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Design, Modelling, Analysis and Implementation of Two Phase Interleaved Buck DC-DC Converter

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Abstract:-In recent year Multiphase converter topologies are getting more interest for use in high performance and low voltage applications. In This paperthe two-phase interleaved buck DC-DC converter (IBC) is designed for desired parameters and further by using state space averaging technique small signals models are derived, steady state performance is investigated in MATLAB-Simulink , closed loop control is achieved by designing PID controller to achieve the proper regulator for the converters.. The hardware implementation of two-phase IBC is performed using ARDUINO UNO as micro controller.

Keywords:-Two-phase interleaved buck DC-DC converter (two phase IBC), conventional buck DC-DC converter (CBC), continuous conduction mode(CCM),ARDUINO micro controller ,sisotool.

I. INTRODUCTION

DC -DC converters which converts the fixed voltage DC source to the variable DC output . A DC-DC converter can be considered as the DC equivalent to an AC transformer with a continuously variable turns ratio. Like a transformer, it can be used to step down or step up DC voltage source[1]. By storing the input energy temporarily and then releasing that energy to the output at a different voltage, the electronic switch-mode DC to DC converters is able to convert one DC voltage level to another, than linear voltage regulation, which dissipates unwanted power as heat. This conversion method is more power efficient, often 80% to 90%. The storage ways may be in either magnetic components like inductors, transformers or capacitors .This is beneficial to increasing the running time of battery operated devices. The demerits of switching converters include cost, intricacy and electronic noise (EMI / RFI)[2].

Presently the new electrical apparatus working on low voltage and high current or high voltage low currents needs Power converters that can supply regulated voltages from a constant power source. The desired output parameters from the apparatus can't obtained with the present converters and hence it is necessary to find new converter topologies. Such that apparatus should be able to give a desired output like constant output voltage even during varying loads and varying sources and providing better switching pulses for switches, for implementation of different control techniques we need to go for close loop control.TwoLevel Interleaved DC-DC Buck converter isintroduced to meet the increased demands such as low current ripple, high efficiency, faster dynamics, light weight and higher power density.Interleaving also called multi-phasing, is a technique that is useful for reducing the size of filter components [3]. In this paper the Two phase Interleaved buck Converter was modeled considering all the parasitic elements of the converter using state space averaging technique [4, 5] and analyzed using small signal analysis. The model is simulated in MATLAB/ Simulation for closed loop with analog PID controller. This paper presents the design of two phase IBC and also modelling and analysis of same. Section II, III presents working principle of two phase IBC with duty cycle D($0<D<0.5$) ($0.5<D<1$). Section IV, describes the steady state characteristics and design of two phase IBC converter. Section V presents modeling and analysis two phaseIBC. Section VI gives the simulation results.Section VII gives the Experimental resultsFinally section VIIIconcludes the paper.

II. CONVENTIONAL BUCK DC-DC CONVERTER (CBC)

Theconventional buck DC-DC converter consist of supply voltage V_S, inductor L1, Freewheeling diode D1,controlled power switch S1, filter capacitor C_O , and load resistance R_O. here we are considering that conventional buck converter is operating in CCM, This converter produces an average output voltage V_O at a level lower than the supply voltage V_S. The switch is turned ON and OFF with a switching frequency f=(1/T) and with duty ratio D = Ton / T, where T_{ON} is the ON time of the switch S1 and T is the switching period. Circuit diagram for CBC is as shown in figure1, the supply voltage is in series with inductor acts as a current source. The energy stored in L1 builds up when S1 is closed. When S1 is opened, current continues to flow through L1 to R_O. As the source and the discharging L1 are both providing energy with the switch open, the effect is to buck the voltage across R_O. The total output current Io, which is the sum of the two inductor currents IL1are shown in Figure.2.

