



## Two Phase Interleaved Boost Converter: Design, Modeling, Analysis and Control with GUI Applications

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**Abstract-** The two level interleaved boost converter (IBC) is for low input voltage (battery or photovoltaic or Fuel Cell) applications. The interleaved multi-channel converter is very popular these days because of its ability to reduce current ripples. In high power applications, parallel operation of boost converters is recommended. These paralleled boost converters can be operated in interleaved mode. Interleaved mode of operation improves the steady state and dynamic performance of the system. In addition, low EMI and low stress in the switches are expected.

The IBC has been designed for low input voltage applications. The IBC has been modelled and analyzed using state space averaging and small signal analysis technique. Graphic User Interface (GUI) applications have been developed to save the timing of designing, modelling and analysis of IBC. Here the theory and application of designing method of the PID controller for interleaved boost converter is discussed. GUI applications have been developed for various tuning methods of PID controller for IBC.

**Keywords-** Interleaved boost converter, photovoltaic, PID, Ziegler-Nichols tuning, GUI

### I. INTRODUCTION

Fuel cell is one of the promising renewable and sustainable power sources because of its high power density and very low emission. It can be utilized as a clean power source for various applications such as portable electronic appliances, transportation and residential building. In order to design a highly efficient fuel cell power system, a suitable DC-DC converter is required. Among the various topologies of DC-DC converters, interleaved boost converter (IBC) has been proposed as a suitable interface for fuel cells to convert low voltage high current input into a high voltage low current output [1]. The advantages of interleaved boost converter compared to the classical boost converter are low input current ripple, high efficiency, faster transient response, reduced electromagnetic emission and improved reliability [2,3]. IBC performs remarkably in terms of magnetics, input and output current ripple and part count [4]. Interleaved DC boost converter can be applied to any renewable energy systems and some related applications [5].

This paper presents the design of IBC and also modelling and analysis of IBC with GUI. This paper also presents the PID control technique with different tuning methods. GUI applications are also developed for the same. Section II presents working principle of IBC. Section III describes the design of IBC. Section IV presents modelling and analysis of two levels IBC. Section V presents closed loop control of IBC with PID controller. Section VI gives the simulation results of various tuning method and comparison. Finally section VII concludes the paper.

### II TWO PHASE INTERLEAVED BOOST CONVERTER

A two-phase interleaved boost converter is shown in Fig. 1. This converter is used to improve power conversion capability, and one of its applications is to match the photovoltaic system or low voltage supply to the load. For a step-up application, an equivalent interleaved boost converter offers several advantages over a conventional boost converter; such as a lower current ripple on the input and output stages. Therefore, there is the opportunity to minimise the output capacitor filter that is often quite large in the conventional boost converter. Furthermore, it provides a fast transient response to load changes and improves power handling capabilities [6]. A higher efficiency may be realized by splitting the input current into two paths, substantially reducing  $i^2R$  losses. The topology of the interleaved boost converter consists of two phases operating at 180 degrees phase difference.

The gating arrangement and the inductor current waveforms of the converter are shown in Fig. 2. Fig.2(a) represents waveforms when duty ratio  $d$  ( $0 < d \leq 0.5$ ). In this duty ratio any one switch will be conducting at time and also at specific period of time both inductors discharge. Fig 2(b) represents waveforms when converter is operated with duty ratio  $d$  ( $0.5 \leq d < 1$ ). In this duty ratio  $d$  for specific period of time both the switches are conducting and also current in inductors rises. With the two level IBC designs, the gating signals  $g_1$  and  $g_2$  for switch S1 and S2 are identical but shifted by  $180^\circ$ . The total input current  $I_{in}$ , which is the sum of the two inductor currents  $i_{L1}$  and  $i_{L2}$  are also shown.

