Two-Stage Dc-Dc Boost Converter using PI and PID Controller

Sanjitha Ranganath, Cheaheng Lim, MadhuShree Kadabur Sugunakar

Abstract - This is report mainly focuses on the simulation design of a DC to DC convertor using the simulation tool called MULTISIM. This converter is used to amplify a 24VDC input to a 48 VDC output and maintains a maximum power of 500W. Its application includes Aero-spatial domain especially in satellites, here it is combined with the energetic system beside the fuel cells, hydrogen and oxygen regeneration systems or in the photovoltaic cells. This circuit uses a PWM with a switching frequency of 5 kHz and a linear variable voltage generator using 555 circuit. This electronic scheme is improved, and the input and the output voltages are modified based on the avionics standards. The behavior of the convertor under different loads - 15 Ω and 35 Ω is observed and the results are noted to be are consistent.

Key Words*: *Boost Dc-Dc converter, PI, and PID

I. Introduction

Dc to Dc power converters are used to transform the input electrical energy to output energy using some parameters. The Boost convertor circuit shown in the figure 1 consists of the components like the switch (a MOSFET), a diode, one coil, one capacitor, its functioning is coordinated by a PWM controller. Some of its applications are in the field of Aeronautic, the spatial domain and most importantly MEA (More Electrical Aircraft). Many different types of Boost convertors made up of different input voltages and output voltages were studied. But they to produce the standardized voltages in avionics systems [1] - [10]. So here in this project the input voltage was modified to 24 Vdc and the output voltage to 48 Vdc and the switching frequency was dropped from 10 kHz to 5 kHz. The maximum power obtained is 500 W. Some of the improvements were also made to this boost convertors that can be seen in the later sections. Details of the classical scheme of boost converter are explained in Section II. Section IV shows the simulation Section V shows the experiment results. In section VI, the conclusion is addressed.

Sanjitha Ranganath, Cheaheng Lim, MadhuShree Kadabur Sugunakar are with the ECE Department at Lyles College of Engineering at California State University, Fresno, CA 93740, (e-mail: cheal@mail.fresnostate.edu)

II. BOOST CONVERTER

A. Classic Boost Converter

The classical scheme of the boost converter is as shown in Fig. 1 [4] - [17].

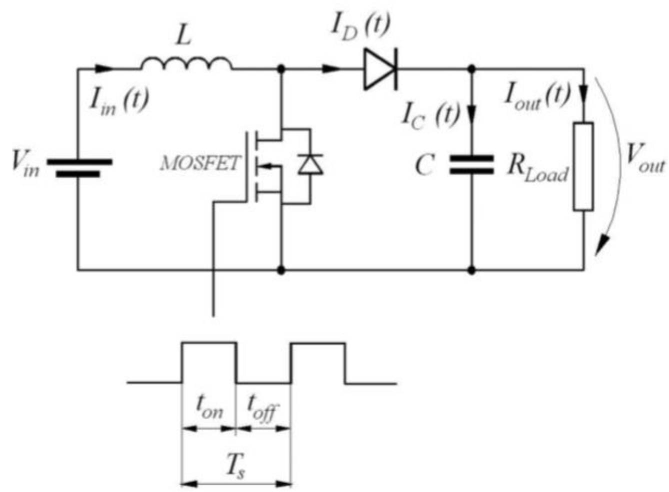


Fig. 1. Principle scheme of the boost converter.

This converter circuit can be used in two modes, that depends on the energy storage capacities and the relative length of commutation period. These modes are called as CCM (Continuous Conduction Mode) and DCM (Discontinuous Conduction Mode). The CCM is better and an efficient conversion mode than that of the DCM, which is the low conversion mode [4] - [6].

B. CCM Mode (Continuous Conduction Mode)

This mode can be discussed under two of the following cases: Case 1: (0< t ≤ t_{on}) It starts when the switch passes to "ON" at t=0 and ends when the switch pass to "OFF" at t = t_{on}. The equivalent circuit for this mode is as shown in the figure 1.2b. Here if the internal resistance of the source is a small value and if the coil current is positive and if they increase linearly, then the coil voltage is equal to that of the input voltage.

Case 2: (t_{on} < t ≤ T_s) starts when the switch passes to "OFF" and ends when it passes to "ON" at t = T_s. Its equivalent circuit is as shown in the figure 1.2c. Here in this case the coil voltage is the difference between the output and the input voltages. In this case, V_{in} < V_{out}. The steady state is characterized by the signal that is determined by these periodical commutations, at constant input voltage and constant output load.

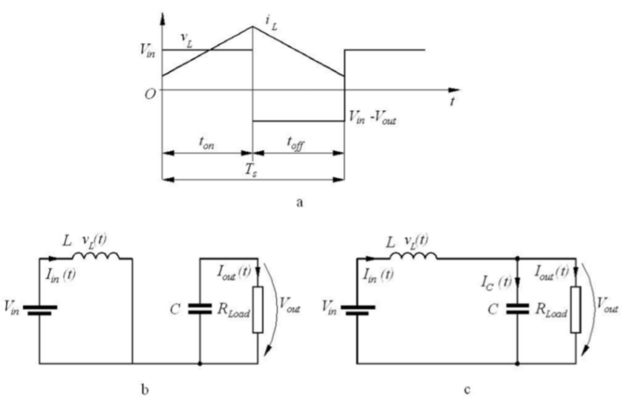


Fig. 2. CCM Mode. a – waveforms; b – switch "ON", c – switch "OFF"

At stationary state, as there are no energy accumulated in the circuit, the integral of the coil voltage V_L over one period $T_s = t_{on} + t_{off}$ is null. So that the total weighted sum of the coil voltages when the switch is "ON" and the switch is "OFF" is zero [4].

