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A Novel Bidirectional DC-DC Converter with high Step-up and Step-down Voltage Gains

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Abstract:-A bidirectional dc-dc converter with high step-up and step-down voltage gain is handling in this paper. High voltage gains are obtained by employing a coupled inductor with same primary and secondary winding turns in the converter. Beside from high voltage gain, its average value of switch current and voltage stress on switches are lower compared to conventional dc-dc converter. The steady state analysis and operating principles in continuous conduction mode are discussed. Pulse width modulation (PWM) is used to control the switches. To study the performance of the proposed converter, simulations has been carried out in MATLAB2010 environment. Feedback is also given to the circuit using a pi controller and relational operator to get a constant output voltage for such applications.

Keywords:-Bidirectional dc-dc converter, coupled inductor, PWM.

I. INTRODUCTION

A DC-DC converter is an electronic circuit which converts a source of direct current from one voltage level to another. It is a class of power converter[11]. Bidirectional DC-DC converters has the ability to direct the current flow in both direction and thereby power. It is increasingly used to transfer power in either direction between the dc sources. These converters has become an option in applications including hybrid vehicle energy system [1]-[3], fuel cell vehicles [9], battery chargers [13] etc.

Most of the existing dc-dc converters can be categorized based on placement of energy storage as buck and boost types. In buck type, it is on high voltage side energy storage is placed and in boost type, it is on low voltage side. For isolated bidirectional dc-dc converters, sub topology is full bridge, a half bridge, a push pull circuit or their variations [9], [20]. In these converters, for operation it utilizes the leakage inductance of transformer as the main element. The half bridge types will have a higher efficiency and will reduce the device count. The full bridge types is one of the choices. But the configuration is complex and large in size and cost is high. Conventional boost/buck [1], multilevel [4], three level, sepic/zeta, switched capacitor and coupled inductor types are there in non-isolated dc-dc converters. Transformer based system is attractive, but its weight or size is a concern in the case of space craft power system applications. So transformer less is more used in high power applications. To increase the density of power, multiphase current interleaving technology with low inductance is used in high power applications. It is having better efficiency. In a three phase dc-dc converters, ripple on total current is small and low value of capacitance is used in both high and low voltage sides. Electronic switch mode dc-dc converter will convert one voltage dc level to another. The half bridge and fly back topologies are similar. Both stored energy in the magnetic core needs to be dissipated. Switched capacitor types used at high voltages applications. It will provide high step-up and step-down voltage gains as coupled inductor types.

The conventional bidirectional dc-dc converter is easy to control and its structure is very simple[1]. But it provides low voltage gains in both step-up and step-down modes. A bidirectional dc-dc converter with coupled inductor is introduced in this paper. This converter can provide a high voltage gain than the conventional dc-dc converter. Besides from high voltage gains, its average value of switch current is low and voltage stress on switches is also low. Here some assumptions are made such as ON state resistance of the switches are ignored; equivalent series resistances of the coupled inductor is ignored; capacitor value is large and capacitor voltage is a constant.