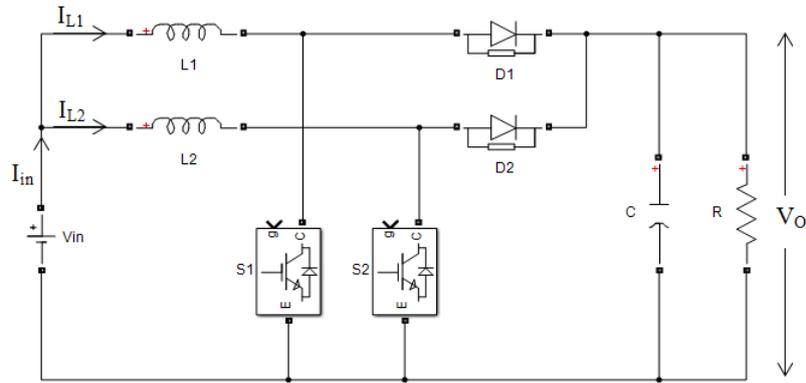


Fig. 1 Two phase interleaved boost converter

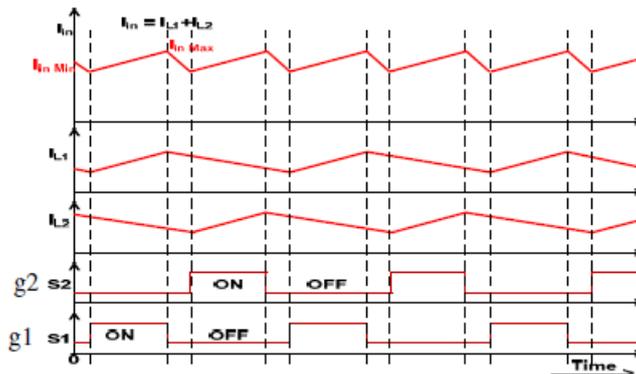


Fig.2 (a). Typical Waveforms of Inductor Currents ( $d \leq 0.5$ )

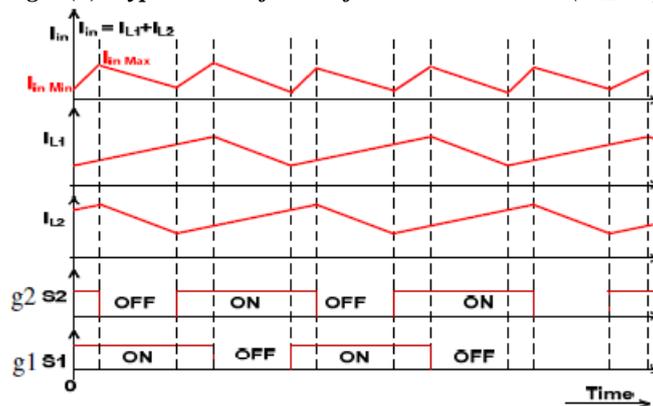


Fig.2 (a). Typical Waveforms of Inductor Currents ( $d > 0.5$ )

### III. DESIGNING OF IBC

#### 3.1. Design Equations

For designing purpose following equations are required [2,6-9]

Boost ratio:

The boost ratio of the converter is a function of the duty ratio

$$\frac{V_{dc}}{V_{in}} = \frac{1}{1-D} \quad (1)$$

Input and Output currents :

$$I_{in} = \frac{P_{in}}{V_{in}} \quad I_o = \frac{P_o}{V_o} \quad (2)$$

Inductor current ripple amplitude:

$$\Delta I_{L1L2} = \frac{V_{in}D}{f_{sw}L} \quad (3)$$

Input current ripple amplitude:

$$\Delta I_{in} = \frac{V_o(D)(1-2D)}{Lf_{sw}} \quad \text{for } 0 < d \leq 0.5 \quad (4)$$

$$\Delta I_{in} = \frac{V_o(1-D)(2D-1)}{Lf_{sw}} \quad \text{for } 0.5 \leq d < 1 \quad (5)$$

