Analysis, Design and Simulation of Bidirectional DC- DC Converter

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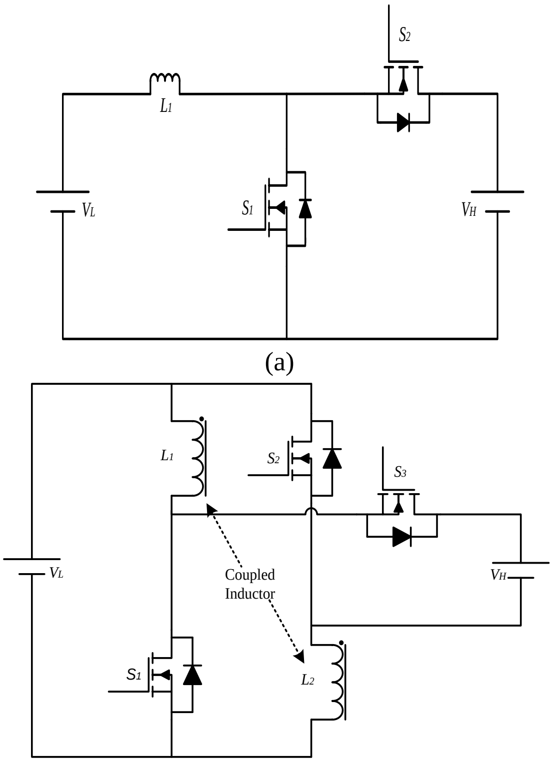
Abstact **- A bidirectional DC-DC Converter by using proportional integral controller is designed and simulated in this paper. The proposed converter employs a coupled inductor with same winding turns in primary and secondary sides. In step-up mode, to achieve high step-up voltage gain, the primary and secondary windings of the coupled inductor are charged in parallel and discharged in series. In step-down mode, to achieve high step-down voltage gain, the primary and secondary windings of the coupled inductor are charged in series and discharged in parallel. The structure of the proposed converter is very simple. Thus, the proposed converter has higher step-up and step-down voltage gains than the conventional bidirectional boost/buck converter. The operating principle and efficiency analysis are discussed in detail. Finally, a 14/42-V circuit in closed loop mode is designed and simulated to verify the performance for the automobile battery system.**

Keywords:Bidirectional dc-dc converter, Proportional Integral Controller, coupled inductor.

1.INTRODUCTION

A Bidirectional dc-dc converter allows the transfer of power between two dc sources in either direction. These bidirectional dc-dc converters are increasingly needed in applications, such as hybrid electric vehicle energy systems, dc uninterrupted power supplies, fuel cell hybrid power systems, photovoltaic hybrid power systems and battery chargers. The bidirectional dc-dc flyback converters, a very simple structure, but the active switch suffer a high voltage stresses due to the leakage inductance of the transformer. The switched capacitor can provide high step-up and step-down gains, but the circuit configurations is complex and have a higher cost. The coupled inductor type converters can provide solutions to achieve high step-up and step-down voltage gains but its circuit configuration in more complicated. The multilevel type is a magnetic less converter which requires more switches to achieve high step-up and step-down voltage gains. The circuit becomes more complicated. The conversion efficiency will be decreased since the sepic/zeta type is combined of two power stages.

The conventional bidirectional dc-dc boost/buck converter which is simple in structure and easy to control is shown in Fig.1(a).However, the step-up and step-down voltage gains of the conventional bidirectional dc-dc converter are low due the effect of power switches. To achieve the high step-up and step-down voltage gains, a novel bidirectional dc-dc converter is proposed as shown in Fig.1(b).



(a)

(b)

Fig.1. Bidirectional DC-DC Converters (a) Conventional Converter, (b) Proposed Converter.

The proposed bidirectional dc-dc converter employs a coupled inductor with same windings turns in the primary and secondary sides. The proposed converter has the following advantages when compared to conventional bidirectional dc-dc converter,1)Higher step-up and step-down voltage gain and 2)lower average value of the switch current under same electric specifications. The operating principles and steady-state analysis for step-up and step-down will be described in the following sections. To analyze the steady-state characteristics, the following conditions are to be assumed.1) The equivalent series resistances of the coupled inductor and capacitors, the ON-state resistance *RDS(ON)* of the switches are ignored-and 2) the capacitor is sufficiently large and the voltage across the capacitor can be treated as constant.