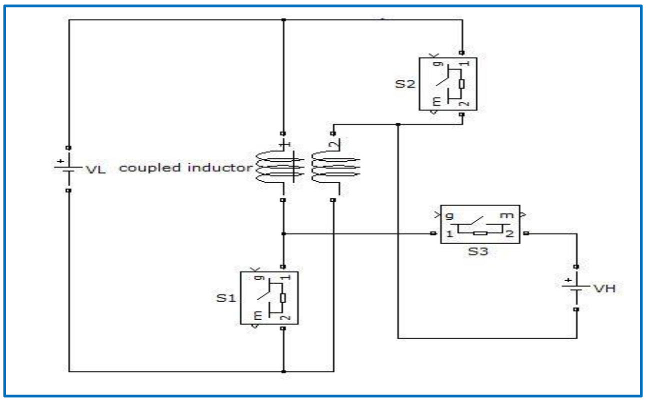


Fig.1 Proposed bidirectional dc-dc converter

II. COUPLED INDUCTOR

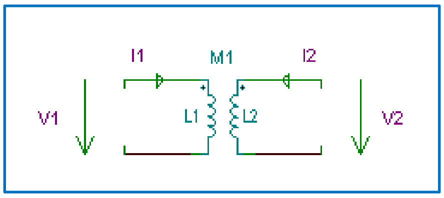


Fig. 2 Coupled inductor

Two inductors or coils that are linked by electromagnetic induction are said to be coupled inductors. The phenomenon of one inductor inducing a voltage in another inductor is mutual inductance. Circuits which contain coupled inductor are more complicated because the voltage of the coils are expressed in terms of their current. Three parameters are required to characterize a pair of coupled inductor: two self-inductances, L_1 and L_2 and the mutual inductance, M. Since the coupled inductor has same turns in the primary and secondary windings, the inductance in the primary and secondary will be same and can be expressed as

$L_1 = L_2 = L$. (1)

Thus, M the mutual inductance of the coupled inductor is

M=KL. (2)

Where K, is the coupling coefficient of the coupled inductor. Coupling coefficient, K is typically around 0.95.The voltage across primary and secondary windings of the coupled inductor are

$$V_{L1} = L_2\frac{di_{L1}}{dt} + M\frac{di_{L2}}{dt} = L\frac{di_{L1}}{dt} + KL\frac{di_{L2}}{dt}. \quad (3)$$

$$V_{L2} = L_2\frac{di_{L2}}{dt} + M\frac{di_{L1}}{dt} = L\frac{di_{L2}}{dt} + KL\frac{di_{L1}}{dt}. \quad (4)$$

III. STEP – UP MODE

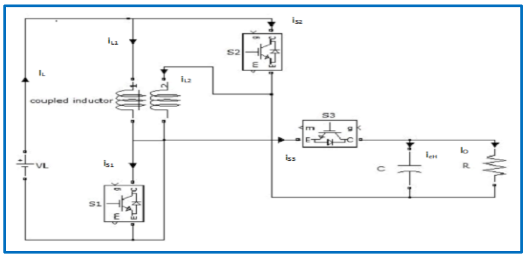


Fig. 3.1 Proposed converter in step-up mode.

The proposed converter in step-up mode[1] is shown in Fig.3.1.The pulse width modulation (PWM)technique is used to control the switches S1, S2 and S3. The operating principles and steady state analysis of continuous conduction mode is described as follows.

1) Mode 1:During this time interval (DTs), switches S_1 and S_2 are turned ON and switch S_3 is turned OFF. The current flow path is shown in Fig. 3.2(a). The energy in the low voltage side V_L is transferred to the primary and secondary windings of the coupled inductor. That time the primary and secondary windings are in parallel. The stored energy in the capacitor is transferred to the load. The voltage across L_1 and L_2 are same since they are in parallel.

$V_{L1} = V_{L2} = V_L$. (5)

Substituting (3) and (4) into (5) we get,

$\frac{di_{L1}}{dt} = \frac{di_{L2}}{dt} = \frac{V_L}{(1+K)L}$, For the periodDTs . (6)

2) Mode 2:During this time interval (1-DTs), S_1 and S_2 are turned OFF and S_3 is turned ON. The current flow path is shown in Fig. 3.2(b). The low voltage side V_L and the coupled inductor are in series .They will transfer their energies to the capacitors C_H and the load. The primary and secondary windings of the coupled inductor are in series. So the current through the primary and secondary will be same.

