Comparison of PI and PID Controlled Bidirectional DC-DC Converter Systems

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Article Info	ABSTRACT
	This paper deals with comparison of responses of the PI and the PID controlled bidirectional DC-DC converter systems. A coupled inductor is used in the present work to produce high gain. Open loop and closed loop controlled systems with PI and PID controllers are designed and simulated using Matlab tool. The principles of operation and simulation case studies are discussed in detail. The comparison is made in terms of rise time, fall time, peak overshoot and steady state error.

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1.   INTRODUCTION

The The High voltage gain converter is widely used in many applications such as renewable energy sources, hybrid electric vehicles, battery chargers etc., [1-9]. However the voltage gain is limited by various facts such as power switches, inductor and capacitor. The high step up and step down voltage gain can be obtained from isolated converter by tuning the ratio of the transformer [11]. It results in high voltage stress on switches which in turns lead to low efficiency. In non-isolated applications, the non-isolated bidirectional dc–dc converters, such as multilevel type requires twelve switches. For the requirement of high step-up and step-down voltage gains, more number of switches has to be added. This makes the circuit more complicated. In three-level type, the voltage stress on the switches is only half of the conventional type [10]. But, the step-up and step-down voltage gains are low. In SEPIC/zeta type, the conversion efficiency is low because it is a combination of two power stages. The switched capacitor and coupled inductor type can afford high step up and step down voltage gains but their circuit configuration is very complicated [12-20]. A conventional bi-directional converter (BDC) with coupled inductor is shown in Figure 1.
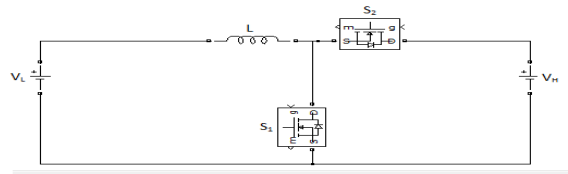
Figure 1. Conventional BDC Boost/Buck Converter

This converter is very simple. But it has the problem of the voltage and current ripples at its input and output. Hence, a large capacitor or inductor filters are required to suppress the ripples. But this result in high loss and low efficiency. Hence in order to overcome this drawback of the conventional converter, a novel bidirectional converter [19-30] is proposed, as shown in Figure 2.
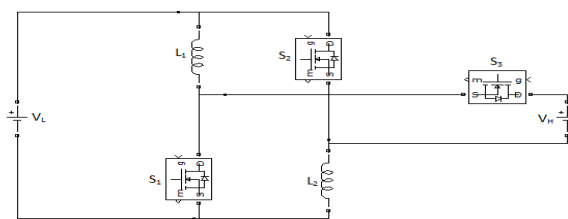

Figure 2. Proposed Bidirectional DC-DC Converter

The Proposed converter consist of two switches namely S1 and S2, a coupled inductor with same winding turns in the primary and secondary. S3 is the synchronous rectifier. The proposed converter provides: 1) Higher step-up and step-down voltage gains and 2) lower average value of the switch current under same electric specifications. The on-state resistance $R_{DS}(ON)$ of the switches and the equivalent series resistances of the coupled inductor and capacitors are ignored; the capacitor is sufficiently large; and the voltages across the capacitor can be treated as constant.

The above literature does not deal with ripple reduction using Pi-filter. This work proposes Pi-filter for ripple reduction. Also the above papers do not deal with the comparison between PI and PID controlled bidirectional DC to DC converter systems. This work tries to identify a suitable controller for closed loop system. This paper is organized as follows: Analysis of Step-up mode is given in section 2. The simulation results in boost mode and buck mode are given in section 3. The work is concluded in section 4.