Inductor L:

$$L = \frac{V_s D}{f_{sw} \Delta I_L} \quad (6)$$

Resistor R:

$$R = \frac{V_o}{I_o} \quad (7)$$

Capacitor C:

$$C = \frac{D}{Rf_{sw}\Delta V_o} \quad (8)$$

**Table 1. Design requirements of IBC**

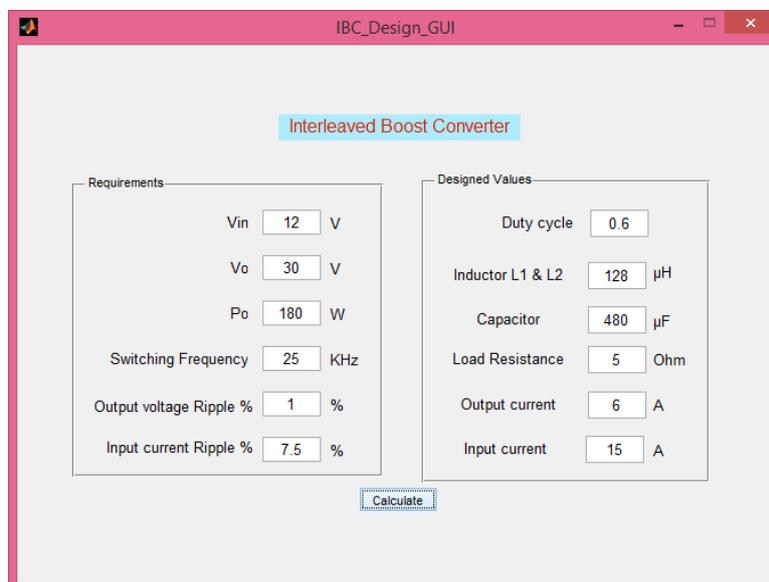
Output Voltage	<b>30 V</b>
Input Voltage	<b>12 V</b>
Output Voltage ripple	<b>1%</b>
Input Current ripple	<b>5%</b>
Output power	<b>180 Watts</b>
switching frequency	<b>25 kHz.</b>

**Table 2. Designed values of IBC as per requirements**

Duty ratio (d)	<b>0.6</b>
Output Current	<b>6 A</b>
Inductor L1 and L2	<b>128 μ H</b>
R	<b>5 Ω</b>
C	<b>480 μ F</b>

### 3.2. GUI Application for Design and analysis of IBC

Fig 4 is the GUI application for designing the IBC. Fig 5 is for the design and analysis purpose of IBC.



**Fig. 4 GUI for designing IBC**

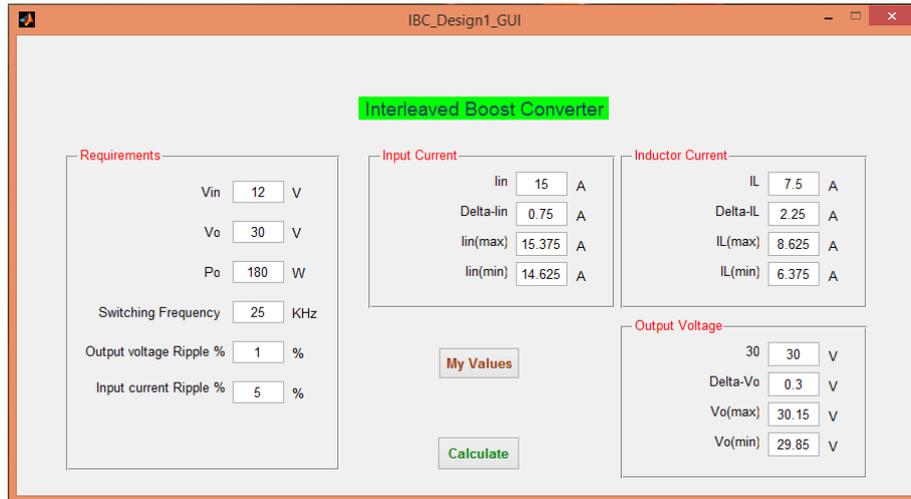


Fig. 5 GUI for analysis of IBC

#### IV. MODELLING OF IBC

Modelling of IBC is done using state space averaging and small signal modelling technique by considering duty ratio  $D > 0.5$ . State variables are  $[I_{L1} \ I_{L2} \ V_C]^T$ .

