DC Power Conversion, CCM Interleave boost converter, interleave boost converter ((IBC), power factor Correction (PFC), total harmonic distortion (THD), PWM

I.INTRODUCTION

Unity Power factor is widely required in various application to decrease the power loss as non- linear nature of loads and frequency of the switches creates disturbance in supply voltage. Poor power factor also produces a large spectrum of harmonic signals that may interfere with other equipments so results in poor output voltage regulation and increased current [1]. The issue of power factor is related with number of factors, like locations, loading level, under voltage etc. Unity power factor is important in circuits since power consumption depends on it as if power loss is more then extra current needs to be carried for the same amount of work [2]. So high power rated devices with extra size and cost is required. Therefore, achieving high (close to one) power factor in power conversion is important especially for the power system with high switching frequency and nonlinear loads.

To mitigate the power factor problem the device like an active power filters, active line conditioners are used because of their dynamic and flexible nature. The boost PFC circuit operating in continuous conduction mode (CCM) is generally chosen for medium and high power applications. The inductor at the input stage of a boost converter has a filtering effect on the line current. The power semiconductor switch of the boost converter is controlled with pulse width modulation in a manner such that the input current is in phase with the rectifier source voltage to achieve unity power factor operation [3]. Variation in current ripple with different types of pulse width modulation is presented in[4]. From the view of power factor improvement, an interleave boost converter (IBC) would be a promising approach. In interleave boost two converter circuits are connected in parallel and the switches in the respective sub circuits operates with a phase difference of 180 degree. Phase difference causes the reduction of the ripple currents in input and output of the converter [5]. Output current is split into two parts to reduce I^2R loss and Inductor loss with higher efficiency.The Interleave boost converter can operate in either continuous conduction mode (CCM) or discontinuous

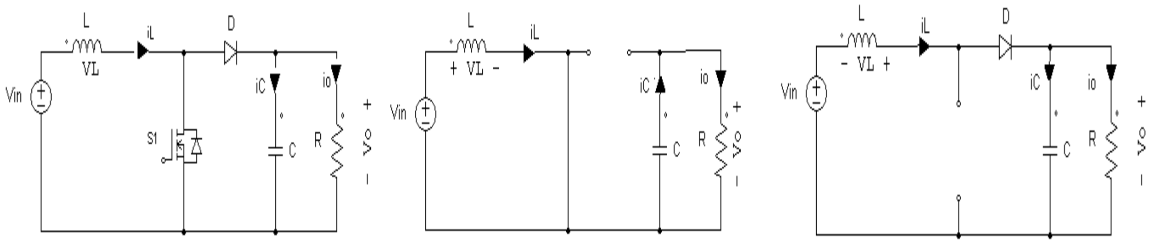
DOI:10.15662/IJAREEIE.2016.0504055

conduction mode (DCM) or both. The work here presented focuses in CCM operation in order to avoid high stresses in components and an additional filter stage.

The major contribution of this paper is to design and implementation of IBC with proportional and integral (PI) average current control method for power factor correction (PFC).This paper is organized as follows. In section II, Operational principal of IB is presented. In section III control design of the IB with PI average current control is proposed. Experimental results are provided in section IV. Finally, conclusion is given in section V.

II. OPERATIONAL PRINCIPALE OF IBC

The operational circuit of Boost converter is shown in Fig.1 (a) Vin is source voltage, VL is the voltage across the inductor. Current iL, iC and io are flowing through the inductor, capacitor and resister respectively. D is a constant and Ts is time period. During the period DTs of a switching period S1 is ON and the inductor current iL flows from the input source to energize the inductor as shown in Fig.1(b) . During the period (1-D) Ts of a switching period S1 is OFF and the inductor current iL cannot change instantly as shown in Fig 1(c).The inductor current iL starts to decrease. This negative di/dt of the inductor current develops sufficient voltage (Ldi/dt) with a polarity such as to drive the inductor current through diode to charge the output capacitor [6].



(a) (b) (c)

Fig. 1. Circuit configuration of a boost converter: a)With operational switch b) ON-state, c) OFF-state**.**

A basic boost PFC rectifier converts a DC voltage to a higher DC voltage.The Interleave boost PFC rectifier does the same but it is consist of two single Boost converters connected in parallel so adds additional benefits with two output stages driven 180 degrees out of phase [7]. Conduction losses can be reduced by splitting the current into two power paths, which will result in gain of overall efficiency as compare to boost converter. Because the two phases are combined at the output capacitor, effective ripple frequency is doubled, making ripple voltage reduction much easier.