2.   STEP-UP MODE

The proposed converter in step-up mode is shown in Figure 3. The pulse width modulation (PWM) technique is used to control the switches S_1 and S_2 simultaneously.
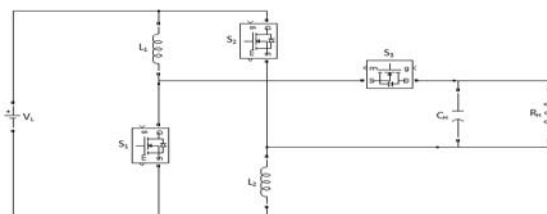

Figure 3. Proposed converter in step-up mode

Thus, the inductance of the coupled inductor can be expressed as

$$L_1 = L_2 = L \tag{1}$$

The mutual inductance M of the coupled inductor is given by

$$M = K\sqrt{(L_1 L_2)} = KL \tag{2}$$

Where *k* is the coupling co-efficient of coupled inductor. Hence the voltage across the primary and secondary winding of the coupled inductor can be expressed as

$$v_{L_1} = L_1 \frac{di_{L_1}}{dt} + M \frac{di_{L_2}}{dt} = L \frac{di_{L_1}}{dt} + kL \frac{di_{L_2}}{dt} \tag{3}$$

$$v_{L_2} = M \frac{di_{L_1}}{dt} + L_2 \frac{di_{L_2}}{dt} = kL \frac{di_{L_1}}{dt} + L \frac{di_{L_2}}{dt} \tag{4}$$

Mode I: During this mode, Switch S1 and S2 are ON and S3 is in OFF condition, as shown in figure3a.
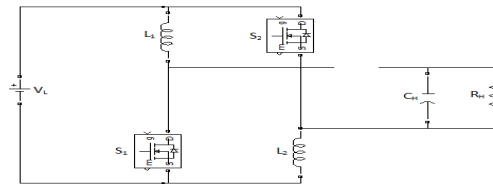
Figure 3a. Proposed Converter in Mode 1

Hence, the low voltage side V_L is transferred to the coupled inductor and the energy stored in the capacitor C_H is discharged to the load. Thus the voltage across L_1 and L_2 are obtained as follows

$$v_{L1} = v_{L2} = V_L \tag{5}$$

Substituting (3) and (4) into (5), yielding

$$\frac{di_{L_1(t)}}{dt} = \frac{di_{L_2(t)}}{dt} = \frac{V_L}{(1+k)L}, t_0 \leq t \leq t_1 \tag{6}$$

Mode II: During this mode, switches S1 and S2 are OFF and S3 is ON condition as shown in Figure 3b.
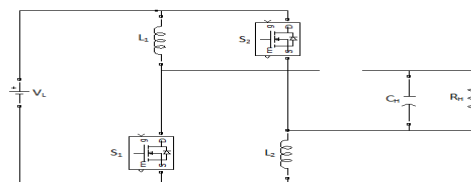

Figure 3b. Proposed Converter in Mode 2

The voltage side V_L and the coupled inductor are in series and their energies are transferred to capacitor C_H and to the load. Thus the voltage and current at this mode are given as follows

$$i_{L1} = i_{L2} \tag{7}$$

$$v_{L1} + v_{L2} = V_L - V_H \tag{8}$$

Substituting (3) and (4) into (8), yielding

$$\frac{di_{L_1(t)}}{dt} = \frac{di_{L_2(t)}}{dt} = \frac{V_L - V_H}{2(1+k)L}, t_1 \leq t \leq t2 \tag{9}$$

By using the state space averaging method, the following equation is derived from (6) and (9)

$$\frac{DV_L}{(1+k)L} + \frac{(1-D)(V_L - V_H)}{2(1+k)L} = 0 \tag{10}$$

Thus the voltage gain during the step up mode is given as

$$G_{CCM(step-up)} = \frac{V_H}{V_L} = \frac{1+D}{1-D} \tag{11}$$

3. SIMULATION RESULTS

The simulation of the bidirectional DC-DC converters was performed for boost mode & buck mode. The results are presented here.