Here all parasitic values of components are considered

r1-Inductor internal resistance=0.02Ω

rs-Switch resistance when ON =0.001Ω

rd-Diode resistance when ON=0.001Ω

rc-Capacitor resistance =0.014Ω

##### Mode-1

Switch S1 is closed and S2 is open

$$A1 = \begin{bmatrix} -\frac{(r1 + rs1)}{L1} & 0 & 0 \\ 0 & -\frac{(r12 + rd2) + \frac{R \times rc}{R + rc}}{L2} & \frac{-R}{(R + rc) \times L2} \\ 0 & \frac{R}{(R + rc) \times C} & \frac{-1}{(R + rc) \times C} \end{bmatrix} \quad B1 = \begin{bmatrix} \frac{1}{L1} \\ \frac{1}{L2} \\ 0 \end{bmatrix} \quad C1 = \begin{bmatrix} 0 & \frac{R \times rc}{R + rc} & \frac{R}{R + rc} \end{bmatrix}$$

##### Mode-2

Switch S1 and S2 is closed

$$A2 = \begin{bmatrix} -\frac{(r1 + rs1)}{L1} & 0 & 0 \\ 0 & -\frac{(r12 + rs2)}{L2} & 0 \\ 0 & 0 & \frac{-1}{(R + rc) \times C} \end{bmatrix} \quad B2 = \begin{bmatrix} \frac{1}{L1} \\ \frac{1}{L2} \\ 0 \end{bmatrix} \quad C2 = \begin{bmatrix} 0 & 0 & \frac{R}{R + rc} \end{bmatrix}$$

##### Mode-3

Switch S1 is open and S2 is closed

$$A3 = \begin{bmatrix} \frac{Rrc + (R+rc)(r1+rd1)}{L1(R+rc)} & 0 & \frac{R}{L1 \times (R+rc)} \\ 0 & \frac{-(r12+rs2)}{L2} & 0 \\ \frac{R}{(R+rc) \times C} & 0 & \frac{-1}{(R+rc) \times C} \end{bmatrix} \quad B3 = \begin{bmatrix} \frac{1}{L1} \\ \frac{1}{L2} \\ 0 \end{bmatrix} \quad C3 = \begin{bmatrix} \frac{R \times rc}{R+rc} & 0 & \frac{R}{R+rc} \end{bmatrix}$$

**Mode-4**

Switch S1 and S2 is closed

$$A4 = \begin{bmatrix} \frac{(r1+rs1)}{L1} & 0 & 0 \\ 0 & \frac{-(r12+rs2)}{L2} & 0 \\ 0 & 0 & \frac{-1}{(R+rc) \times C} \end{bmatrix} \quad B4 = \begin{bmatrix} \frac{1}{L1} \\ \frac{1}{L2} \\ 0 \end{bmatrix} \quad C4 = \begin{bmatrix} 0 & 0 & \frac{R}{R+rc} \end{bmatrix}$$

Averaged state space model over one particular cycle can be written as

$$\begin{aligned} \dot{x} &= Ax + BV_s \\ V_o &= Cx + DV_s \end{aligned} \quad (9)$$

$$\begin{aligned} A &= (A1+A3)(1-D) + (2D-1)A2 \\ B &= (B1+B3)(1-D) + (2D-1)B2 \\ C &= (C1+C3)(1-D) + (2D-1)C2 \end{aligned} \quad (10)$$

Finally, the transfer function of system is

$$G(S) = \frac{4134s^2 + 5.314 \times 10^9 s + 5.192 \times 10^{13}}{s^3 + 2.393 \times 10^4 s^2 + 2.283 \times 10^9 s + 2.111 \times 10^{13}} \quad (11)$$

Transfer function given in equation 11 is state space averaged model. For controlling purpose we require the transfer function which is the ratio of change in output voltage with respect to change in duty cycle. This can be obtained by small signal analysis. The following GUI application of Fig.6 has been created for the small signal modelling and analysis of IBC.