$$V_{in}t_{on} + (V_{in} - V_{out})t_{off} = 0 \tag{1}$$

where V_{in}- is the input voltage, V_{out}- medium output voltage, t_{on} , t_{off} and T_s are represented in fig.2. From eq(1) results

$$\frac{V_{out}}{V_{in}} = \frac{T_s}{t_{off}} = \frac{1}{1-D} \tag{2}$$

Where, D is the duty cycle. The duty cycle is between 0 and 1 and it is observed that the output voltage is higher than the input voltage. Relation in eq(2) represents the control characteristic of the boost converter. Considering the ideal boost converter, where $P_{in} = P_{out}$, so

$$V_{in}I_{in} = V_{out}I_{out} \tag{3}$$

$$\frac{I_{out}}{I_{in}} = \frac{V_{in}}{V_{out}} = 1 - D \tag{4}$$

Where, I_{out} is the output medium current, I_{in} is the medium input current. When the switch is "ON", the coil voltage is equal with the input voltage, so [4]

$$V_L = V_{in}; \mathrm{L}\frac{\mathrm{d}i_L}{\mathrm{dt}} = V_{in} \tag{5}$$

$$\frac{\mathrm{d}i_L}{\mathrm{dt}} = \frac{V_{in}}{L} \tag{6}$$

$$\frac{\mathrm{d}i_L}{\mathrm{dt}} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{\Delta T}; \frac{\mathrm{d}i_L}{\mathrm{dt}} = \frac{V_{in}}{L} \tag{7}$$

Obtaining in the final,

$$\Delta i_{L(s-close)} = \frac{\mathrm{V}_{in}DT}{L} \tag{8}$$

When the switch is "OFF",

$$V_s = V_{in} - V_{out} = \mathrm{L}\frac{di_L}{\mathrm{dt}} = V_{in} - V_{out} \tag{9}$$

$$\frac{\mathrm{d}i_L}{\mathrm{dt}} = \frac{(V_{in}-V_{out})}{L} \tag{10}$$

$$\frac{\mathrm{d}i_L}{\mathrm{dt}} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-\mathrm{D})T}; \frac{\mathrm{d}i_L}{\mathrm{dt}} = \frac{(V_{in}-V_{out})}{L} \tag{11}$$

We obtain,

$$\Delta i_{L(s-open)} = \frac{(V_{in}-V_{out})(1-D)T}{L} \tag{12}$$

C. DCM Mode (Discrete Conduction Mode)

In DCM mode, before the switching period is accomplished the coil current falls to zero, as shown in figure below. The integral of the coil voltage over one switching period is zero, as in CCM mode, therefore the weighted sum is given by the following equation below.

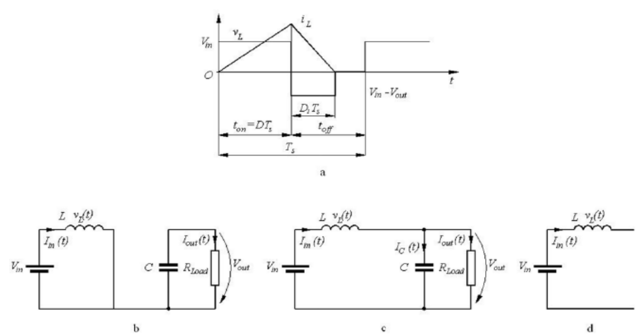


Fig.3 DCM mode (a), case1 (b), case2 (c)

Fig.3 represents the equivalent circuit in DCM mode comprising of three cases: Case 1: (0< t < ton) and figure 3b represents Case 2: (ton< t < $(D_1 + D)\ T_s$) and Figure 3c represents Case 3: ($(D_1 + D)\ T_s < t < T_s$)

$$V_{in}DT_S + (V_{in} - V_{out})D_1T_s = 0 \tag{13}$$

$$\frac{V_{out}}{V_{in}} = \frac{(D_1+D)}{D_1} \text{ and } \frac{I_{out}}{I_{in}} = \frac{D_1}{D_1+D} \tag{14}$$

The coil current is equal to the medium input current

$$I_{in} = \frac{V_{in}}{2L}DT_s(D_1 + D) \tag{15}$$

Replacing equation 13 in 15 we get,

$$I_{out} = \frac{V_{in}T_S}{2L}DD_1 \tag{16}$$

Further, using equation 14 and 16 the duty cycle can be obtained,

$$D = \sqrt{\frac{4V_{out}}{27V_{in}}}\ (\frac{V_{out}}{V_{in}} - 1)\frac{I_{out}}{I_{out,avg,max}} \tag{17}$$

where, $I_{out,avg,max}$ is the maximum averaged value of the output current Iout found from the following equation

$$I_{out} = \frac{V_{out}T_s}{2L} D(1-D)^2 \qquad (18)$$

III. CONVERTER SCHEME IN MULTISIM

The Dc-Dc Boost converter circuit is implemented in Multisim as shown in Fig 4. The basic elements or components of the converter are the coil L1, capacitor C1, diode D3, MOSFET transistors Q1 and Q2 and the loads Rload1 and Rload4. A single MOSFET is not able to achieve a power of 1 kW. Hence, in this scheme two transistors in parallel with two resistors R1 and R2 acting as balancing resistors are used to step up the output power and the target power is dropped to 500 W. For testing the converters at the load step variations with switches S1-S4 one can commute the loads Rload1-Rload4. The loads 35, 27, 20 and 15 Ohms can be used by operating the switches S1-S4.

The boost converter circuit's PWM consists two of 555s and a voltage comparator LM311. The first A1 555 virtual, is used to generate frequency of 5 kHz pulses. As Multisim is not capable of handling at very small duty cycles of the 555, therefore the transistor Q4 is used in inverting configuration. The second A2 555 virtual is used as a linear variable voltage generator (LVV). The output signal from A2 is not a pure linear variable voltage, but an exponential curve, due to the loading effect of the capacitor. The above configuration of A2 and the capacitor with specific good adjustments can be used to generate PWM pulses for MOSFETs.

PWM pulses are generated using the LM311 component, previously 741 IC was used as a comparator, but it was seen that by both numerical simulations and experimental tests results the IC was too slow for this switching application. Therefore 741 was replaced by LM311 specialized comparator. The LM311, compares the output from A2, that is the LVV signal with the voltage obtained from the P-I controller. The error signal is obtained by a differential op-amp U1 of 741type. It takes the difference between the reference given by the divider R4 and R5 and the voltage obtained from the voltage divider of R17 and R16, which is directly proportional to the output voltage. This difference voltage obtained is now applied to the P-I controller implemented with a 741 type U2.