3.1. Boost Mode

The open loop controlled DC-DC converter system is shown in Figure 4a. A step change of 5V is applied at the input as shown in Figure 4b.The change in output voltage is shown in Figure 4c. The output voltage changes by 10V.The load current increases by 1A as shown in Figure 4d. The change in output power is shown in Figure 4e. The power increases from 90W to 170W. The increase in power is due to the increase in the input voltage.
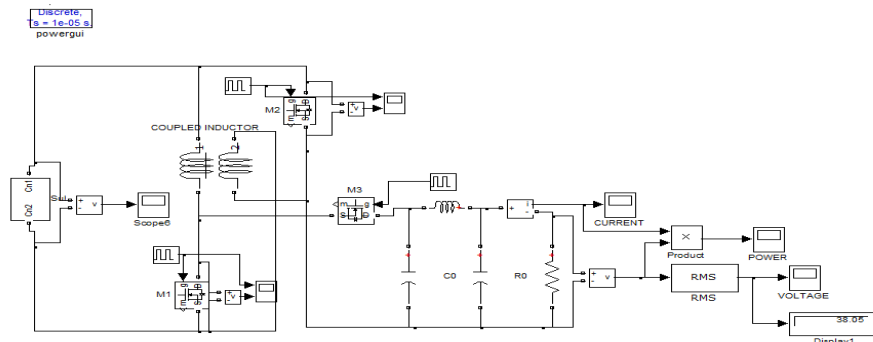

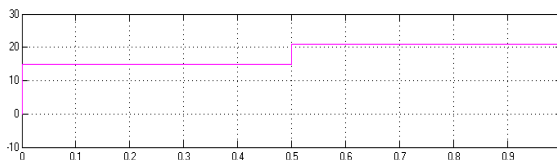
Figure 4a. Circuit Diagram for the Boost Mode
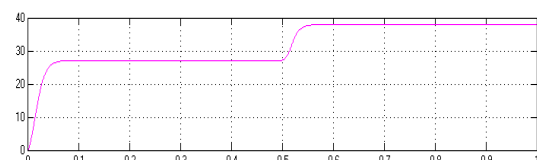

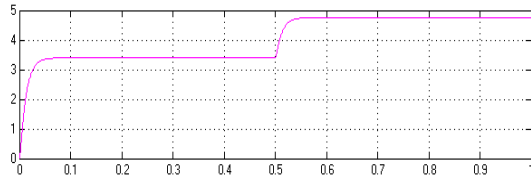Figure 4b. Input Voltage

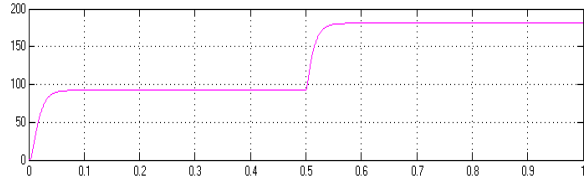Figure 4c. Output Voltage

Figure 4d. Output Current

Figure 4e. Output Power

Closed loop PI controlled system is shown in Figure 5a. Output voltage is sensed and it is compared with the reference voltage to obtain the error.The error is applied to a PI controller.The output of PI controller is compared with time base voltage to produce updated pulses.
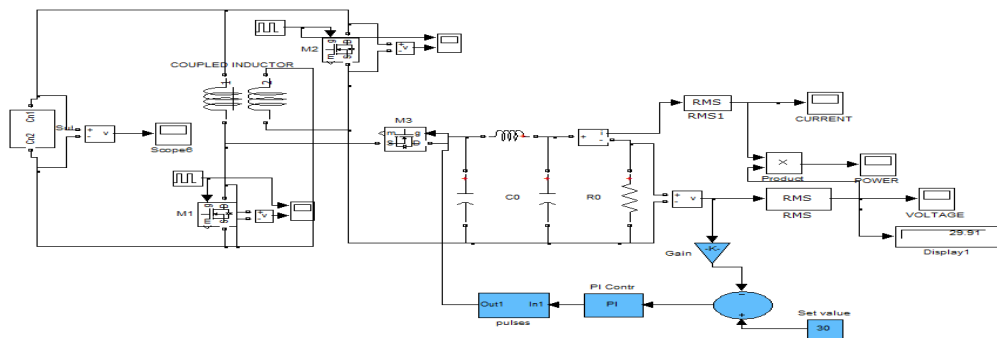