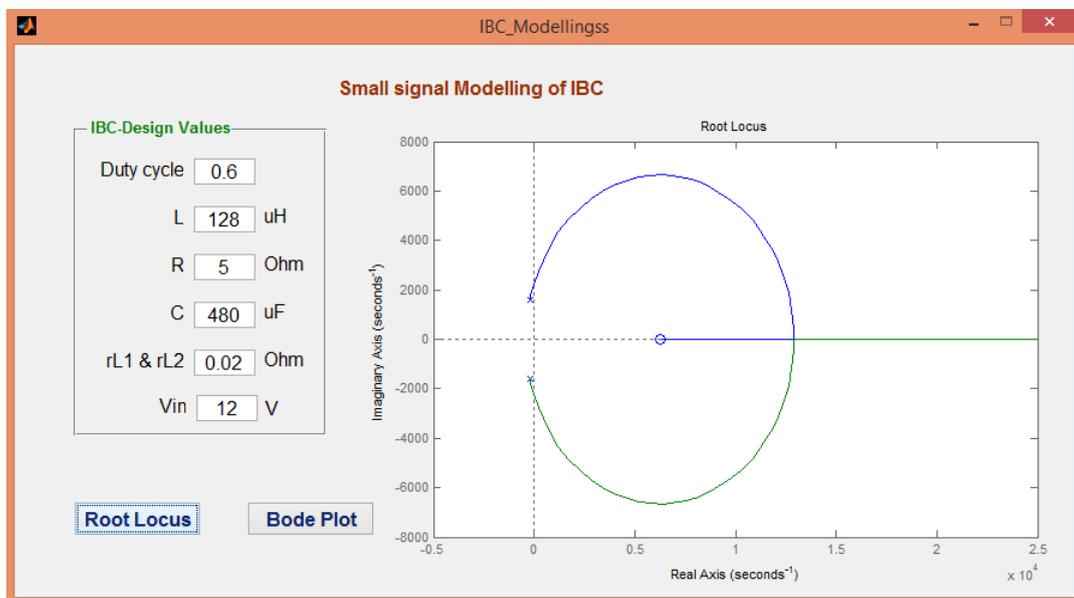
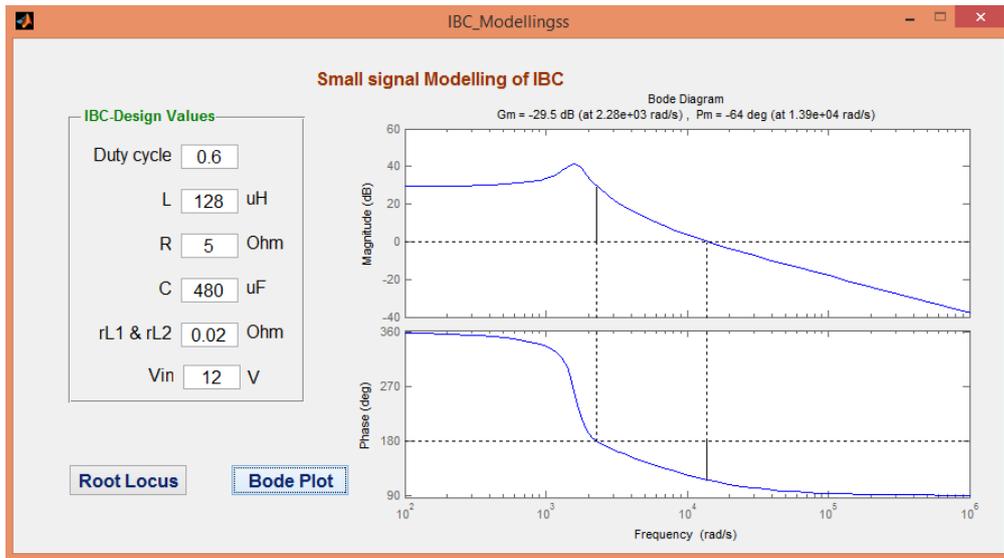


Fig. 6 (a) GUI for modelling and analysis of IBC (root locus)

Fig 6 (a) shows the root locus of the small signal transfer function. Root locus shows that the system is stable for the limited range of the gain. If the gain  $K$  increases then the system becomes oscillatory and unstable. Fig 6 (b) is the bode plot where the phase and gain margins are also mentioned. Here using close loop control we have to improve the phase margin and gain margin of the overall system.