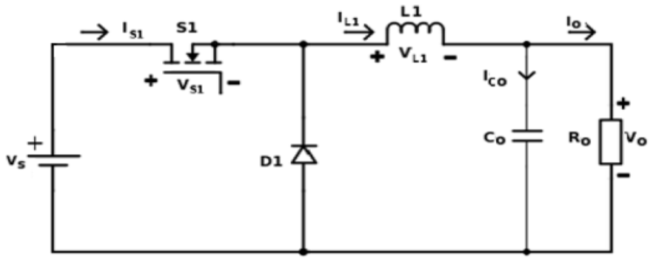

Figure 1 : Circuit Diagram of Conventional Buck dc-dc Converter

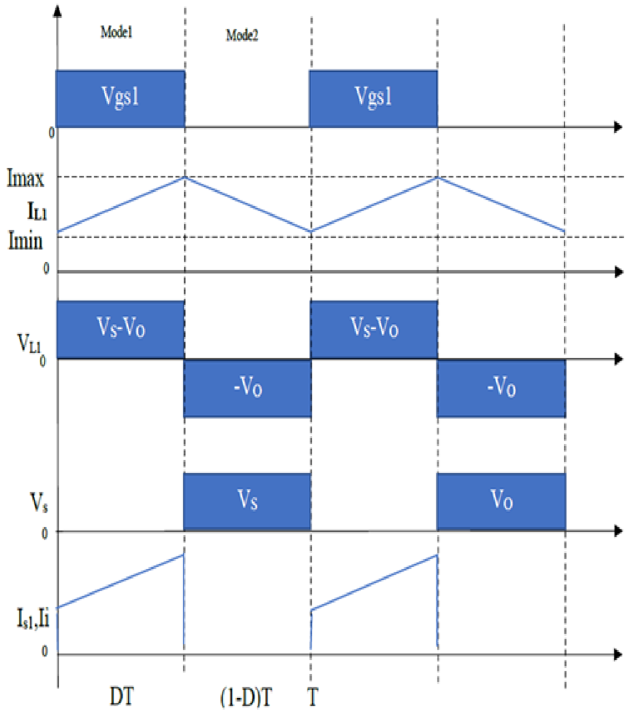

Figure 2 : Circuit Diagram of Conventional Buck dc-dc Converter

III. TWO PHASE INTERLEAVED BUCK CONVERTER

The two phase interleaved buck converter is as shown in Figure.3.The two conventional converters are essentially connected in parallel but operate in an interleaved mode. The first converter is composed of inductorL1, Switch S1, and Diode D1, whereas the second converter consists of L2, S2 and D2. The two phase IBC share the same filter capacitor C at the output. It is assumed that the parameters of the two converters are identical. The gating signals and the inductor current waveforms of the converter are shown in Figure.2. Figure.2a, represents waveforms of inductor currents and input current and the converter is operated with duty ratio D(0<D<0.5). In this duty ratio (0<D<0.5) any one switch will be conducting at time and also at specific period of time both inductors discharge. With the two phase IBC designs, the gating signals Vgs1and Vgs2 for switch S1and S2 are identical but shifted by 180°. The total output current Io, which is the sum of the two inductor currents IL1 and IL2 are shown in Figure.4.

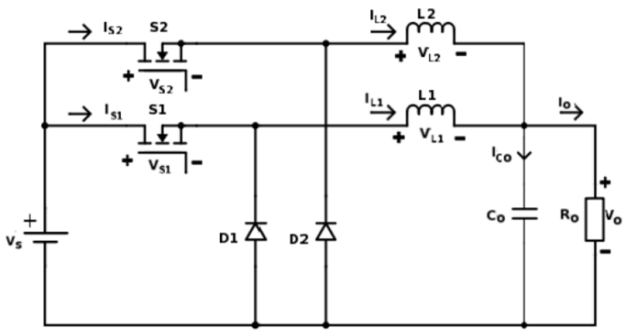

Figure 3 : Circuit Diagram of Two Phase Interleaved Buck dc-dc Converter

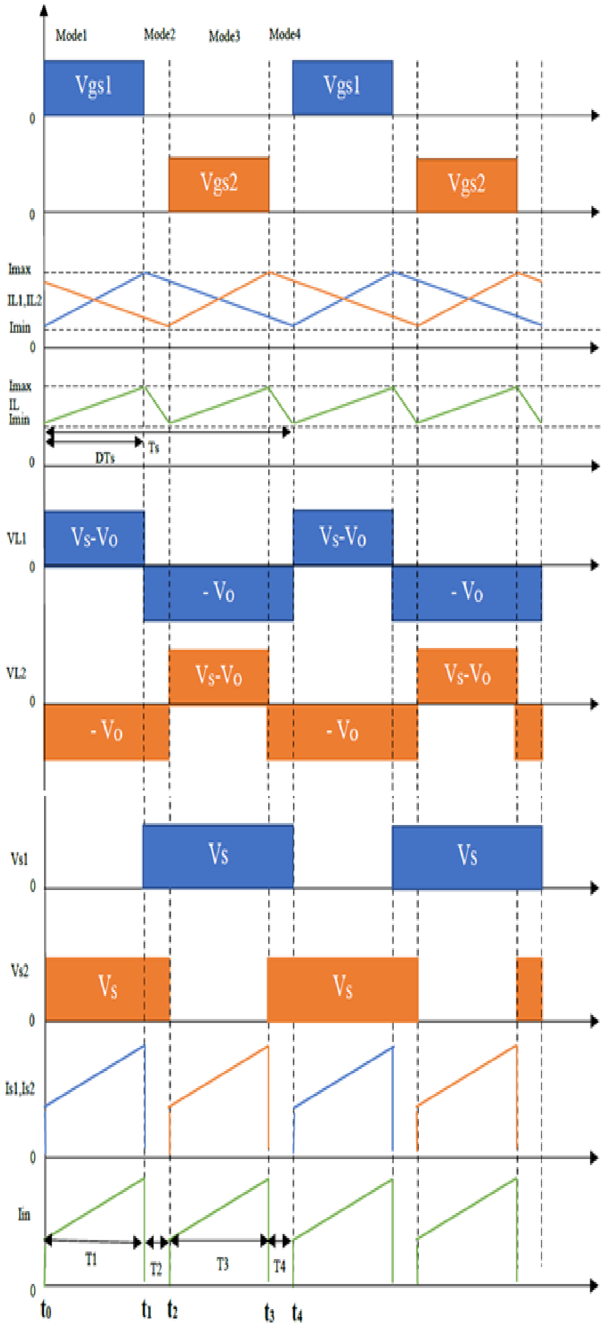

Figure 4 : Circuit Diagram of Two Phase Interleaved Buck dc- dc Converter

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A. Nomenclature

Symbol	Description	unit
V_0	Output Voltage	volt
R_0	Output resistance	ohm
T	Time period	sec
T_{ON}	Time	sec
C_O	Filter capacitor	µF
I_{CO}	Capacitor current	Amps
I_O	Output current	Amps
I_{S1}	Current through switch one	Amps
I_{S2}	Current through switch one	Amps
V_{L1}	Voltage across inductor L1	volt
Vgs1	Gate voltage across switch one	volt
D	Duty ratio	
L_{min}	Critical inductance	Henry
ΔI_{L1}	Ripple current through L1	Amps
ΔI_{L2}	Ripple current through L2	Amps
V_{S1}	Voltage across through switch S1	volt
V_{S2}	Voltage across through switch S2	volt