2. OPERATION

2.1. Step-up Mode

The proposed converter in step-up mode, the primary and secondary windings of the coupled inductor are operated in parallel charge and series discharge. The proposed converter in step-up mode in shown in Fig.2(a). The pulse width modulation technique is used to control the switches.

The voltages across the coupled inductor can be expressed as follows

$$v_{L1} = L_1\frac{di_{L1}}{dt} + M\frac{di_{L2}}{dt} = L\frac{di_{L1}}{dt} + kL\frac{di_{L2}}{dt} \qquad (1)$$

$$v_{L2} = M\frac{di_{L1}}{dt} + L_2\frac{di_{L2}}{dt} = kL\frac{di_{L1}}{dt} + L\frac{di_{L2}}{dt} \qquad (2)$$

Mode 1: The Fig.2(b). Shows the current flow path of the proposed converter in step-up mode, *Mode 1* operation. During this mode, the switches S_1 and S_2 are turned on and S_3 is turned off. The energy of the low voltage side V_L is transferred to the coupled inductor. The energy stored in capacitor C_H is discharged to the load. The primary and secondary windings of the coupled inductor are in parallel.

Thus voltages across inductors L_1 and L_2 is obtained as

$$v_{L1} = v_{L2} = V_L \qquad (3)$$

Substituting Eq's(1&2) in Eq(3), we get

$$\frac{di_{L1}(t)}{dt} = \frac{di_{L2}(t)}{dt} = \frac{V_L}{(1+k)L}, \quad t_0 \le t \le t_1 \qquad (4)$$

Mode 2: During this mode of operation, the switch S_1 and S_2 are turned off and switch S_3 of the proposed converter is turned on. The Fig.2(c). Shows the current flow path of the proposed converter in step-up mode, *Mode 2* operation. The low-voltage side V_L and the coupled inductor are in series; their energies are transferred to the capacitor C_H and the load. The primary and secondary windings of the coupled inductor are in series. Thus the inductor currents through the primary and secondary windings of the coupled inductor and the voltages across the inductor L_1 and L_2 are obtained as follows

$$i_{L1} = i_{L2} \qquad (5)$$

$$v_{L1} + v_{L2} = V_L - V_H \qquad (6)$$

Substituting Eq's(1,2 and 5) in Eq(6), we get

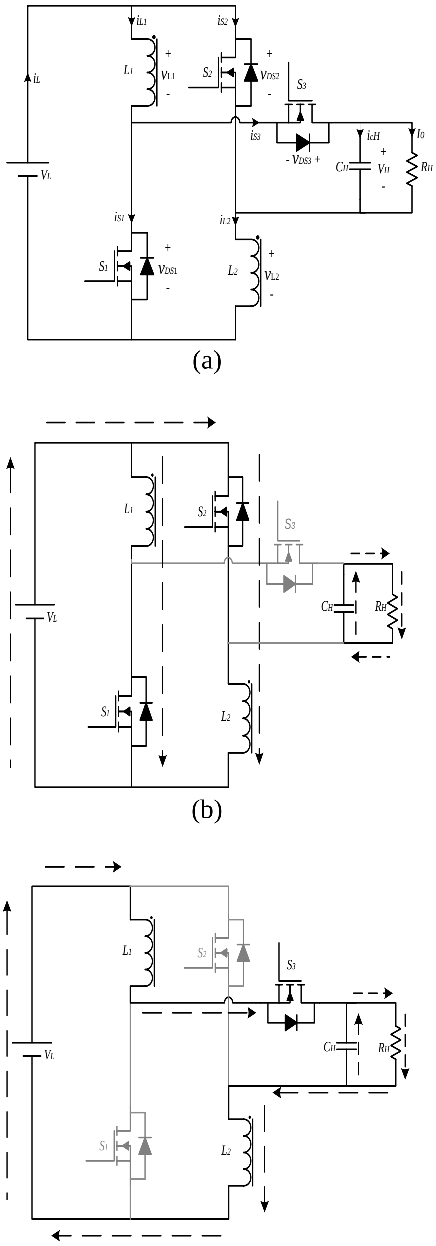
$$\frac{di_{L1}(t)}{dt} = \frac{di_{L2}(t)}{dt} = \frac{V_L - V_H}{2(1+k)L}, \; t_1 \le t \le t_2 \qquad (7)$$