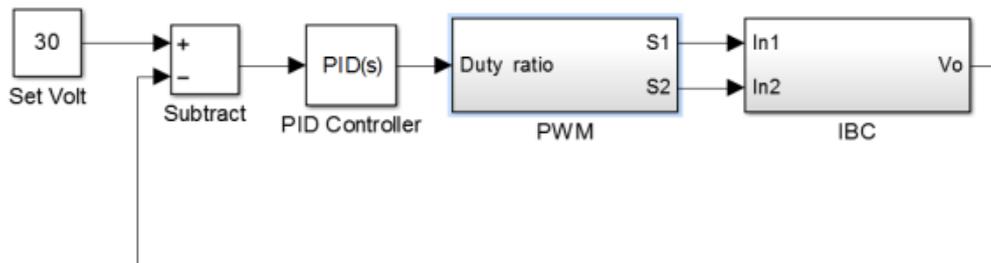
**Fig. 6 (b) GUI for modelling and analysis of IBC (bode plot)**

## V. CLOSE LOOP CONTROL

### 5.1. Controller design

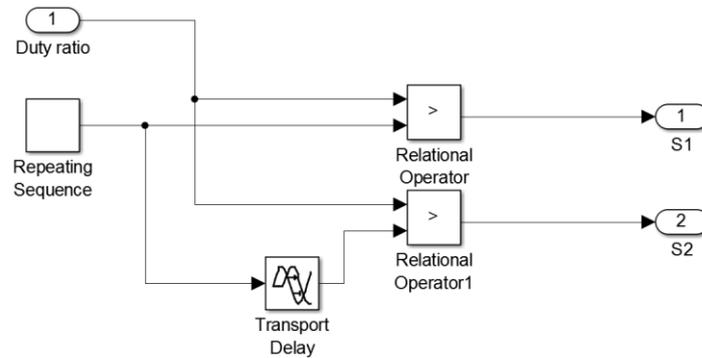
To get the accurate output with the required dynamic performance IBC is used in closed loop control using the PID controller as shown in Fig 7. Here the output of IBC is compared with required voltage (set point) and the error signal is generated. The generated error signal is applied to PID controller.

The values of  $K_p$ ,  $K_i$  and  $K_d$  is obtained from the various tuning method. The output from the PID controller is fed into the PWM block, where the pulses are generated with variable duty cycle. These generated pulses are used to control the ON/OFF of the two switches. These variable duty cycle pulses control the output voltage of the IBC.



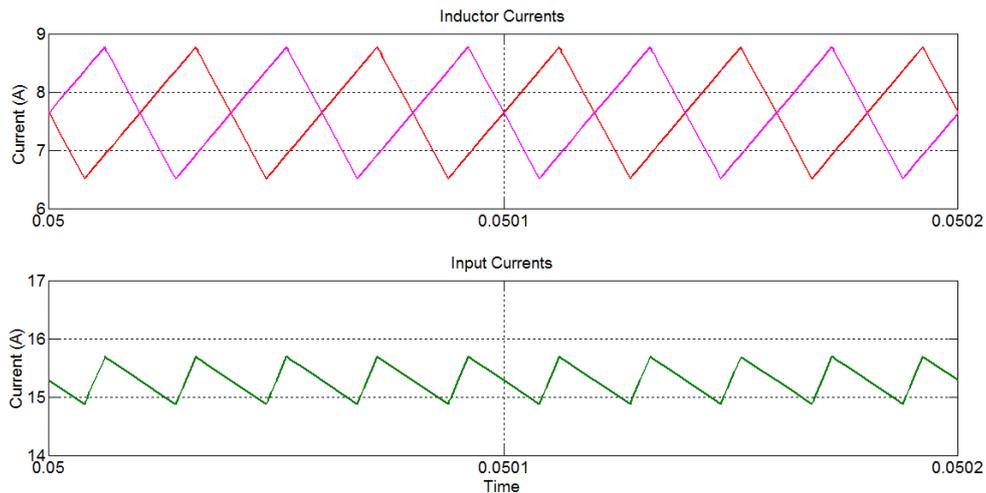
**Fig. 7 Two stage IBC in closed loop PID control (block diagram)**

The block diagram created in SIMULINK for generation of PWM is shown in Fig. 8. Here input is duty ratio and accordingly two PWM signals are generated for controlling two switches. S2 signal is  $180^\circ$  lagging with S1.