A similar DC-DC boost converter circuit was implemented in Multisim as shown in fig.5, an input voltage of 24 V was applied and stepped up to 48 V with a maximum power of 1.7 kW. The important components of the two-stage parallel boost converter are the 47uH inductor, 20mF capacitors and two MBR diodes. The circuit in fig.5 works in similar way as the Dc-Dc boost converter in fig.4 except the fact that it uses a PID controller.

Boost DC-DC Converter with PI controller: Multisim's Simulation Results:

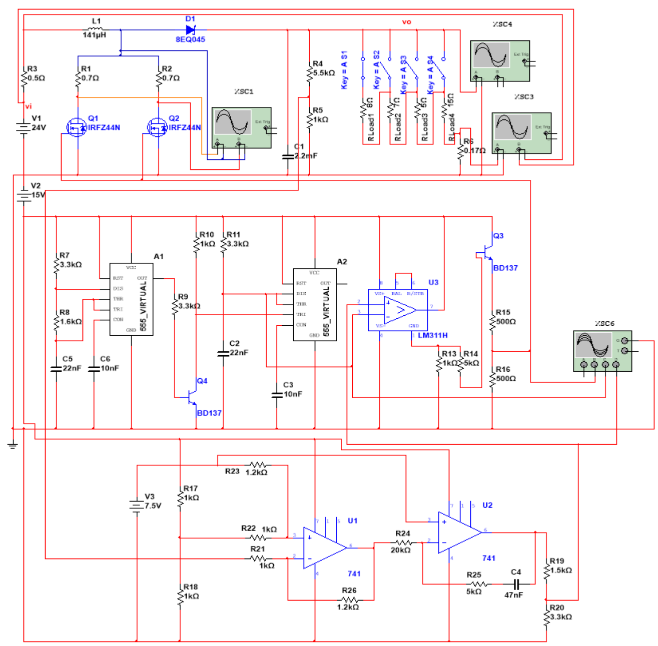


Fig. 4. Multisim implementation of DC-DC boost converter with PI controller

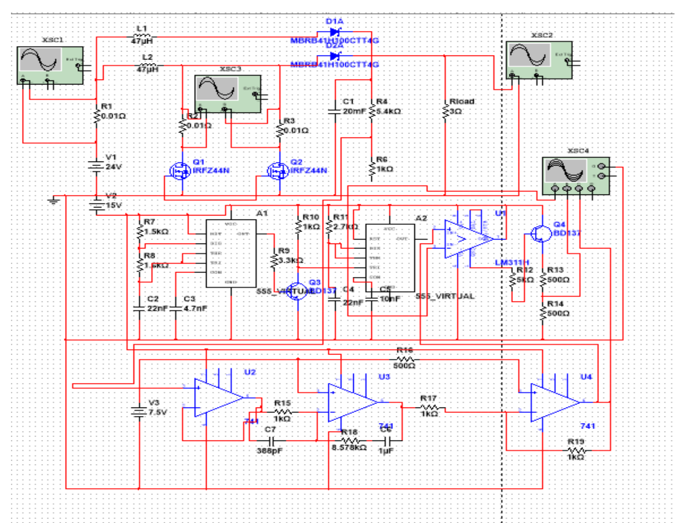


Fig. 5 Multisim implementation of DC-DC boost converter with PID controller

IV. CONVERTER SCHEME IN SIMULINK

A. PID Controller

PID stands for Proportional Integral Derivative controller that is in a closed feedback network which is used to calculate the error value and tries to minimize the error value. This is done by comparing the output voltage with the desired set value. This controller mainly has three basic parameters like Kp, Ki and Kd that can be adjusted to minimize the error this process of adjustment is called as the Tuning. This Tuning can be either done automatically or manually. The Proportional gain (Kp) relay on the current error, the integral gain (Ki) relays on the precedent error value and the Derivative gain (Kd) depends on the future error. The variation in these gain values leads to the changes in Rise Time, Overshoot, Settling Time , Steady state Error and Stability. The variation in this values is as shown in the table 1. The fig.6. shows the PID controller [18].

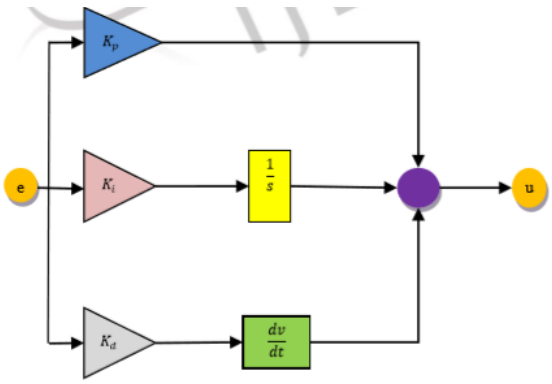


Fig 6. Block diagram of the PID controller

Table 1. Effect of Independent Kp, Ki and Kd Tuning.

Closedloop Response	Rise Time	Overshoot	Settling time	Steady state Error	Stability
Increasing K_P	Decrease	Increase	Small Increase	Decrease	Degrade
Increasing K_I	Small Decrease	Increase	Increase	Large Decrease	Degrade
Increasing K_D	Small Decrease	Decrease	Decrease	Minor Change	Improve

B. DC to DC Boost Converter using the Simulink

The Boost convertor is built using the Simulink Simulation tool. A DC To DC Boost Convertor was built with a and without the PID controller circuit. The fig.7. shows the convertor without the PID controller and the fig.8. shows the convertor with the PID controller. The circuit is designed to obtain an output voltage of 48 V with a 24 V input voltage. Here the MOSFET acts as a switch.

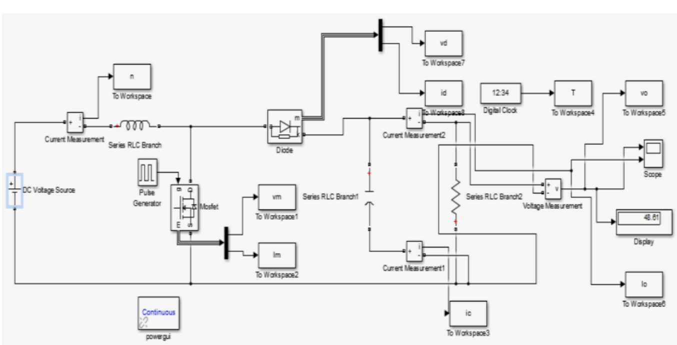


Fig. 7 DC To DC Boost Convertor without PID controller built using the Simulink.