By using the state-space averaging method, the following equation is derived from Eq(4) and Eq(7)

$$\frac{DV_L}{(1+k)L} + \frac{(1-D)(V_L - V_H)}{2(1+k)L} = 0 \qquad (8)$$

Simplifying (8), the voltage gain is given as

$$G_{(step-up)} = \frac{V_H}{V_L} = \frac{1+D}{1-D} \qquad (9)$$



(a)

(b)

(c)

Fig.2. (a) Proposed Converter in step-up mode, Current flow paths of the proposed converter (b) Mode1, (c) Mode2.

2.2.Step-down Mode

The proposed converter in step-down mode, the primary and secondary windings of the coupled are operated in series charge and parallel discharge. The proposed converter in step-down mode is shown in Fig.3(a). The Pulse width modulation technique is used to control the switch S_3 Meanwhile; the switches S_1 and S_2 are the synchronous rectifiers.

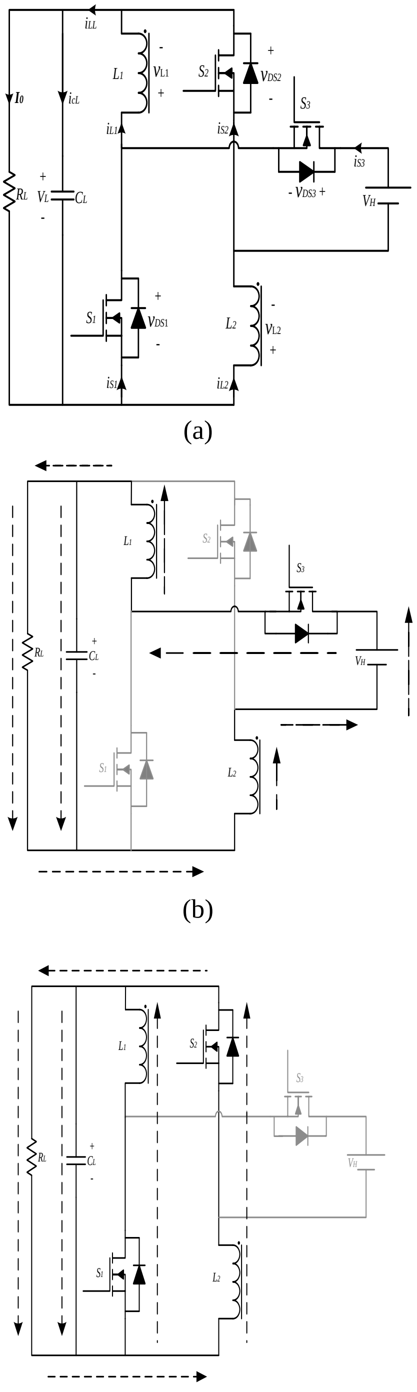
Mode 1: During this mode of operation, the switches S_1 and S_2 are turned off and switch S_3 is turned on. Fig.3(b). shows the current flow path of the proposed converter in step-down *Mode 1* operation. The energy is transferred from high-voltage side V_H to the coupled inductor, to the capacitor C_L and to the load R_L. The current flowing through the inductors and the voltages across the primary and secondary windings of the coupled inductor are expressed as follows

$$i_{L1} = i_{L2} \tag{10}$$

$$v_{L1} + v_{L2} = V_H - V_L \tag{11}$$

On substituting Eq's (1),(2) and Eq(10) in Eq(11),we get

$$\frac{di_{L1}(t)}{dt} = \frac{di_{L2}(t)}{dt} = \frac{V_H - V_L}{2(1+k)L}, t_0 \le t \le t_1 \tag{12}$$



(a)

(b)

(c)

Fig.3. (a) Proposed Converter in step-down mode, Current flow paths of the proposed converter (b) Mode1, (c) Mode2.