Figure 5a. Circuit Diagram for the Closed loop PI Controller in the Boost Mode

Voltage control is used to maintain a value of 30V at the output. The variation of input voltage is shown in Figure 5b.The input voltage increases from 15V to 22V.The output voltage, current and power are shown in figures 5c, 5d & 5e respectively. The output voltage gets corrected and comes back to the normal value.
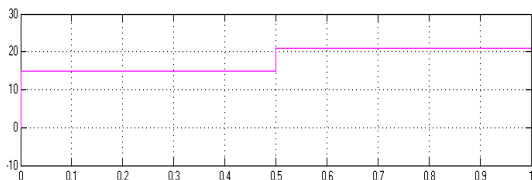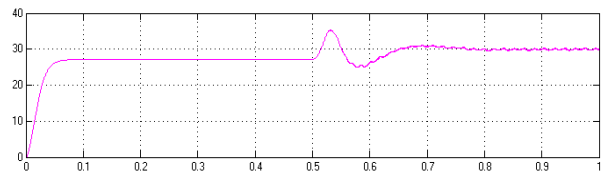

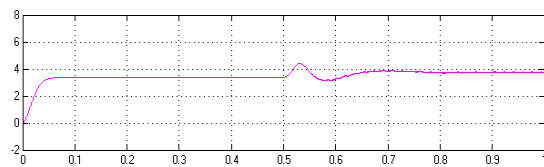Figure 5b. Input Voltage

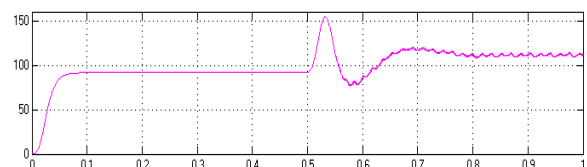

Figure 5c. Output Voltage

Figure 5d. Output Current

Figure 5e. Output Power

The PI controller is replaced by PID controller.The closed loop PID controlled DC to DC converter operating in boost mode is shown in Figure 6a.The variation of input voltage is shown in Figure 6b.The curves of output voltage, output current and output power are shown in figures 6c, 6d & 6e respectively. The output gets settled quickly with reduced overshoot as compared with PI controlled system.
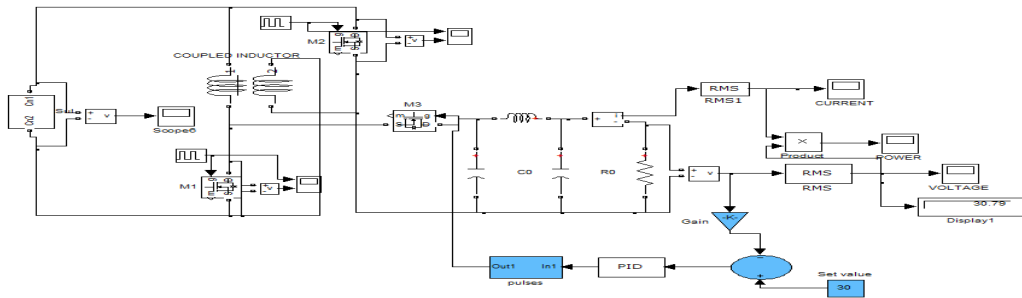
Figure 6a. Circuit Diagram for the Closed loop PID Controller in the Boost Mode
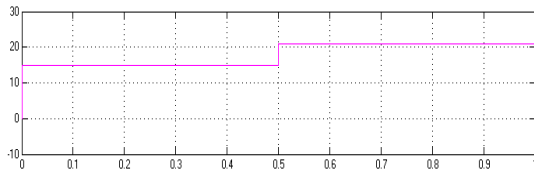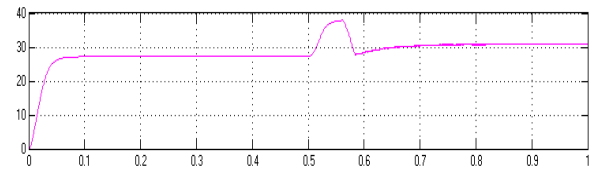