The operational circuit of IB converter is shown in Fig.2 (a). Vin is source voltage, VL1 and VL2 are the voltage across the inductor1 and inductor2 respectively. Current iL1, iL2, iC and io are flowing through the inductor1, inductor2, capacitor and load respectively. Four modes of the interleaved boost topology are shown in Fig.2. When S1 and S2 turns on in mode 1, current ramps up in L1and L2 with a slope depending on the input voltage, storing energy in L1and L2 as shown in Fig.2(b),. The sum of voltage VL1 and VL2 during this time is Vin. The inductor current rises linearly with the slope of Vi/2L.During this time the current through S1 and S2 is same as iL1 and iL2 respectively. In mode 2, S2 turns OFF, D2 turns on as input voltage becomes greater than the output voltage to deliver part of its stored energy to the load and the output capacitor as shown in Fig.2(c).Current in L2 ramps down with a slope dependent on the difference between the input and output voltage. Mode 3 is same as Mode 2 here S1 turns off and D1 turns on as shown in Fig.2 (d),. Current in L1 ramps down with a slope dependent on the difference between the input and output voltage in mode 4 as shown in Fig.2 (e), S1 and S2are off both L1 and L2 deliver their part of energy to the load and the output capacitor as a result current in L1 and L2 ramps down. Control of interleave boost converter for PFC operation using PI average current control method requires sensing of both the input voltage and current . A low-frequency transformer or an optical coupler can be used to sense the input voltage [8]. An input current can be sensed by using unidirectional current transformer. In average current control method there is inherent over current protection for the entire converter because the switch is turned off when the switch current reaches the reference current limit [9]. Here several similar converters may be connected in parallel to share the load as shown in interleave boost converter. Each converter will deliver only the portion of the power that it is programmed for by its reference current limit. The inductor saturation is also eliminated by the reference current limit.

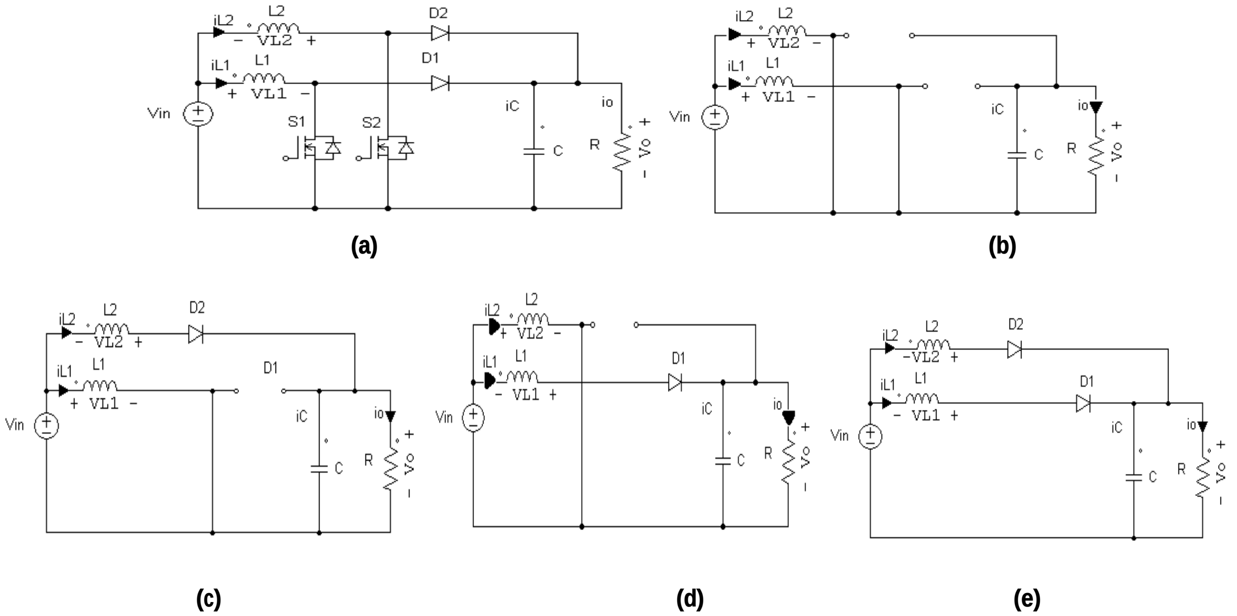


Fig. 2: Circuit configuration of a interleave boost converter a)With operational switch, b)S1andS2 on, c)S1 on and S2 off ,d)S1 off and S2 on ,e)S1 and S2 off

The state variables are assumed as inductor currents *iL1* and *iL2* and the capacitor voltage *Vo*. This converter comprises of four modes of operation.