Mode 2: The current flow path of the proposed converter in step-down *Mode 2* operation is shown in Fig.3(c). During this, mode of operation, switches S_1 and S_2 are turned on and switch S_3 is turned off. Therefore the voltages across the inductors L_1 and L_2 are expressed as

$$v_{L1} = v_{L2} = -V_L \tag{13}$$

On substituting Eq(1),(2) in Eq(13), we get

$$\frac{di_{L1}(t)}{dt} = \frac{di_{L2}(t)}{dt} = -\frac{V_L}{(1+k)L}, t_1 \le t \le t_2 \tag{14}$$

The following equation is obtained from Eq's(12&14), by using the state space averaging method.

$$\frac{D(V_H - V_L)}{2(1+k)L} - \frac{(1-D)V_L}{(1+k)L} = 0 \tag{15}$$

Finally, on simplifying Eq(15), the voltage gain of the proposed converter in step-down mode CCM operation is obtained as

$$G_{(step-down)} = \frac{V_L}{V_H} = \frac{D}{2-D} \tag{16}$$

3.CLOSED LOOP OPERATION OF THE PROPOSED CONVERTER BY USING PROPORTIONAL INTEGRAL CONTROLLER

P-I controller is mainly used to eliminate the steady state error resulting from P controller. However, in terms of the speed of the response and overall stability of the system, it has a negative impact. This controller is mostly used in areas here speed of the system is not an issue. Since P-I controller has no ability to predict the future errors of the system it cannot decrease the rise time and eliminate the oscillations. If applied, any amount of I guarantees set point overshoot.

PI controller forms control signal in the following way:

$$u(t) = K\left[e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau\right] \tag{17}$$

Where: Ti – integral time constant of PI controller

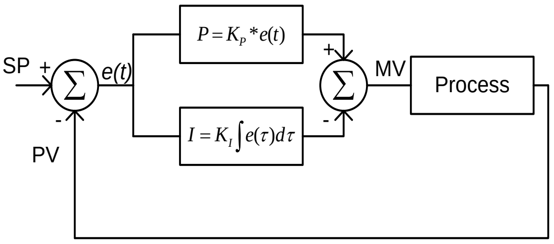


Fig.4.Basic block of a PI controller

The controller output is given by

$$K_p\Delta + K_i\int \Delta dt \tag{18}$$

Where $\Delta(\Delta = SP - PV)$is the error or deviation of actual measured value (PV) from the set point (SP).

3.1.Ziegler-Nichols Method

To tune in the parameters for the PI controller can be a challenge, and if the time constants in the process are huge the time to do the optimization can be too long! But there are some rules of thumb, of which the rule lined out by Ziegler-

Nichols back in 1942 is well known. It can be used for simulations and is probably the most common for use in real life. This method is used for both open and closed loop systems in the concern project a closed loop converter is to be tuned so explaining about the tuning of closed loop converter. The converter control system should be "closed". This statement means that the controller should be in normal operation. This method follows a given procedure. The procedure is as follows:

i. Turn off the I-term and the D-term in the controller. This can be done by setting the reset time (τ_N =tau_N) to "infinite" and the derivative time (τ_V =tau_V) to 0.

ii. Turn K_P =K_P to zero, and the increase it slowly, while you are looking at the controllable variable (y) or - some times better - the output of the controller,u. Increase KP until the output exhibits sustained oscillations.

iii. At this "quasi steady-state" point you have the critical gain, called $K_{P,crit}$=K P crit, and a given period of time, T_{crit}=T_crit.

iv. Then you should turn on the I-term by using the following values, see the table below.

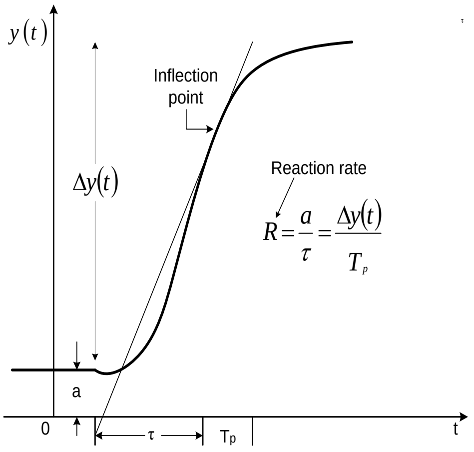


Fig.5.Graph related to Ziegler Nicholas method

If the output does not exhibit sustained oscillations for whatever value K_P may take, then this method does not apply.

4.DESIGN PARAMETERS

Mode of Operation	Step-up	Step-down
Input	14v	42v
Output	42v	14v
Frequency	50KHz	50KHz
Power	200W	200W
Inductance	15.5µH	15.5µH
Capacitance	330 µF	330 µF

Table No.1.Tabular form indicating the Design Parameters of the proposed converter.