Figure 6b. Input Voltage

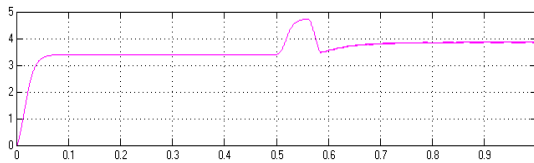Figure 6c. Output Voltage

Figure 6d. Output Current

Figure 6e. Output Power

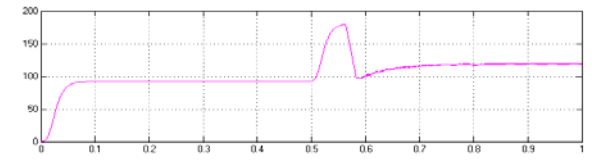## 3.2. Buck Mode

The open loop controlled DC-DC converter operating in buck mode is shown in Figure 7a. The variation of input voltage, output voltage, output current and output power are shown in figures 7b, 7c, 7d & 7e respectively. The output voltage increases by 5V.The power increases by 20W.
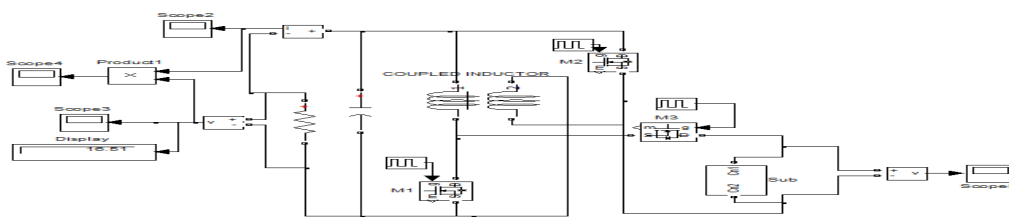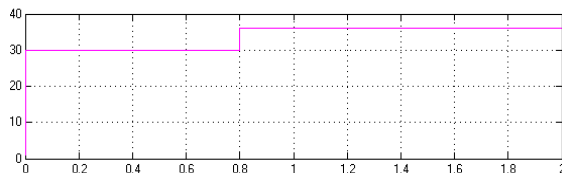

Figure 7a. Circuit Diagram for the Buck Mode
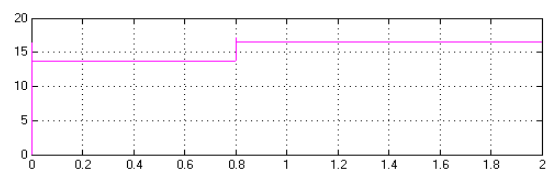

Figure 7b. Input Voltage
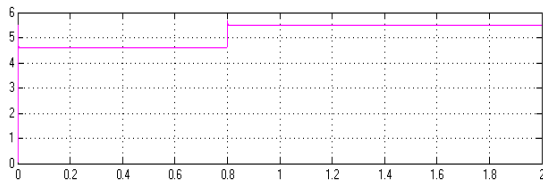

Figure 7c. Output Voltage

Figure 7d. Output Current
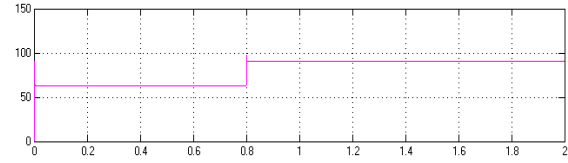
Figure 7e. Output Power

The closed loop PI controlled DC to DC converter system is shown in Figure 8a. The variation in input voltage is shown in Figure 8b.The input voltage increases from 30V to 37V.The output voltage in buck mode is shown in Figure 8c. The output voltage is 15V.Output current and output power are shown in figures 8d & 8e respectively. The current is 3.5A and the output power is 48W.