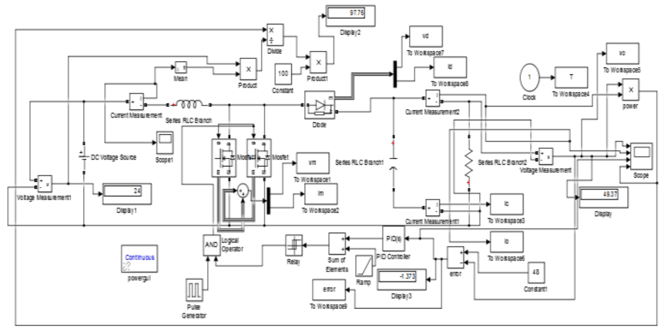


Fig. 8. DC To DC Boost Convertor with PID controller built using the Simulink.

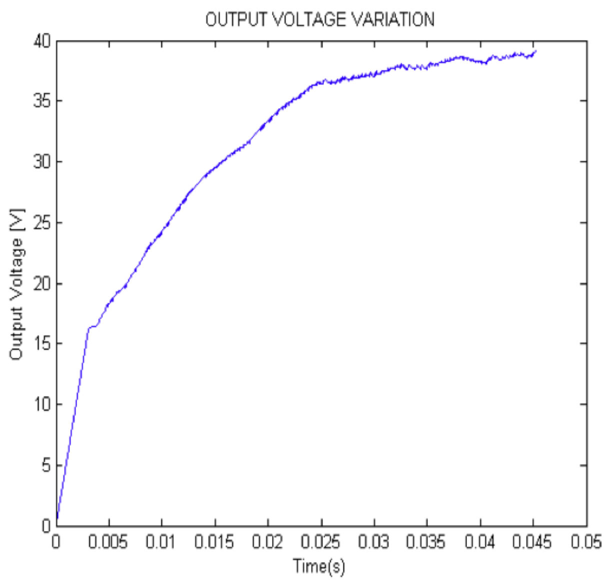
RESULT ANALYSIS AND DISCUSSION

The results of this boost dc-dc converter from Multisim's simulation show that the output voltage was not exactly 48 V. The steady state output voltage was fluctuating between 48.74 V and 49.1 V depending on different resistor load values. With the simulation results, steady state output voltage was approximately 48 V under the entire different resistor loading conditions. The steady state output voltages are shown in fig 9(b), fig 12 (b), and fig 15 (b). Also, during this boost dc-dc converter multisim's simulation, its transient response was observed. The results showed that it took longer for the boost dc-dc converter to reach a steady state when resistor load value was decreased. The transient responses for different resistor load values are shown in fig 9(c), fig 12 (c), and fig 15 (a). The two transistors' current for the different load values was analyzed, and the results shown that the boost dc-dc converter transistors' current did not affected by different loading conditions. The transistors' currents under different load conditions are shown in fig 10 (a), fig 13 (a), and fig 16 (a). Boost dc-dc converter's input current and output current were also looked at. The results for different loading conditions are shown in fig 10(b), fig 13(b), and fig 16 (a). One can see that with small value of resistor load, the input and output current were increased, and decreased when the resistor load was increased. The command circuit or the pulse width modulation was also analyzed. The MOSFETs' voltage, linear variable voltage generator, A2, and P.I.'s, U2, voltages were observed under the different load conditions. The results are shown in fig 11, fig 14, and fig 16. The results show that three components' values were increased when the resistor load was increased. Furthermore, their frequencies component was observed, and simulation results show that their frequencies remained constant, which the calculation value equaled to 9346 Hz. This frequency of 9346 Hz did not agree with the 5 kHz as the original author had claimed.

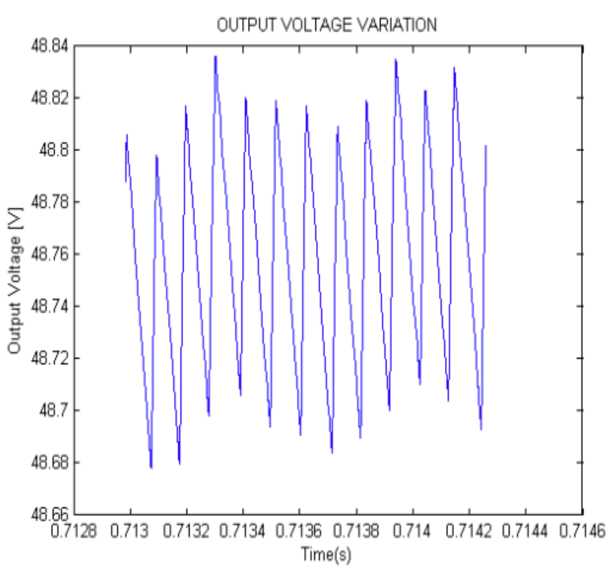
The Output waveform for the output voltage, output Current for the DC to DC Convertor circuit without PID controlled is as shown in the fig 10 and the Output voltage and the Output current was found to be Vout=48.6V and Iout=1.38A. The Output waveform for the output voltage, output Current for the DC to DC Convertor circuit with PID controlled is as shown in the fig 10 and the Output voltage and the Output current was found to be Vout=49.37V Iout=1.38A and the efficiency is 97.76 %. Fig 11 shows the Output waveform for the output voltage, output Current, error and output power with respect to Time (Time scale of 1s).