5.SIMULINK MODELS AND RESULTS

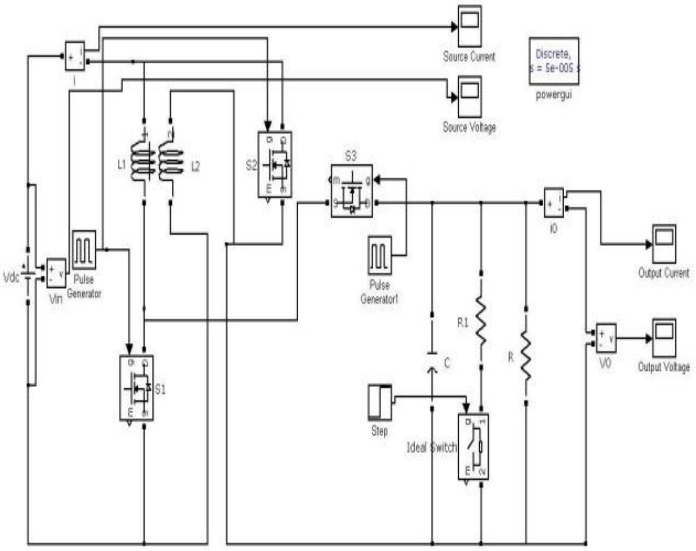


Fig.6.Simulink Model of the Proposed Converter when step change in load from 20W to 200W.

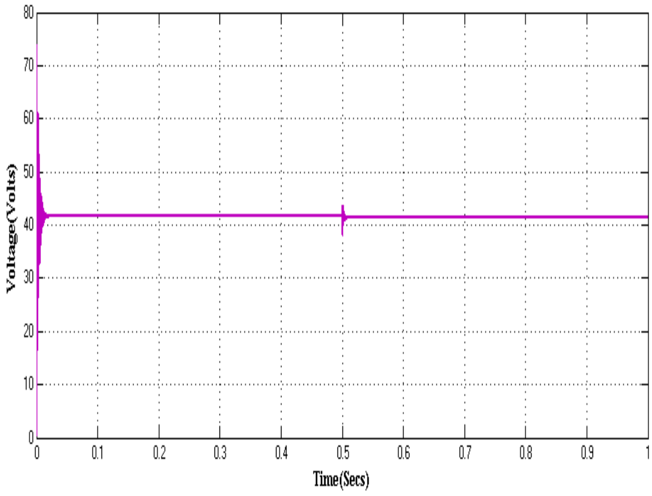


Fig.7.Output Voltage Waveform of the proposed converter when a step change in load from 20W to 200W at t=0.5sec.

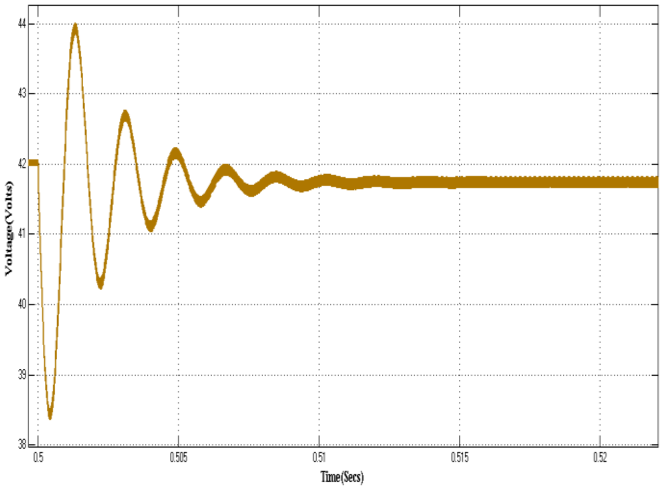


Fig.8.Transient Voltage Deviation (Output Voltage) of the proposed converter when a step change in load from 20W to 200W at t=0.5sec.