Figure 8a. Circuit Diagram for the Closed loop PI Controller in the Buck Mode

Figure 8b. Input Voltage

Figure 8c. Output Voltage

Figure 8d. Output Current

Figure 8e. Output Power

The closed loop PID controlled DC to DC converter is shown in Figure.9a. The input voltage increases from 30V to 36V as shown in Figure.9b.The curves of output voltage, output current and output power are shown in figures 9c, 9d & 9e respectively. The output reaches the required value due to the closed loop control action.
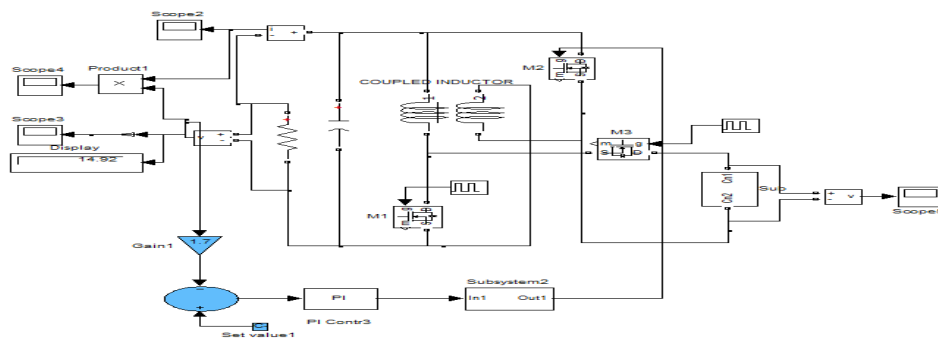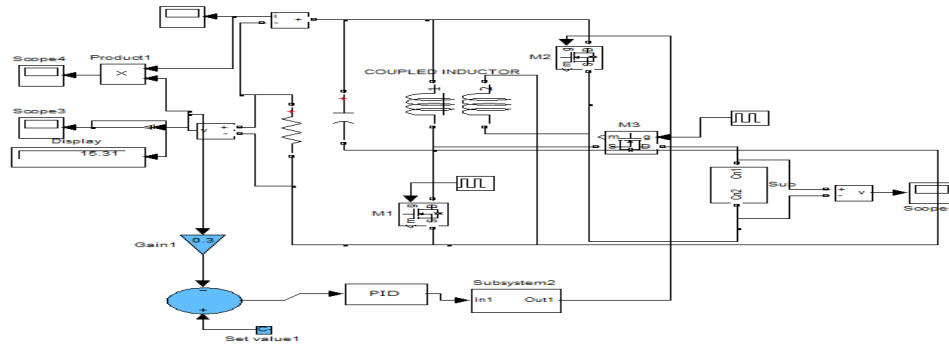
Figure 9a. Circuit Diagram for the Closed loop PID Controlled system in Buck Mode
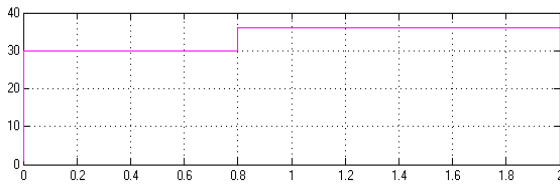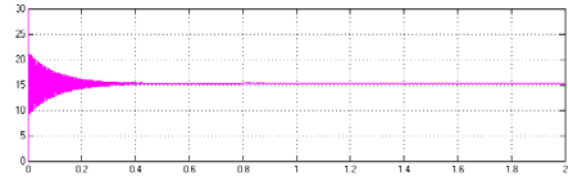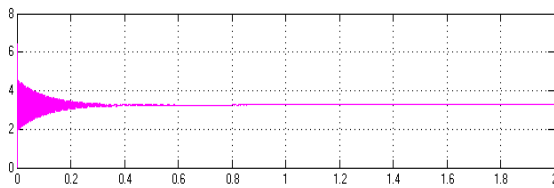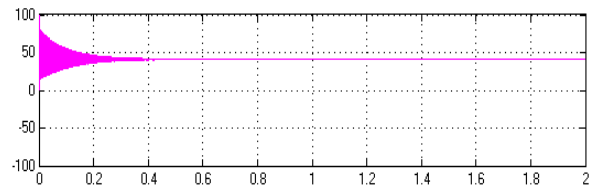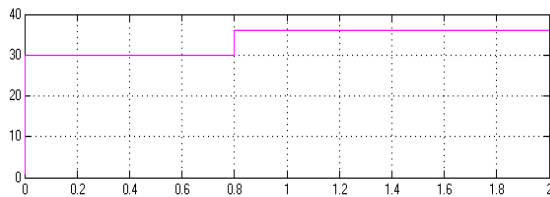