$I_{L1} = I_{L2}$ (7)

$V_{L1} + V_{L2} = V_L - V_H$. (8)

Substituting (3), (4), and (7) into (8), get

$\frac{di_{L1}}{dt} = \frac{di_{L2}}{dt} = \frac{V_L - V_H}{2(1+K)L}$. for the period (1-D) Ts. (9)

From (6) and (9):

$$\frac{DV_L}{(1+K)L} + \frac{(1-D)(V_L - V_H)}{2(1+K)L} = 0 . \quad (10)$$

Simplifying (10), the voltage gain is

$$\text{GCCM(step-up)} = \frac{V_H}{V_L} = \frac{1+D}{1-D} . \quad (11)$$

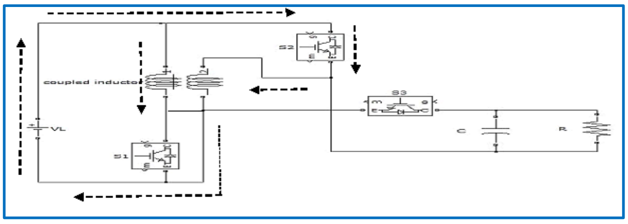


Fig. 3.2(a) current flow path in mode 1.

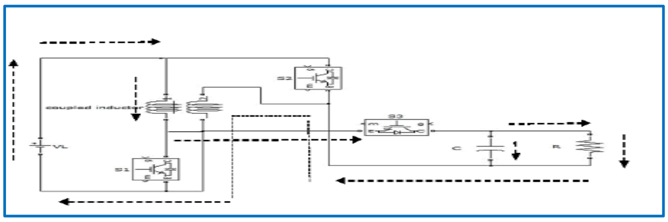


Fig. 3.2(b) current flow path in mode 2.

a) SIMULINK Model

Simulation has been carried out to study the performance of a proposed bidirectional dc-dc converter. A low voltage of 14v is given as input voltage. Three switches S_1, S_2 and S_3 are controlled by PWM technique. Fig. 3.6 shows the gate signals for the switches. The voltage and current waveform across the resistive load is simulated for an input voltage of 14v, R = 200Ω, C = 2mF. With a resistive load the output voltage and current are pulsating. We get an output voltage of 60.56v. Total harmonic distortion is also measured as 9.748 value. The voltage across the switches, current through the switches and a coupled inductor are also simulated.

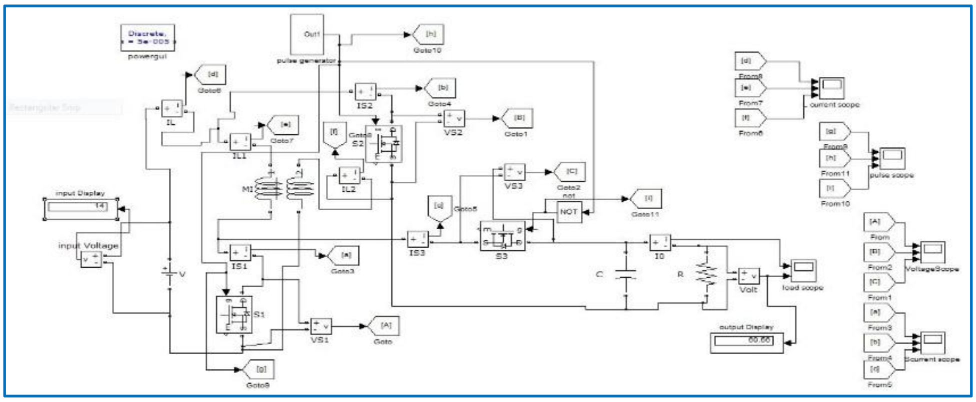


Fig. 3.3 SIMULINK Model.

b) SIMULATION results

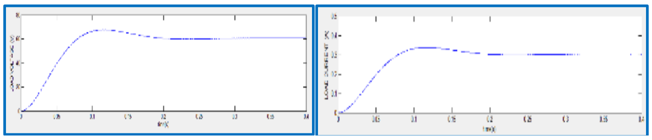
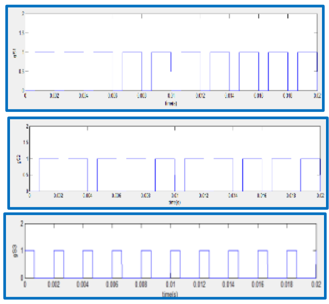


Fig. 3.5 Output current and voltage waveforms.