IV. STEADY STATE CHARECTERISTICS AND DESIGN TWO PHASE IBC

Steady state characteristics of CBC and two phase IBC:

Parameters	**CBC**	**Two phase IBC**
Buck ratio	$D = \frac{V_O}{V_S}$	$D = \frac{V_O}{V_S}$
Output current	$I_O = \frac{P_O}{V_O}$	$I_O = \frac{P_O}{V_O}$
Inductor current ripple amplitude	$\Delta I_{L1} = \frac{V_S - V_O}{L1}(DT)$	$\Delta I_{L1} = \Delta I_{L2} = \frac{V_S - V_O}{L1}(DT)$ Total ripple $\Delta I_L = \Delta I_{L1} + \Delta I_{L2}$
Operating currents in semiconductors	I_{in}	$\frac{I_{in}}{2}$

Table1: Parameters and its Expression for both CBC and IBC

For two phase IBC individual inductor current ripple will vary for duty ratio as shown in figure 5, In figure 6 it is seen that In two phase IBC total inductor current ripple will be zero for duty ratio 0.5 and % ripple of IBC is less compared to CBC.

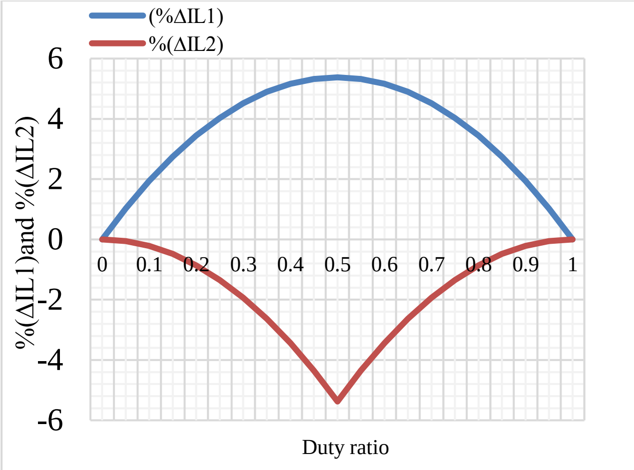

Figure 5: %ΔIL1 and %ΔIL2 versus Duty Ratio of two Phase IBC

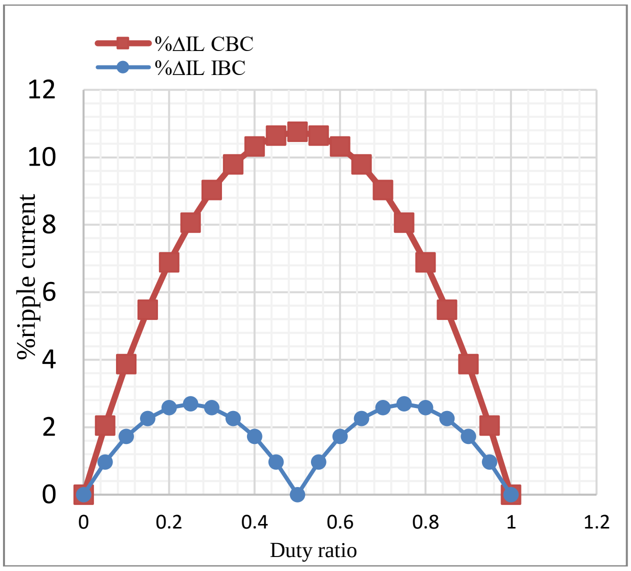

Figure 6: %ΔIL Versus Duty ratio of both CBC and two Phase IBC

Design of Two phase IBC:Input data for designing two phase interleaved buck converter output of 10 V from a 20 V source inductor current is continuous and output ripple of less than 1%. The output power 25Watts, switching frequency 31.33kHz.individualInductor current ripple is considered as 5%.

$$\text{Duty ratio (D)} = \frac{V_O}{V_S}$$

$$D = \frac{10}{20} = 0.5$$

$$\text{output current} = I_O = \frac{P_O}{V_O} = \frac{25}{10} = 2.5A$$

$$\text{output resistance} = R_O = \frac{V_O}{I_O} = \frac{10}{2.5} = 4\Omega$$

Input current $= I_{in} = I_O D = 2.5 * 0.5 = 1.25$ A

For two phase IBC inductance and capacitance values calculated as:

Inductor current $IL1 = IL2 = \frac{I_O}{2} = \frac{2.5}{2} = 1.25A$

$$\Delta I_{L1} = \Delta I_{L2} = \left(\frac{I_O/2}{100}\right) * 5$$

$$\Delta I_{L1} = \Delta I_{L2} = \left(\frac{2.5/2}{100}\right) * 5 = 0.0625$$

Since ΔI_{L1} , ΔI_{L2} are out of phase and as same value they will cancel each other and

$\Delta I_{L1} + \Delta I_{L2} = 0$ therefore there is no need of capacitor filter

$$L1 = L2 = \left(\frac{V_S - V_O}{\Delta I_{L1} * n * f}\right) * D$$

$$= \left(\frac{20-9}{\left(\frac{(5*2.77)}{100}\right) * 2 * 31.3K}\right) * 0.45 = 570\mu H$$

$$Imin = \frac{I_O}{2} - \frac{\Delta I_{L1}}{2} = \left(\frac{2.5}{2}\right) - \left(\frac{0.125}{2}\right) = 1.187 \text{ A}$$

$$Imax = \frac{I_O}{2} + \frac{\Delta I_{L1}}{2} = \left(\frac{2.5}{2}\right) + \left(\frac{0.125}{2}\right) = 1.31 \text{ A}$$