**Fig. 8 Pulse Width Modulation signal generation**  
**5.2. Steady state current waveform**

Fig. 10 explicates key waveforms of a 2-phase IBC converter operating in the CCM. Here the inductor currents  $i_{L1}$  and  $i_{L2}$  are shown in upper waveform for the duty cycle  $D = 0.6$ . While the effective input current  $I_{in}$  is shown in lower waveform. It is clear from the waveform that the ripple current is reduced much by using the interleaved two inductors.



**Fig. 10 Inductor currents of IBC (D=0.6)**

## VI. PID TUNING METHODS

Tuning of the PID controller is the vast topic. There are various techniques for the tuning of PID according to the system type and order. Following GUI has been created for the tuning of PID.

### 6.1. Ziegler Nichols Instability method.

Put the system in a feedback loop with a proportional controller, whose gain is increased until the closed loop system becomes unstable. At the verge of instability, note down the gain of the controller ( $K_u$ ) and the period of oscillation ( $P_u$ ). Then the PID settings are as given in Table 3. This is known as the instability method of Ziegler–Nichols [10].

**Table 3 Ziegler–Nichols settings using instability method**

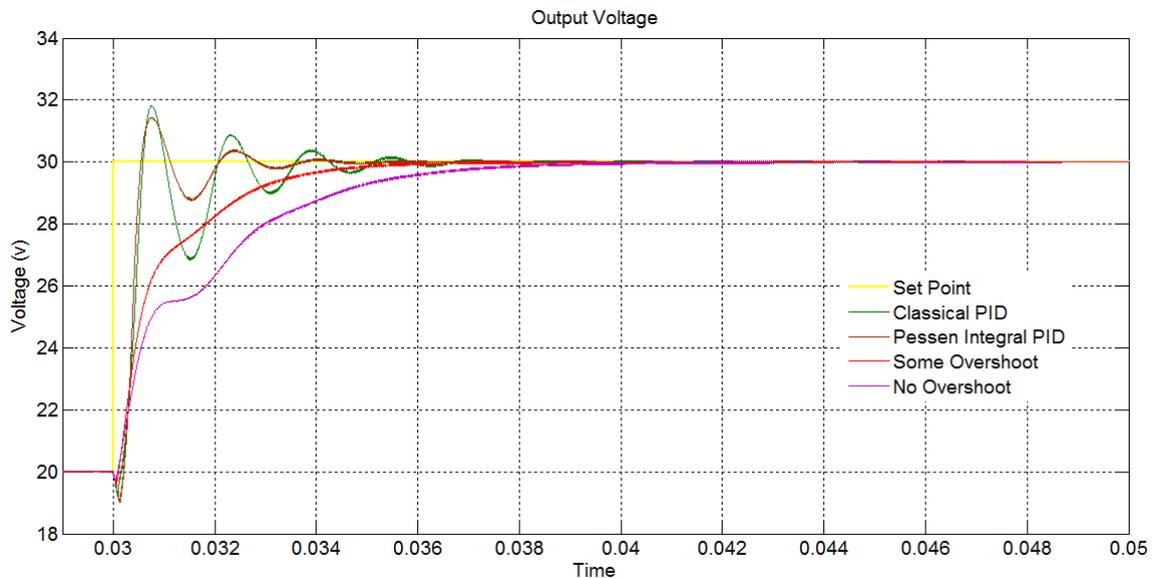
Controller	$K_p$	$K_i$	$K_d$
P	$K_u/2$	-	-
PI	$K_u/2.2$	$1.2K_p/T_u$	-
Classical PID	$0.6K_u$	$2K_p/T_u$	$K_pT_u/8$
Pessen Integral rule	$0.7K_u$	$2.5K_p/T_u$	$0.15K_pT_u$
Modified PID	$0.2K_u$	$2K_p/T_u$	$K_pT_u/3$

Obtained ultimate gain is  $K_u=0.045$ , and the sustained oscillation in output with ultimate period  $P_u=1.7$  ms. Fig 11 is the GUI application developed to get the value of various gain of PID controller. Here we have to provide values of

Ku and Pu and then have to select controller type. We can get the gains and then can be exported directly to the circuit of IBC for getting the closed loop response.