Boost DC-DC Converter with PI controller: Multisim's Simulation Results:

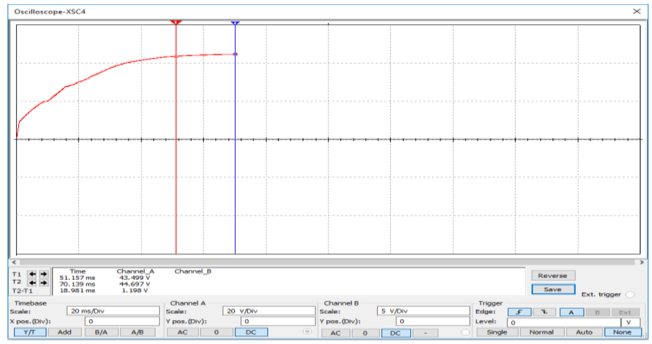
A. Result for 15 Ω Resistor Load



(a)

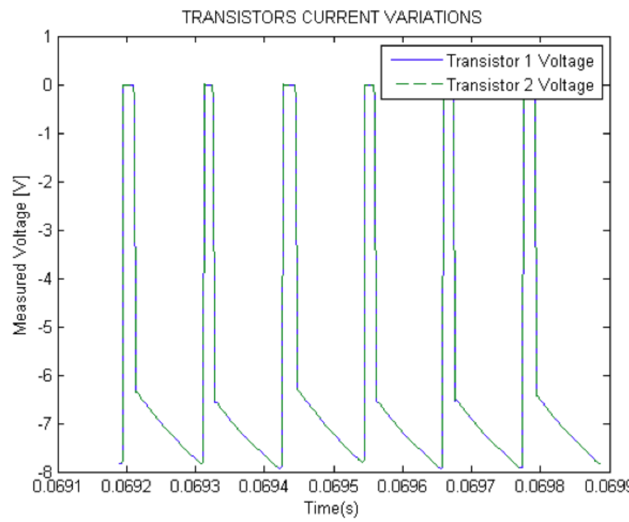


(b)

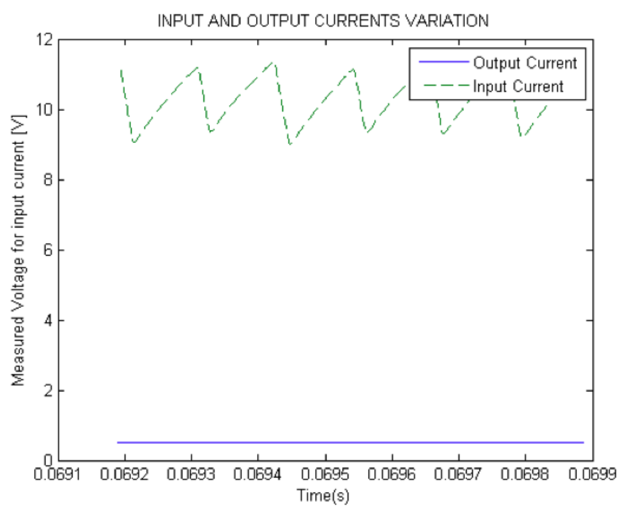


(c)

Fig. 9 : (a) Output voltage, (b) Steady state output voltage, and (c) Output voltage as shown in Multisim's oscilloscope



(a)



(b)

Fig. 10 : (a) Transistors output currents, (b) Input current and output current

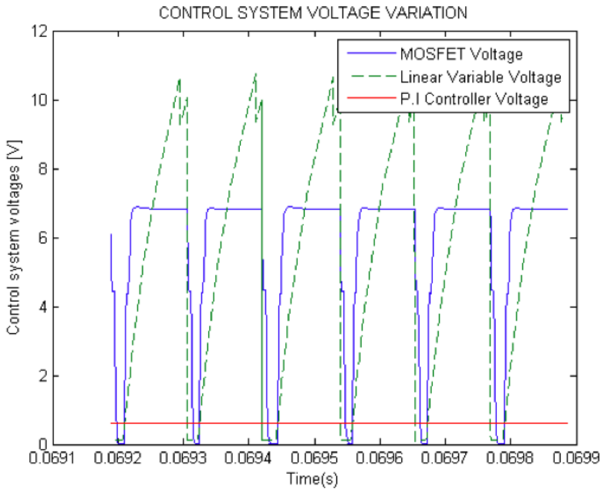
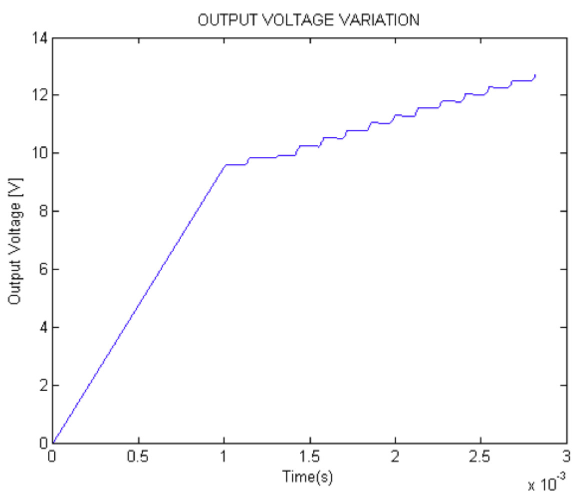
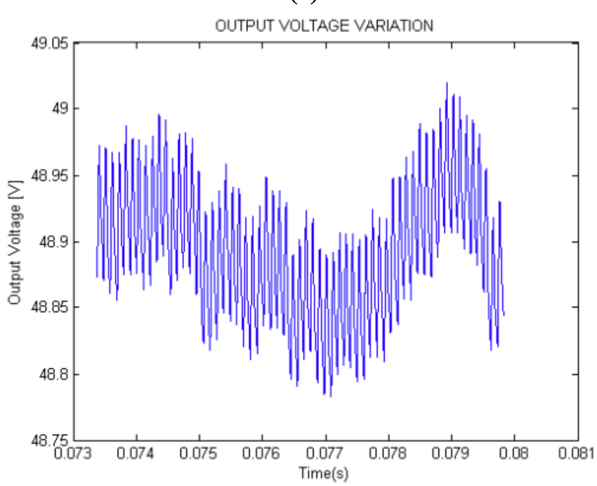


Fig. 11: Control system voltages

B. Result for 27 Ω Resistor Load



(a)