$$\Delta V_O = \frac{V_O}{100} = \frac{10}{100} = 0.1$$

Efficiency calculation

1.Losses in the switches due to drain-source resistance R_{NMOS}

$$P_{switch} = 2 * R_{NMOS} * (I_{O1})^2 = 2 * 0.077 * (2.5/2)^2 = 0.24W$$

2.Losses in the diode due to diode series resistance R_D

$$P_{diode} = R_D * \left(I_{O1}(1-D)\right)^2 + V_F I_{O1}(1-D)$$

$P_{diode} = (0.3 * (1.25/2)^2 + (0.875 * 1.25 * .5))*2=1.32W$

3.Losses in the inductor due to internal series resistance R_L

$$P_{inductor} = 2 * R_L * (I_{O1})^2 = 2 * 0.6 * (1.25)^2 = 1.875W$$

4.The input power is the sum of the output power and all the above losses.

$$P_{in} = P_{inductor} + P_{diode} + P_{switch} + P_o$$

$$P_{in} = 1.875 + 1.32 + .24 + 25 = 28.45W$$

5.Efficiency= (P_o/P_{in})*100=(25/28.45) =87.9%

V. MODELLING AND ANALYSIS TWO PHASE IBC

A. Modelling

Analysis of two phaseIBC is done using state space averaging technique. The two phase IBC is analyzed for duty ratio D. The circuit can be analyzed in four modes of operation by considering parasitic elements.

Mode-1:Switch S1 are closed, S2 is open. Analyze the Figure7 ,by applying KVL and KCL we get the equation in matrix form.

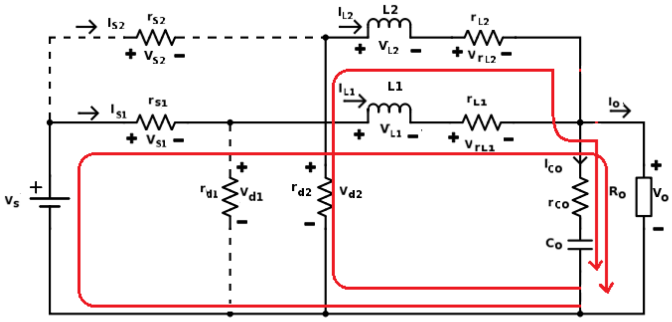

Figure 7:Equivqlent Circuit of Two phase IBC Equivalent During mode1

$$A_1 = \begin{bmatrix} \frac{-r_{L1} - r_{s1} - r_{co}}{L_1} & -\frac{r_{co}}{L_1} & -\frac{1}{L_1} \\ -\frac{r_{co}}{L_2} & \frac{-r_{L2} - r_{d2} - r_{co}}{L_2} & -\frac{1}{L_2} \\ \frac{R_O}{C_O(r_{co} + R_O)} & \frac{R_O}{C_O(r_{co} + R_O)} & \frac{1}{C_O(r_{co} + R_O)} \end{bmatrix}$$

$$B_1 = \begin{bmatrix} \frac{1}{L_1} & \frac{r_{co}}{L_1} \\ 0 & \frac{r_{co}}{L_2} \\ 0 & 0 \end{bmatrix}$$

$$C_1 = \begin{bmatrix} \frac{R_O r_{co}}{R_O + r_{co}} & \frac{R_O r_{co}}{R_O + r_{co}} & \frac{R_O}{R_O + r_{co}} \end{bmatrix}$$

Mode-2 Mode-4:Switch S1 and S2 both are open. Analyze the Figure8 ,by applying KVL and KCL we get the equation in matrix form**.**

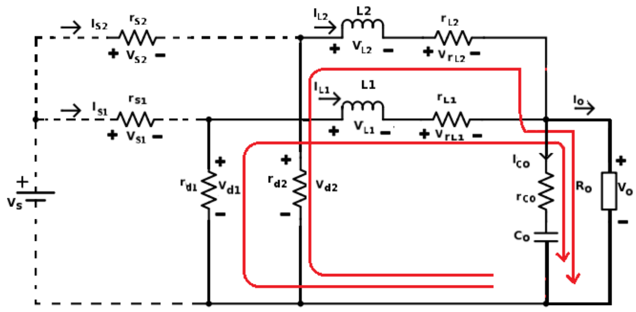

Figure 8: Two Phase IBC Equivalent During Mode2

$$A_2 = \begin{bmatrix} \frac{-r_{L1} - r_{d1} - r_{co}}{L_1} & -\frac{r_{co}}{L_1} & -\frac{1}{L_1} \\ -\frac{r_{co}}{L_2} & \frac{-r_{L2} - r_{d2} - r_{co}}{L_2} & -\frac{1}{L_2} \\ \frac{R_O}{C_O(r_{co} + R_O)} & \frac{R_O}{C_O(r_{co} + R_O)} & \frac{1}{C_O(r_{co} + R_O)} \end{bmatrix}$$

$$B_2 = \begin{bmatrix} 0 & \frac{r_{co}}{L_1} \\ 0 & \frac{r_{co}}{L_2} \\ 0 & 0 \end{bmatrix}$$

$$C_2 = \begin{bmatrix} \frac{R_O r_{co}}{R_O + r_{co}} & \frac{R_O r_{co}}{R_O + r_{co}} & \frac{R_O}{R_O + r_{co}} \end{bmatrix}$$

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Mode-3Switch S1 is open, S2 is close. Analyze the Figure 9,by applying KVL and KCL we get the equation in matrix form