**Fig. 11 GUI application for ZN instability method**

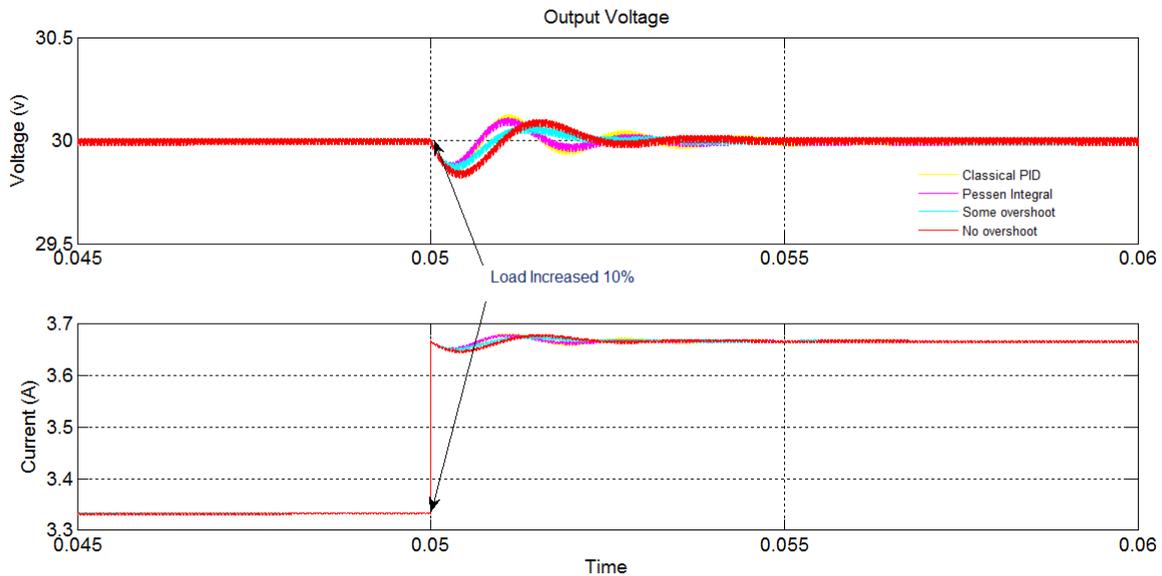


**Fig. 12 Step responses: Ziegler Nichols tuning methods**

**Table 4 Analysis form Ziegler Nichols tuning method**

Controller	Peak Overshoot	Rise time	Settling time	ITAE
<b>Classical PID</b>	6.00%	0.58 ms	3.38 ms	3.15E-04
<b>Pessen Integral</b>	4.73%	0.54 ms	1.89 ms	2.31E-04
<b>Some Overshoot</b>	0.07%	1.07 ms	3.35 ms	3.90E-04
<b>No Overshoot</b>	0.00%	2.33 ms	5.19 ms	6.20E-04

Figure 12 shows output voltage step response with four different tuning method of Ziegler-Nichols tuning method. Here the classical PID and Pessen Integral rule tuning methods are more aggressive. They give fast transient response but also with some overshoot as mentioned in table 4. Other two modified methods are also applied for tuning and result also shown in same figure. These two methods do not give overshoot with reasonable rise time and settling time. So whenever the overshoot is not desirable in system then these two modified methods should be used. To show performance indices of controllers ITAE parameter for each tuning method is also shown in table 4.



**Fig. 13 Output voltage and current of IBC when load increased by 10%.**

Figure 13 shows result when load changed from 100 W to 110 W. It is observed that output voltage decreases slightly as load is increased and then stabilizes to desired value. So all four methods assured the stability of control system against load and line regulation.

## VII. CONCLUSION

The two phase interleaved boost converter is designed, modelled and analysed using state space averaging and small signal analysis method which gave accurate modelling of IBC. IBC gives less ripple input current compared to simple boost converter, also due to parallel operation of two inductors give less power loss and more power capability. Ziegler-Nichols tuning methods with some modified methods give good result in step response and also in load and line regulation. Inverse process model also gives good result. GUI applications developed in MATLAB are good for design, modelling, analysis and tuning of IBC.

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