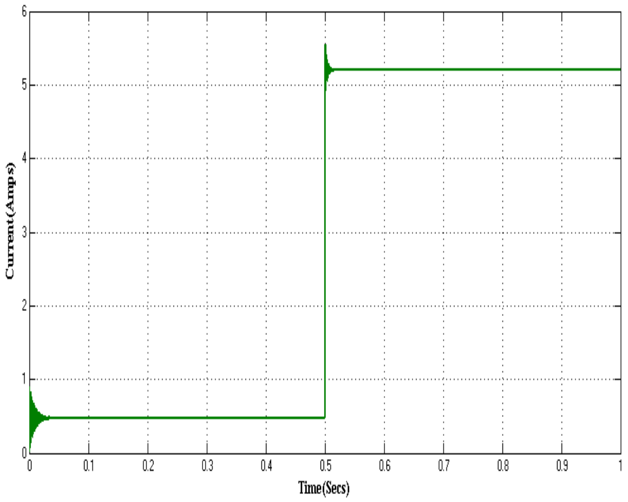


Fig.9.Output Current Waveform of the proposed converter when a step change in load from 20W to 200W at t=0.5sec.

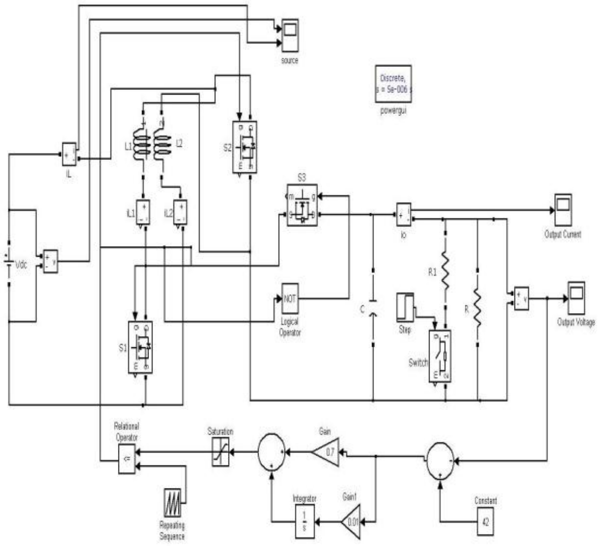


Fig.10.Simulink Model of the Proposed Converter by Using Closed Loop Proportional Integral Controller when a step change in load from 20W to 200W at t=0.5sec.

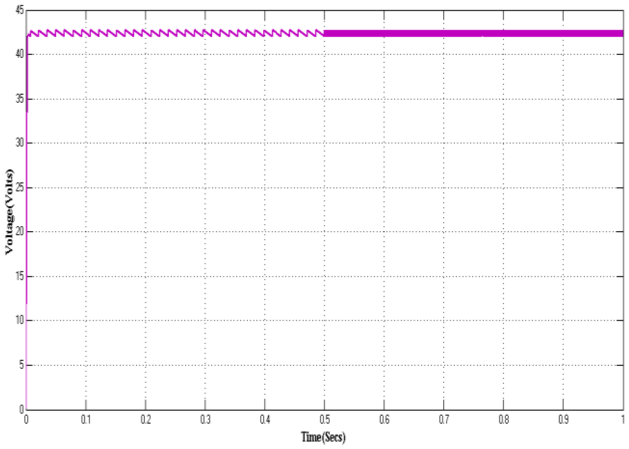


Fig.11.Output Voltage Waveform of the proposed converter by Using Closed Loop P-I Controller when a step change in load from 20W to 200W at t=0.5sec.

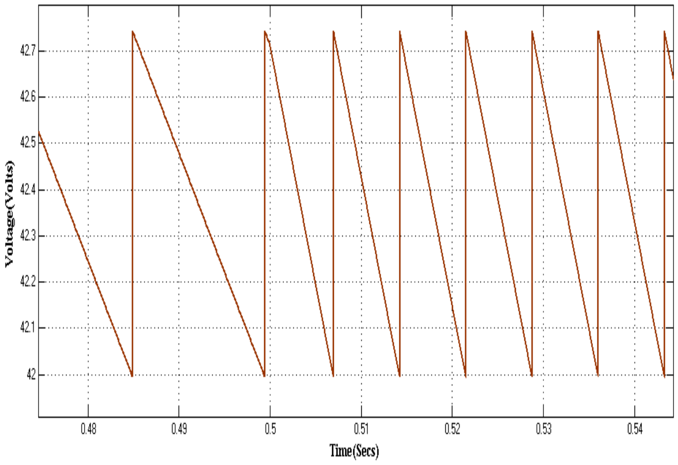


Fig.12.Transient Voltage Deviation Waveform (Output Voltage) of the proposed converter by Using Closed Loop Proportional Integral Controller when a step change in load from 20W to 200W at t=0.5sec.