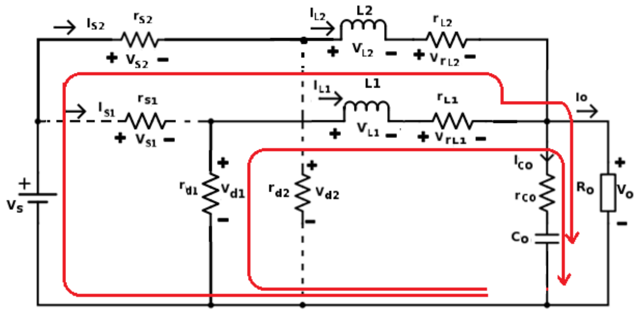

Figure 9: Two Phase IBC Equivalent During Mode3

$$A_3 = \begin{bmatrix} \frac{-r_{L1} - r_{s1} - r_{co}}{L_1} & -\frac{r_{co}}{L_1} & -\frac{1}{L_1} \\ -\frac{r_{co}}{L_2} & \frac{-r_{L2} - r_{d2} - r_{co}}{L_2} & -\frac{1}{L_2} \\ \frac{R_O}{C_O(r_{co} + R_O)} & \frac{R_O}{C_O(r_{co} + R_O)} & \frac{1}{C_O(r_{co} + R_O)} \end{bmatrix}$$

$$B_3 = \begin{bmatrix} \frac{1}{L_1} & \frac{r_{co}}{L_1} \\ 0 & \frac{r_{co}}{L_2} \\ 0 & 0 \end{bmatrix}$$

$$C_3 = \begin{bmatrix} \frac{R_O r_{co}}{R_O + r_{co}} & \frac{R_O r_{co}}{R_O + r_{co}} & \frac{R_O}{R_O + r_{co}} \end{bmatrix}$$

B. Analysis using Small Signal Modeling

The general, waveforms of inductor currents at steady state in a particular switching cycle of an N-phase interleaved will be shifted by $\frac{2\pi}{N}$ degrees , Based on the assumption that all switching cells carry equal average current and are operated at the same duty ratio in a switching cycle of interest we can write duty cycle as follows,

$$D_{2i-1} = D \ldots \ldots 1$$

$$D_{2i} = \frac{1}{N} - D \ldots \ldots 2$$

Where i= 1, 2, ...*N*, and Dis the duty ratio in the switching cycle considered. Here D is assumed to be constant cycle to cycle, it is defined as the steady-state duty ratio. According to the averaged state-space model over one particular cycle can be written as

$$\dot{x} = Ax + Bu \ldots \ldots 3$$

By applying state space model to the N phase interleaved inductor current waveforms , we obtain

$$A = \sum_{j=1}^{2N} D_j + A_j \ldots \ldots 4$$

$$B = \sum_{j=1}^{2N} D_j + B_j \ldots \ldots 5$$

whereA_j and $B_j$are the state matrix and the control vector of the interval D_jTrespectively, and

j = 1, 2, ... , 2N.

now using Eqs.28,29, 31,32 we obtain

$$A = D\sum_{i=1}^{N} A_{2i-1} + \left(\frac{1}{N} - D\right) D \sum_{i=1}^{N} A_{2i} \ldots \ldots 6$$

$$A = D\sum_{i=1}^{N} B_{2i-1} + \left(\frac{1}{N} - D\right) D \sum_{i=1}^{N} B_{2i} \ldots \ldots 7$$

For two phase Substituting N=2 then we can write as

$$A = D[A_1 + A_3] + [1 - 2D]\, A_2$$

$$B = D[B_1 + B_3] + [1 - 2D]\, B_2$$

To investigate the small-signal behavior, we now assume that duty cycle d varies from cycle to cycle. consider the perturbations in the input voltage, in the duty ratio and in the state equations are introduced to Eqs 6 . By neglecting the non-linear second-order term, the perturbed state-space equation for an N-phase interleaved converter is obtained as,

$$\dot{x} = Ax + Bu + A\hat{x} + B\hat{u} + \left[\sum_{i=1}^{N}(A_{2i-1} - A_{2i})X + \sum_{i=1}^{N}(B_{2i-1} - B_{2i})u\right]\hat{d}$$

When all perturbations are set to zero, the steady-state model is obtained as

$$X = -A^{-1}BU$$

Consequently, the small-signal model is found to be

$$\dot{x} = A\hat{x} + B\hat{u} + \left[\sum_{i=1}^{N}(A_{2i-1} - A_{2i})X + \sum_{i=1}^{N}(B_{2i-1} - B_{2i})u\right]\hat{d}$$

Using the Laplace transform , we have the small signal model for N parallel cells as

$$\dot{x}(s) = (SI - A)^{-1}\left\{B\hat{u}(s) + \left[\sum_{i=1}^{N}(A_{2i-1} - A_{2i})X + \sum_{i=1}^{N}(B_{2i-1} - B_{2i})u\right]\hat{d}(s)\right\}$$

On substituting the $\hat{u}(s) = V_s(s)$ and corresponding values in the above equation and on simplification the transfer function can be obtained.

$$\frac{\dot{\hat{V}_o}(s)}{\hat{d}(s)} = (SI - A)^{-1}[A_1 + A_3 - 2A_2]X \ldots \ldots \ldots .8$$

$$G_{vd}(s) = \frac{s(1 - D)(L_1 + L_2) - s^2 L_1 L_2 (IL_1 + IL_2)}{s^3 L_1 L_2 C + \frac{sL_2 L_2}{R} + s(1 - D)^2 (L_1 + L_2)} \ldots 9$$

After getting the transfer function and Two phase IBC , the same is fed into the SISO design tool command in the MATLAB closed loop step response of compensated systemof two phase IBC is as shown in figure 10 and using automated PID tuning we can find the Kp, Ki and Kd values.The same values are fed in to the PID controller these values are set into the PID controller.