1）*Mode1*：Switches S1 and S2 are on, diode D1 and D2 are off. At this stage, the state differential equations of the circuit are given by:

$$\frac{di_{L1}}{dt} = \frac{V_{in}}{L_1}$$

$$\frac{di_{L2}}{dt} = \frac{V_{in}}{L_2}$$

$$\frac{dV_o}{dt} = \frac{-V_o}{RC}$$

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \frac{dV_o}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \end{bmatrix} V_{in} \tag{1}$$

2）*Mode2*：Switches S1 diode D2 are on, and S2 and D1 are off.

$$\frac{di_{L1}}{dt} = \frac{V_{in}}{L_1}$$

$$\frac{di_{L2}}{dt} = \frac{V_{in}}{L_2} - \frac{V_o}{L_2}$$

$$\frac{dV_o}{dt} = \frac{i_{L2}}{C} - \frac{V_R}{RC}$$

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \frac{dV_o}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{L_2} \\ 0 & \frac{1}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \end{bmatrix} V_{in} \tag{2}$$

3）*Mode3*：Switch S2 and diode D1 are on, and Switch S1 and diode D2 are off.

$$\frac{di_{L1}}{dt} = \frac{V_{in}}{L_1} - \frac{V_o}{L_1}$$

$$\frac{di_{L2}}{dt} = \frac{V_{in}}{L_2}$$

$$\frac{dV_o}{dt} = \frac{i_{L1}}{C} - \frac{V_R}{RC}$$

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \frac{dV_o}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{-1}{L_1} \\ 0 & 0 & 0 \\ \frac{1}{C} & 0 & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \end{bmatrix} V_S \qquad (3)$$

4）*Mode4*：Switches S1 and S2 are off, diode D1and D2 are on.

$$\frac{di_{L1}}{dt} = \frac{V_{in}}{L_1} - \frac{V_o}{L_1}$$

$$\frac{di_{L2}}{dt} = \frac{V_{in}}{L_2} - \frac{V_o}{L_2}$$

$$\frac{dV_o}{dt} = \frac{i_{L1}}{C} + \frac{i_{L2}}{C} - \frac{V_R}{RC}$$

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \frac{dV_o}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{-1}{L_1} \\ 0 & 0 & \frac{-1}{L_2} \\ \frac{1}{C} & \frac{1}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \end{bmatrix} V_{in} \qquad (4)$$

III. CONTROLLER DESIGN

IB converter is decomposed into two boost converters and one converter is controlled in each half cycle [10]. During positive half cycle one boost converter formed of S1 and D1 and line inductor is controlled to shape the input current. Similarly during negative half cycle second boost converter formed of S2 and D2 and line inductor is controlled to shape the input current. An average current mode PWM controller with single loop is used in order to obtain the control objectives. The two outputs of the controller operate 180° out of phase and have separate current limit inputs for each channel. Here inductor current is directly controlled, whereas the output voltage is controlled indirectly by the current loop. A control reference is used to regulate the average current of the converter with average PI current-mode control as shown in Fig.3. The current loop achieves low distortion in the input current and unity power factor. For this, the current controller shapes the inductor current with a reference waveform. Thus, it is possible to keep the input current in phase with input voltage. The controller operates in the CCM mode since during each switching period only part of energy stored in the inductor is delivered to the load. The input current of the boost converter is feedback and compared with the reference that has a rectified sinusoidal wave shape such that it is in phase with the boost input voltage. The error is passed to PI control whose output is compared with a triangular signal to generate the PWM signal.