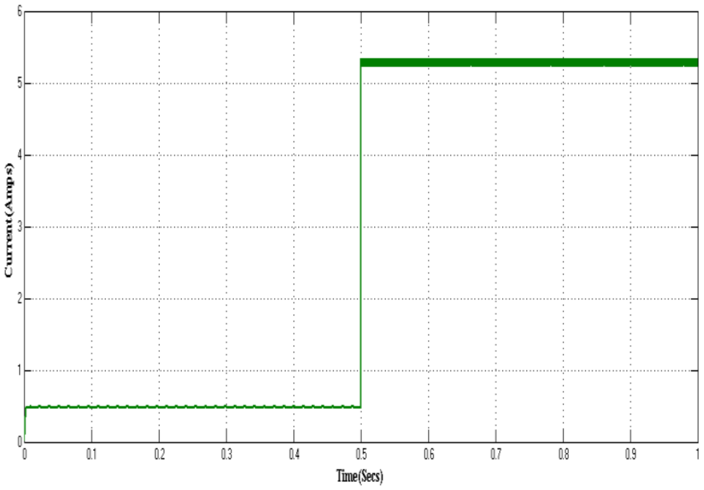
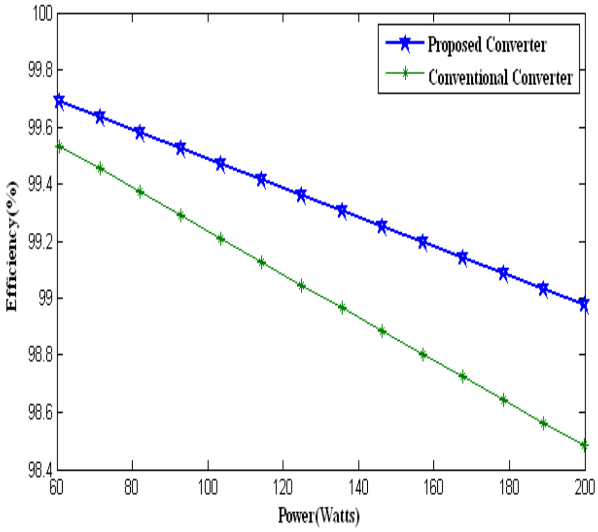
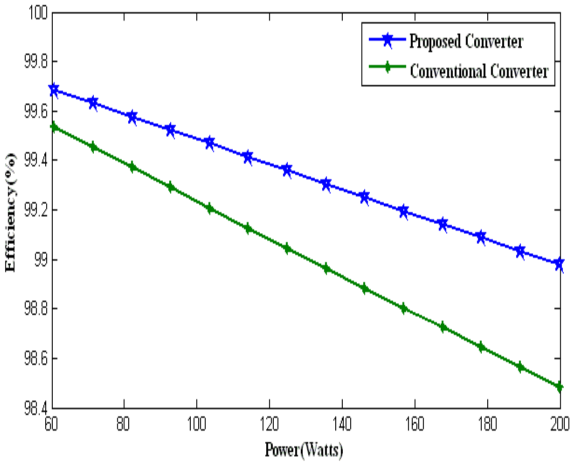


Fig.13.Output Current Waveform of the proposed converter by Using Closed Loop Proportional Integral Controller when a step change in load from 20W to 200W at t=0.5sec.



(a)



(b)

Fig.14.Efficiency Plots of the proposed converter and conventional bidirectional DC-DC converter (a) Step-up (b) Step-down.

6.CONCLUSION

A bidirectional dc-dc converter in Closed Loop Mode by Using Proportional Integral Controller is designed and simulated in this paper. The dynamic performance of the proposed converter by using P-I is better than the open loop performance and also the proposed converter achieves the higher step-up and step-down voltage gains than conventional bidirectional boost/buck converter. The efficiency of the proposed converter in step-up mode is 99.2% and in step-down mode is 88.5% at full load condition, which is higher than the conventional bidirectional boost/buck converter.

7.REFERENCES

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