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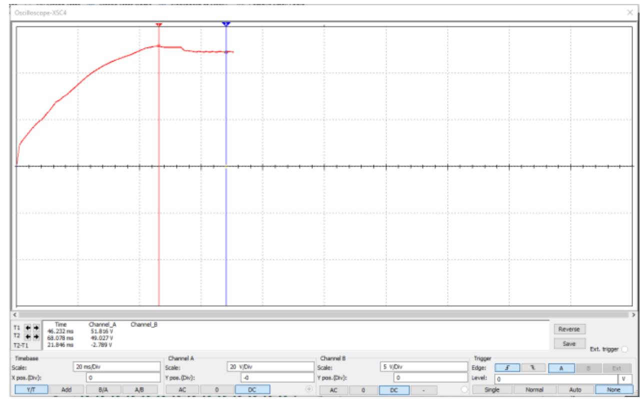
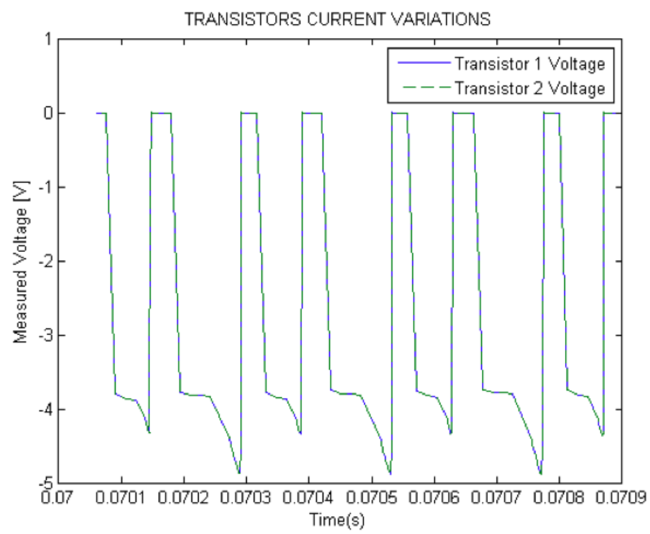
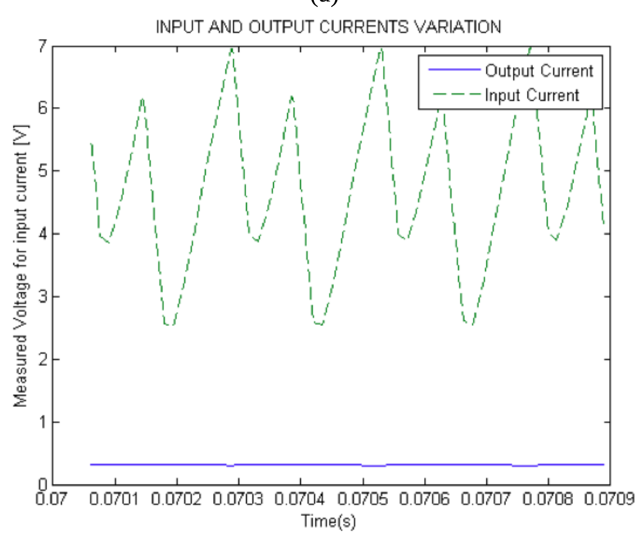


(c)

Fig. 12: (a) Output voltage, (b) Steady state output voltage, (c) Output voltage as shown in Multisim's oscilloscope



(a)



(b)

Fig. 13: (a) Transistors output currents, (b) Input current and output current

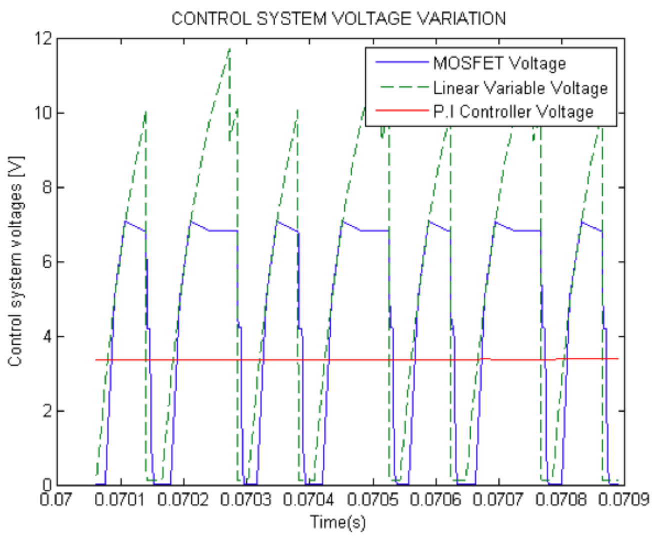
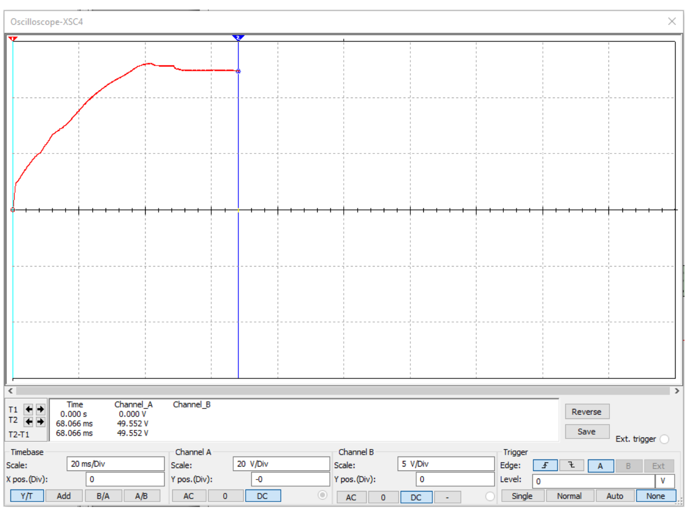
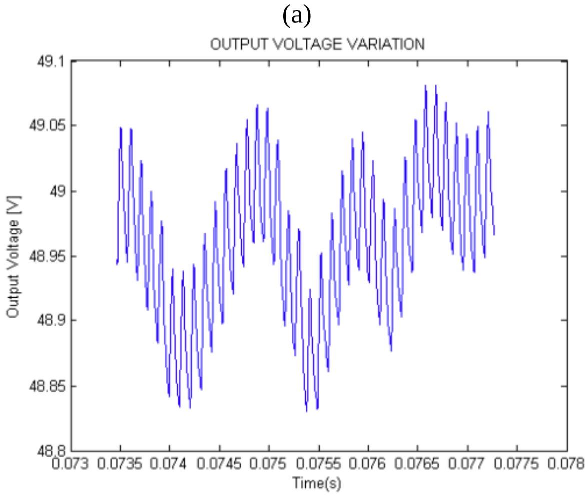