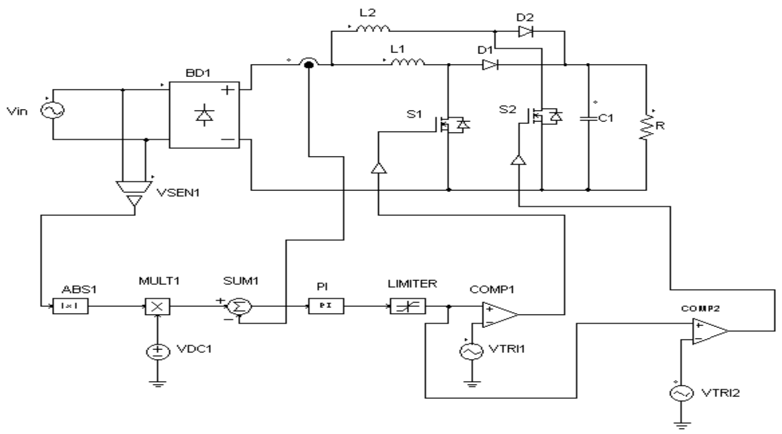
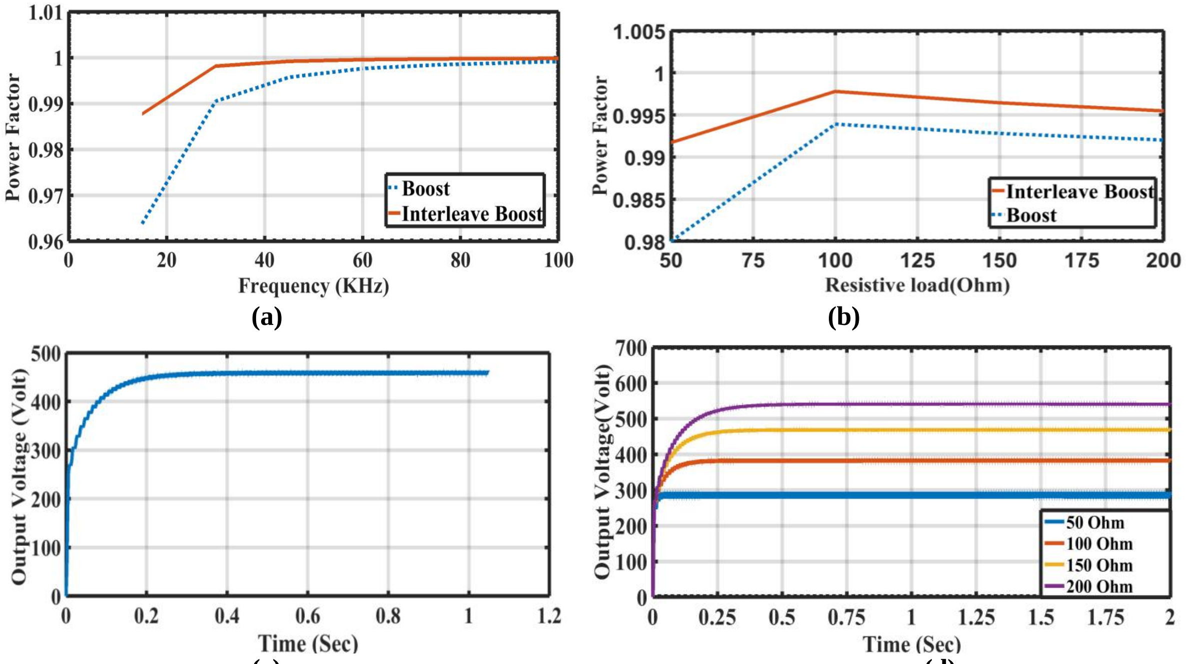


Fig. 3. Control scheme of the boost PFC with current control

The generated PWM is passed to turn on and off the boost converter switch. The PI controller ensures that the error at its input is zero, which implies that input current tracks reference current.

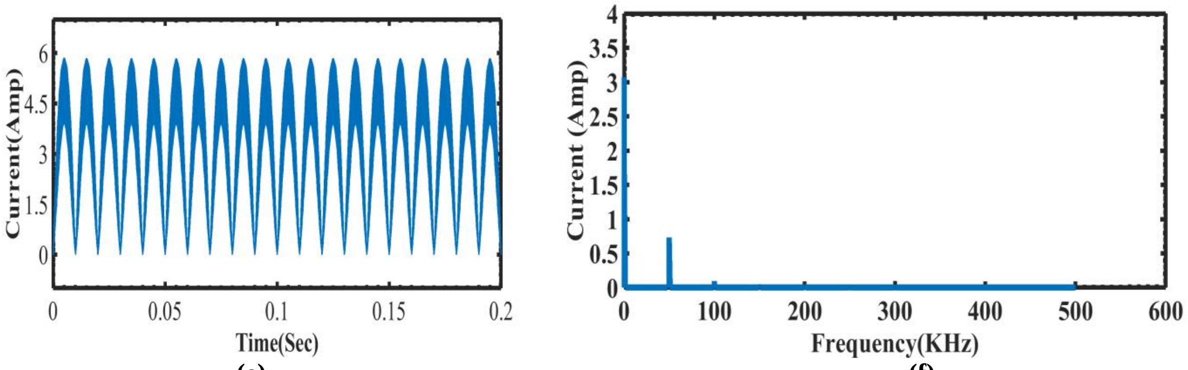
IV. EXPERIMENTAL VERIFICATION

A 1500-W model is built in PSim to asses Boost control and IB control with PI current control method. The Input rms voltage is 220 V and the output voltage is 457V. The Power Factor (PF), Total harmonic Distortion (THD), Current and voltage ripple waveform under variable load and variable switching frequency in Boost and IB converter is shown in fig.4. Here AC input voltage is rectified by a diode bridge rectifier and then the rectified voltage is boosted using Interleave boost converter. It clearly shows that only input voltage and inductor current is sensed for the closed loop. Interleave converter is operated at 50kH frequency and pulse width is adjusted with the reference current value of 6.3A.