Compensator gain values	**Two phase IBC**
Proportional constant Kp	Kp=0.01
Integral constant Ki	Ki=50
Derivative constant Kd	0

Table 2: Compensator Gain Values two Phase IBC

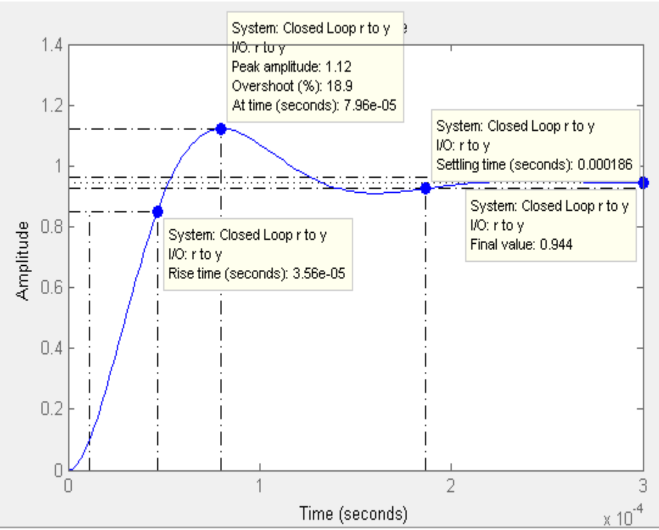

Figure 10: Closed loop step Response of Compensated System of two Phase IBC.

VI. SIMULATION RESULTS

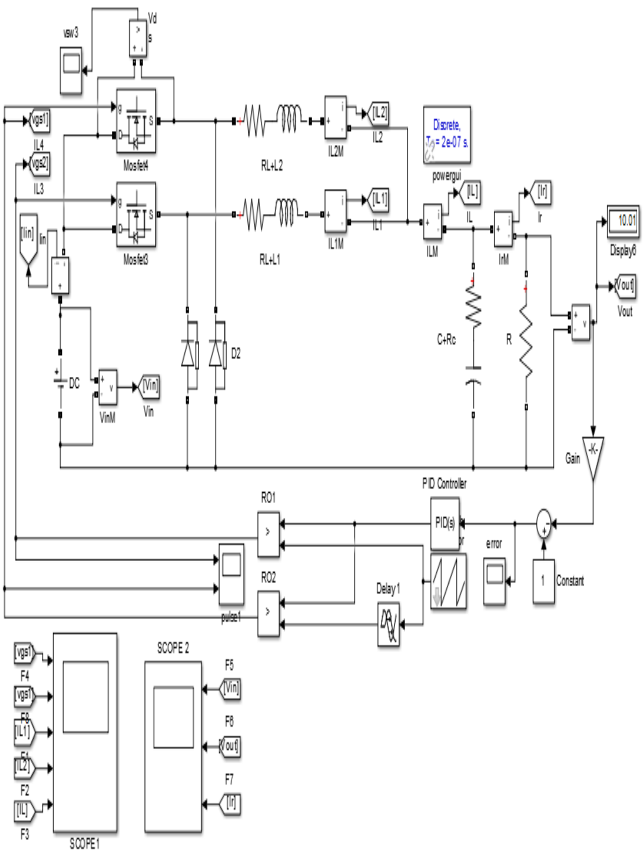

Figure 11: Two Phase IBC in Closed Loop

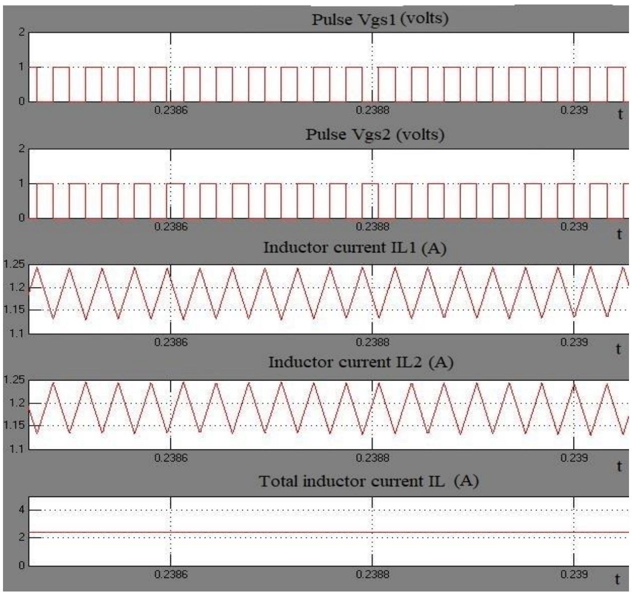

Figure 12:Simulated Operating Waveforms During Closed Loop Operation

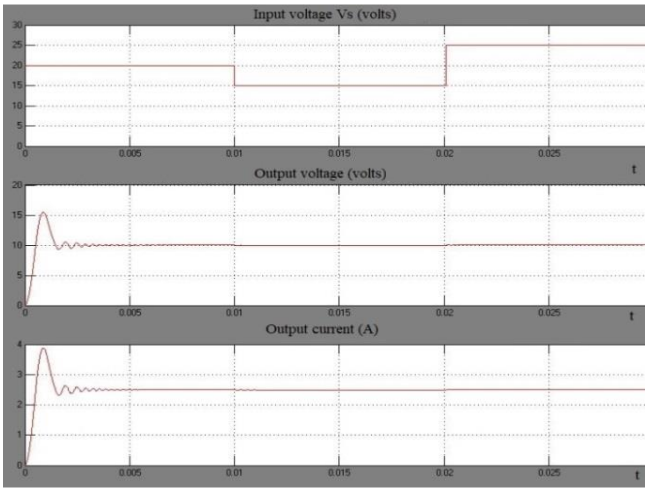

Figure 13:Output Voltage and Current Waveform for Variation of Supply voltage ±25%