Fig. 14 : Control system voltages

C. *Result for 35 Ω Resistor Load*

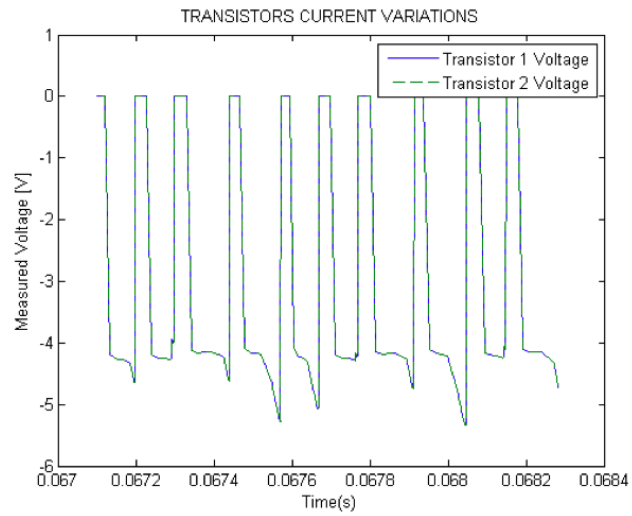


(a)

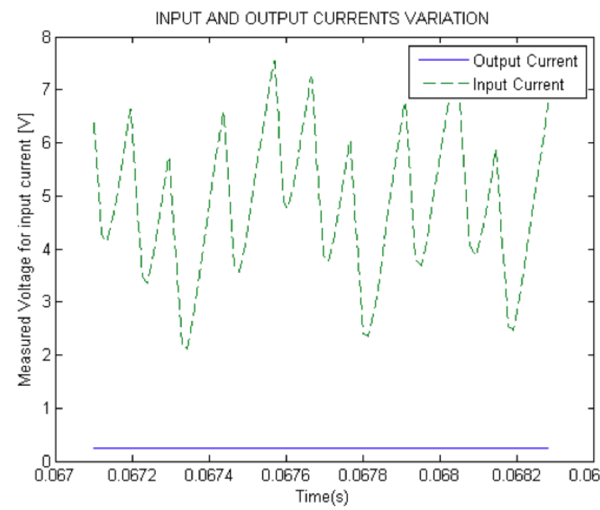


(b)

Fig.15 : (a) Output voltage, and (b) Steady state Output Voltage



(a)



(b)

Fig. 16: (a) Transistors output currents, (b) Input current and output current, and (c) Output voltage as shown in Multisim's oscilloscope