(a) (b)

(c) (d)



(e) (f)

Figure 4. Simulation results: a) Variation of Power factor with switching frequency in boost and interleave boost; b) Power factor versus load of boost and interleave boost; c)Variation of output voltage with time in interleave boost converter; d) Plot of output voltage versus time at different loads in interleave boost converter; e) Steady state current waveform of Interleave boost converter ; f) Fast Fourier transform of ripple current in interleave boost converter.

The turn off time is determined by the time at which the average inductor current reaches a reference current limit. This involves an inner fast current control loop. The curve of Power factor versus frequency is shown in fig.4(a). Each switch operates at 50 kHz and total switching frequency is 100 kHz for Interleave Boost converter. It is observed that power factor increases with the switching frequency. The close observation shows that boost converter power factor is 0.9976 at 100 kHz. The interleave boost converter exhibits 0.9995 power factor at same switching frequency. Similar kind of results is also achieved in [4] with cascade control loop. The variation of Power factor of Boost and Interleave Boost converter is shown in fig.4(b). At maximum load of 100Ω power factor for boost converter is 0.9977 and for interleave boost converter it is 0.9992. Fig 4(c) shows the waveform for Boost converter's output voltage. *Vout* is maintained to a constant value of 457V and output voltage ripple is up to 2%.Variation of ripple under load 50kΩ,100kΩ,150kΩ,200kΩ load is shown in Fig 4(d).Input current ripple of IB converter with FFT transform is shown in Fig.4(e),(f). Fundamental component is of 3.072A with current ripple of 0.731 A.

V. CONCLUSION

The average PI current controlled closed loop for boost and interleave boost converter is described, analyzed and compared. The fundamental issues Power factor correction, Output voltage regulation, Total Harmonic Distortion, Output voltage ripple and inductor current ripple is discussed. Frequency spectrum of the input current is shown. The comparative study of two topologies show the superior performance of the interleave boost converter. The result allows continuing future works in IB with a current loop or a cascade control using an adaptive control approach.

VI. ACKNOWLEDGMENT

This work has been supported by DST-PURSE, Savitribai Phule Pune University. One of the authors R.Rashmi is thankful to University Grant commission for JRF.

REFERENCES

[1] R.C Dugan, M.F Mcgranaghan, S Santoso, H.W Beaty, Electrical power system quality 2nd edition McGraw Hill New York 2002.
[2] M.H.J Bollen, "Understanding power quality problems "voltage sags an Interruptions". IEEE Press New York 2000.
[3] M. Rashid. "Power Electronics Handbook", 2nded,Prentice- Hall,2001, pp.167-185.
[4] M.Arun Devil, K.Valarmathi, R.Mahendran;" Ripple Current Reduction in Interleaved Boost converter by Using Advanced PWM Techniques",IEEE International Conference on Advanced Communication Control and Computing Technologies (lCACCCT), 2014.
[5] Burak Akın "Comparison of Conventional and Interleaved PFC Boost Converters for Fast and Efficient Charge of Li-ion Batteries Used in Electrical Cars". 2012 International Conference on Power and Energy Systems *Lecture Notes in Information Technology, Vol.13*
[6] L.Umanand. "Power Electronics Essentials and application."Wiley India Pvt. Ltd.,2013, pp.201-213.

[7] Vaddi Ramesh, U. Haribabu, "Simulate the implementation of interleaved boost converter with zero voltage transition," International Journal of Engg Research and Applications, vol.2, no.6, pp.1129-1135, Nov-Dec.2012.
[8] B. Lu, R. Brown, and M. Soldano, "Bridgeless PFC implementation using one-cycle control technique," in Proc. IEEE Appl. Power Electron. Conf., 2005, pp. 812–817.
[9] Sun, J.; Bass, R.M.; , "Modeling and practical design issues for average current control," in proc. IEEE APEC 1999, vol.2, pp.980-986 , 14-18 Mar 1999
[10] Hegazy, O.; Van Mierlo, J.; Lataire, P.; ,"Analysis, Modeling, and Implementation of a Multidevice Interleaved DC/DC Converter for Fuel Cell Hybrid Electric Vehicles," IEEE Trans. Power Electron. , vol.27, no.11, pp.4445-4458, Nov. 2012.