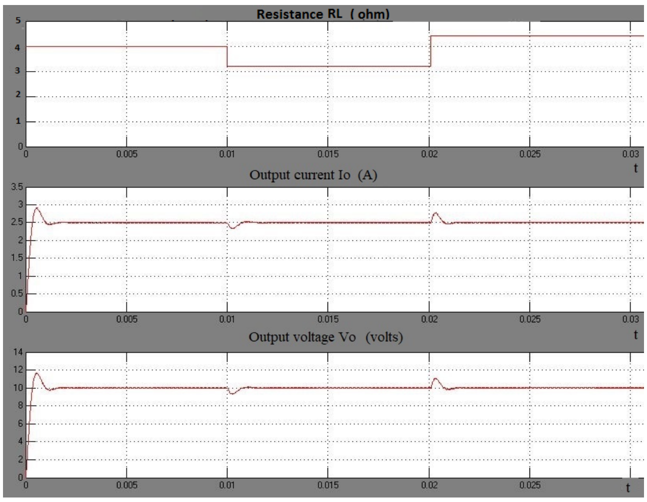

Figure 14 :Output Voltage and Current Waveform For Variation of load ±20%

VII. HARDWARE IMPLEMENTATION AND RESULTS

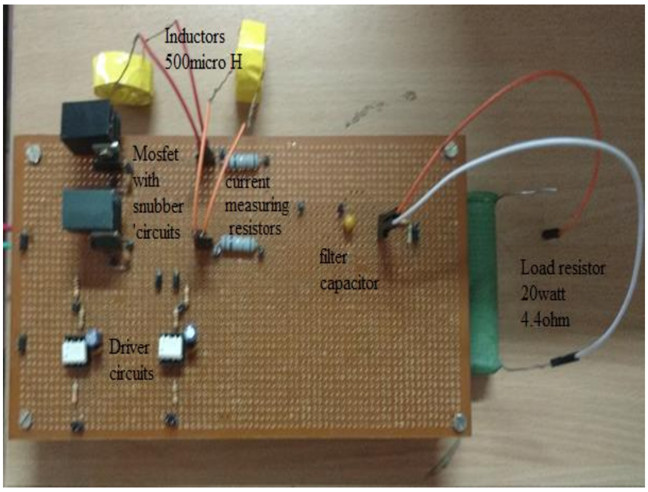

Figure 15 :Practical Circuit Connection of Two Phase IBC

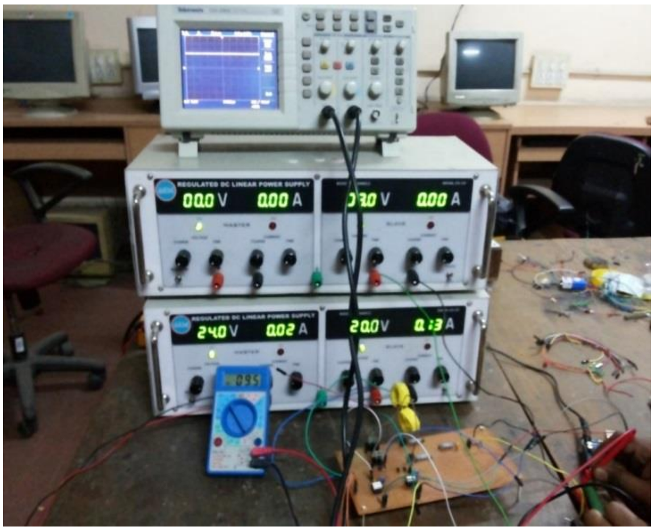

Figure 16: Complete Practical Setup of Two Phase IBC

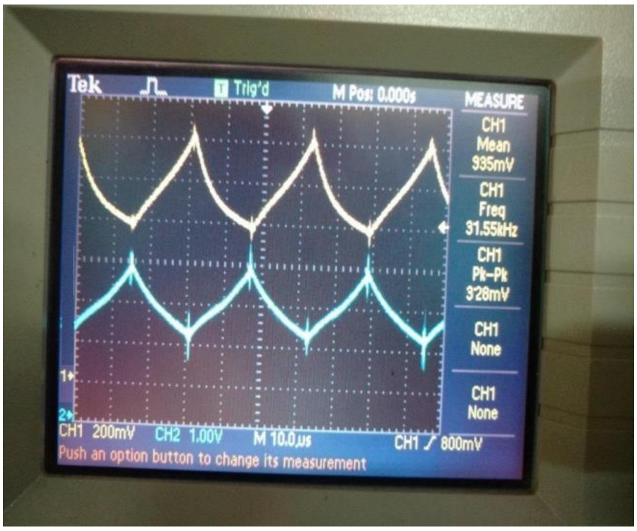

Figure 17: Individual Inductor Current Waveform of IBC

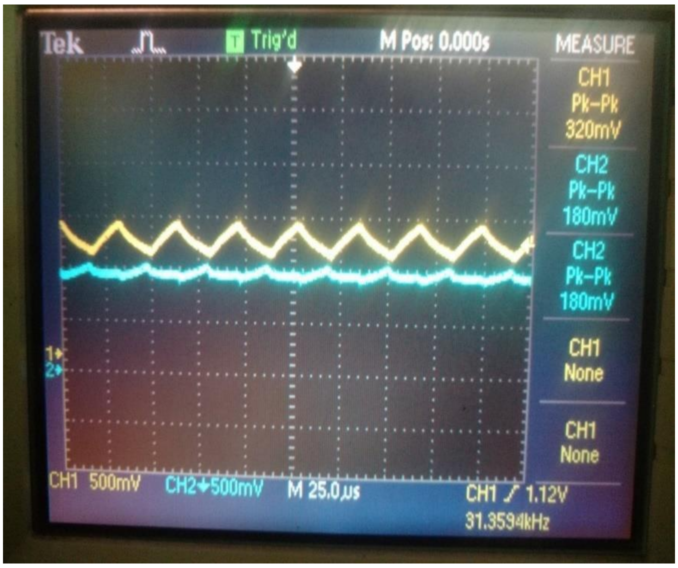

Figure 18: Individual Inductor Current and Total Inductor Current of IBC

A. Line Regulation

Line regulation with R=5.5Ω				
Vs	Vo	Vf	D	%regulation
16	9.4	5.4	0.588	6
17	9.56	5.43	0.562	4.4
18	9.6	5.47	0.533	4
19	9.9	5.51	0.521	1
20	10	5.53	0.5	0
21	10.2	5.5	0.483	-1.5
22	10.2	5.52	0.464	-2
23	10.3	5.53	0.448	-3
24	10.5	5.53	0.438	-5

Table 3: Line Regulation with R= 5.5 Ω

By close loop operation by varying input voltage V_S ,but still output voltage is still near to the desired output voltage.

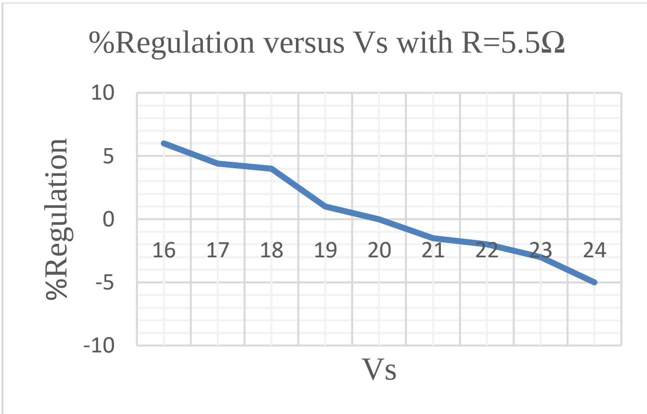

Figure 19: Plot of %Regulation versus V_S

B. Load Regulation

	Load regualtion with Vs=20				
%loading	R	Vo	Vf	D	%regulation
8	47	10.2	5.4	0.217	-2
12	33	10.1	5.43	0.3061	-1
16	25	10	5.47	0.4	0
40	10	9.9	5.51	0.99	1
72	5.5	9.8	5.53	1.7818	2
121	3.3	9.6	5.53	2.9091	4

Table 4: Load Regulation with Vin=20V for Closed Loop

By close loop operation varying load resistance and still output voltage is still near to the desired output voltage ie 10 V.

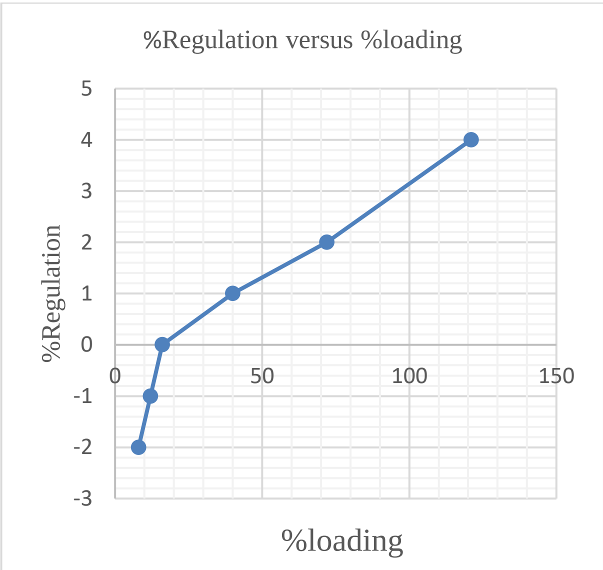

Figure 22: Plot of %Regulation versus %loading

VIII. CONCLUSION AND FUTURE SCOPE