Figure 9b. Input Voltage
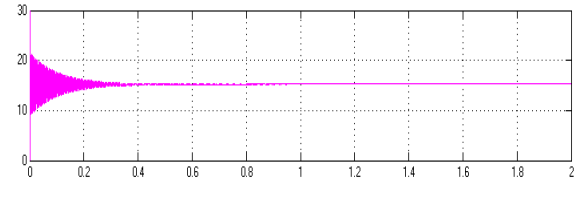
Figure 9c. Output Voltage
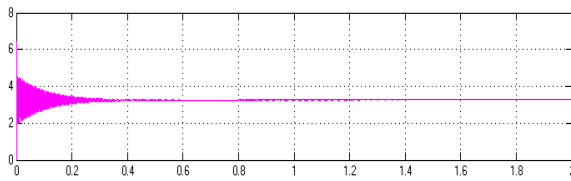
Figure 9d. Output Current
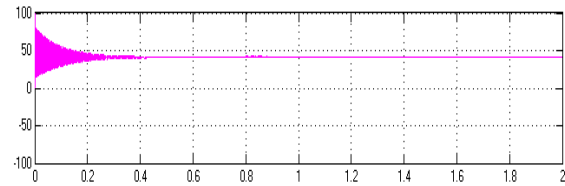
Figure 9e. Output Power

The summary of boost mode and buck mode are given in Table 1 & 2 respectively.

Table 1. Summary of Boost Mode

Boost Mode	Rise Time, Tr (Secs)	Settling Time, Ts (Secs)	Peak Time, Tp (Secs)	Steady State Error, Ess (Volts)
PI Controller	0.050	0.81	0.53	0.8
PID Controller	0.045	0.6	0.51	0.5

Table 2. Summary of Buck Mode

Buck Mode	Rise Time, Tr (Secs)	Settling Time, Ts (Secs)	Peak Time, Tp (Secs)	Steady State Error, Ess (Volts)
PI Controller	0.08	1.21	0.83	0.92
PID Controller	0.06	1.12	0.63	0.71

It can be seen that the rise time, the settling time, the peak time and the steady state error are reduced by using the PID controller.

4. CONCLUSION

Closed loop controlled bidirectional DC-DC converter operating in boost mode and buck mode are designed and simulated successfully. Closed loop system is simulated with PI and PID controllers.The converter has bidirectional ability and high voltage gain. From the results, it was observed that the response was better with PID controller than PI controller since PID controlled system produces reduced settling time and steady state error.The contribution of this work is to reduce the ripple using Pi-filter and improve

dynamic response using PID controller. The scope of the present work is the simulation with PI and PID controllers. The fuzzy logic based converter will be simulated in future. The comparison will be made between PID and fuzzy based converter systems.

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