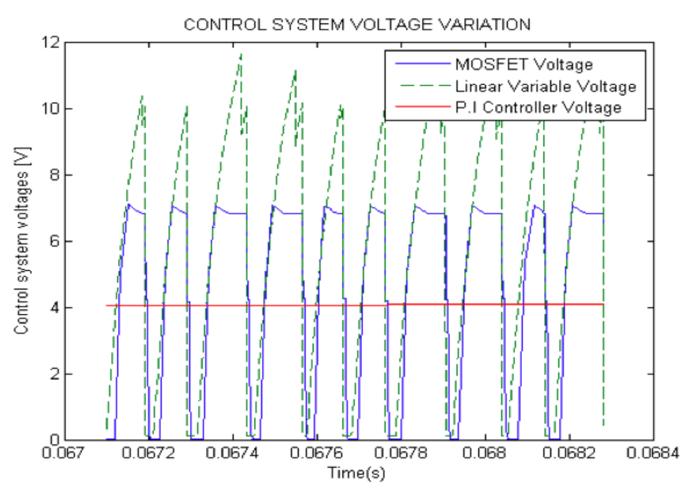


Fig. 17: Control system voltages

A. Boost DC-DC Converter with PID controller: Multisim's Simulation Results:

A. For a load of 3 Ohms:

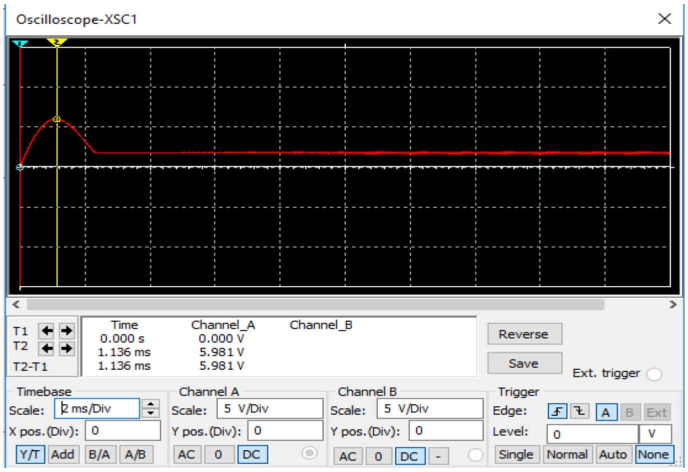


Fig. 18 Input current variation

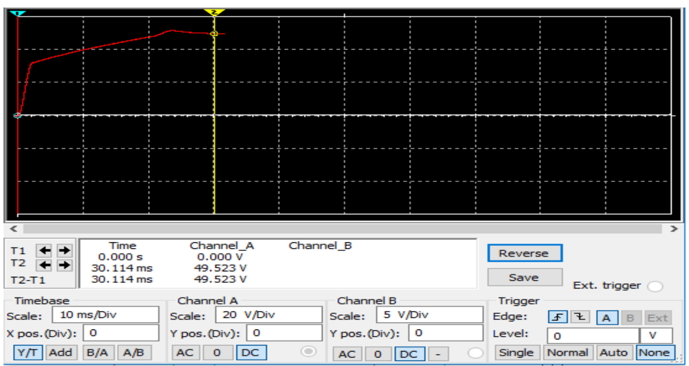


Fig. 19. Output voltage variation

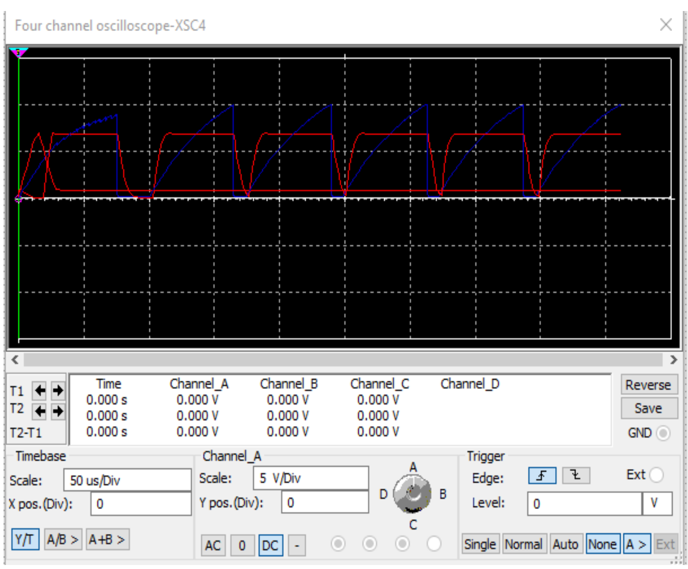


Fig 20. Control system signals

B. Boost DC-DC Converter with and without PID controller: Simulink Simulation

The Output waveform for the output voltage, output Current for the DC to DC Convertor circuit without PID controlled are that the Output voltage and the Output current was found to be Vout=48.6V and Iout=1.38A as shown in fig 21. The Output waveform for the output voltage, output Current for the DC to DC Convertor circuit with PID controlled are that the Output voltage and the Output current was found to be Vout=49.37V Iout=1.38A and the efficiency is 97.76 % as shown in the fig 22. Fig 23 shows the Output waveform for the output voltage, output Current, error and output power with respect to Time (Time scale of 1s).

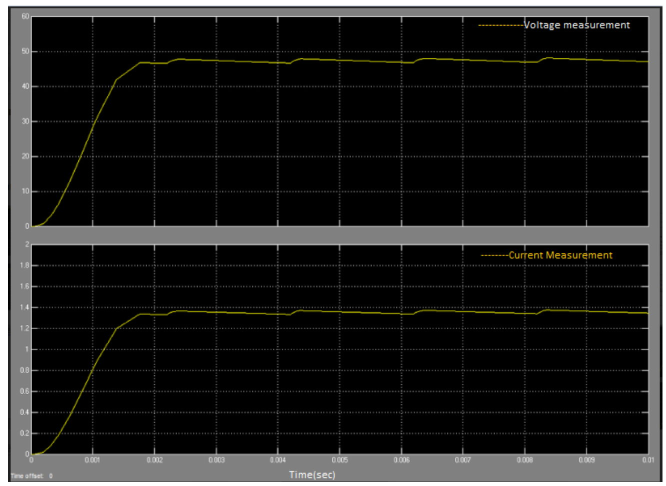


Fig. 21: The Output waveform for the output voltage, output Current Without PID

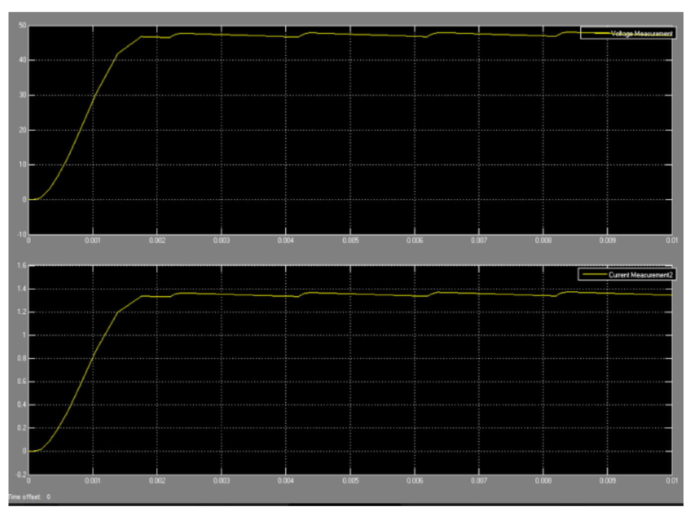


Fig 22: The Output waveform for the output voltage, output Current With PI

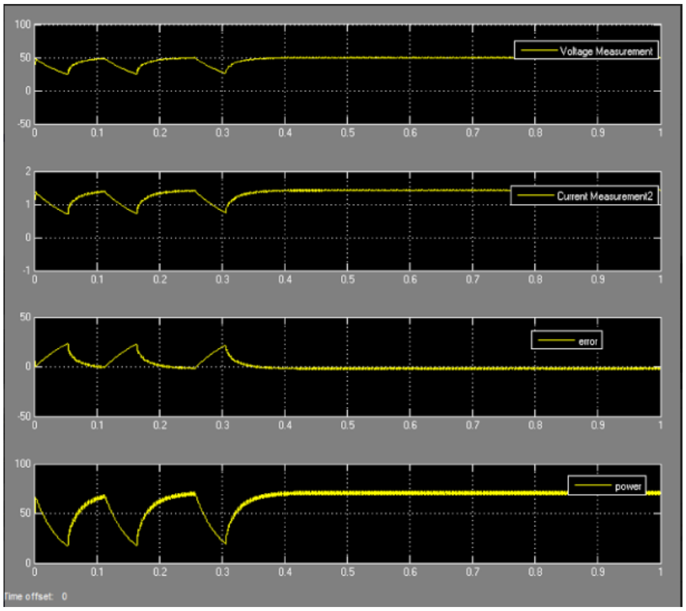


Fig. 23: The Output waveform for the output voltage, output Current, error and output power with respect to Time (Time scale of 1s).

VI. CONCLUSION

The results for the boost dc-dc converter, circuit schematic as shown in fig.4, in Multisim's simulation were very closed to the expected value. The system was analyzed under different load conditions and the results showed that the system reached the steady state faster when the resistor load value was increased. For three the loading conditions' simulation, the output voltages were between 48.74 V and 48.91 V, which were approximately closed to the expected 48 V. For the circuit in fig.5, the system was analyzed for a load of 3 Ohms and the simulation results of the output voltage was 49.5 V after it was stabilized.From the above design of Boost DC-DC Converter with and without PID controller using Simulink Simulation shows that we can control the error by using the PID controller. So the circuit with the PID controller has reliable Output voltage than the one without the PID controller and also the error is minimized in circuit with PID controller when compared to the one without the PID controller.

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