The two phase IBC is designed, in which the size of passive components i.e, output filter inductors and output side capacitor filter is decided.Simulation is performed in Matlab-Simulink for the calculated values and an expected output is achieved in closed loops. Also the results obtained depicts that the peak-to-peak ripple in inductor current is reducedto 0A for duty ratio 0.5.By considering all parasitic elements two phase IBC is modeled using state space averaging technique the accurate modeling of the converter and is analyzed based on small signal analysis and found the transfer function of output voltage to variations in duty ratio.The hardware implementation has done two-phase IBC for the designed values and tested. From Arduino Uno Microcontroller the gate pulses for a duty ratio of 50% and at a frequency of 31.33 kHz is generated. Also from the experimental results, it can be seen that for two phase IBC ripple in the total inductor current is reduced to minimum value .Then thus two phase IBC is able to achieve the objectives of reducing the size of the passive components and decreasing the ripple in input current and output current thus achieves a higher efficiency.Closed loop implementation as done by using PID controller taking voltage as feedback for both CBC and two phase IBC and thus line regulation and load regulation graph plot as done and results obtained are satisfactorily for close loop operation As a future scope, a high step down interleaved buck converter can be implemented and also better tuning procedure with fuzzy logic controller can be used so that it can as less ripple and better power quality and high efficiency, and constant output voltage so that it support different appliances with different voltage ratings.

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