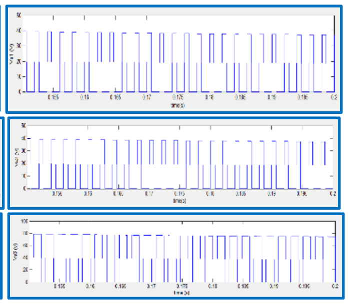
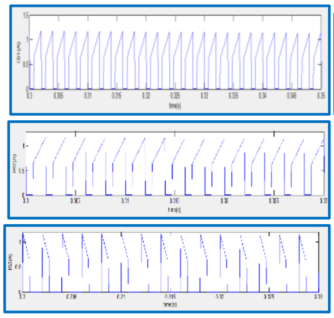


Fig. 3.6 Pulses given to switches. Fig. 3.7 Voltage across the switches



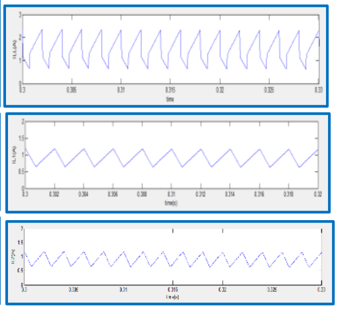


Fig. 3.8 Current through switches. Fig. 3.9 Input current and current through inductors.

c) SIMULINK Model With Feedback

With a resistive load the output voltage will be pulsating. For a constant voltage application, the voltage is to be constant. To achieve this a feedback circuit is given to the Simulink model Fig. 3.10.The PI controller has the values of Kpas 0.006 and Ki as 11.458 approximately. Here also the total harmonic distortion is measured and it is reduced to 1.34 value when a filter is given.

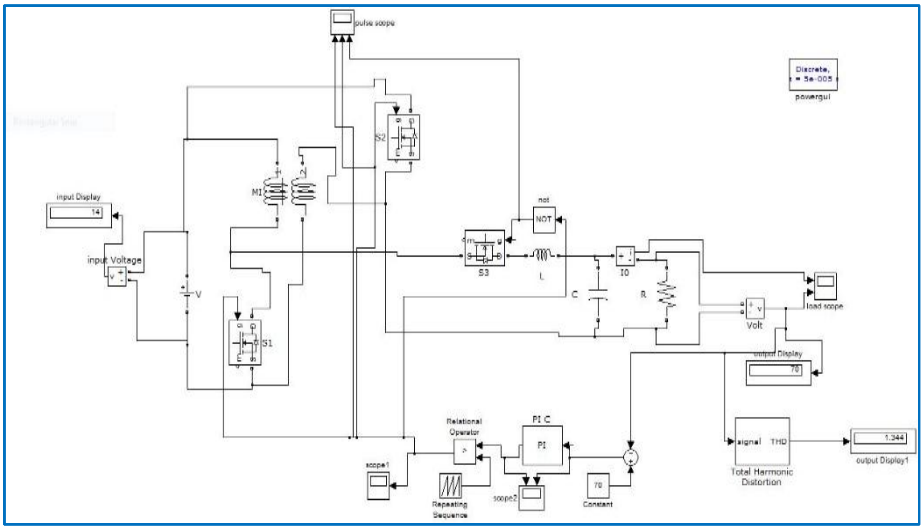


Fig. 3.10 SIMULINK Model with feedback

d) SIMULATION result with feedback

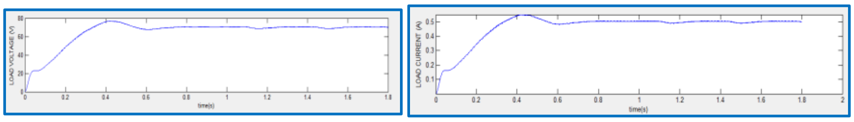


Fig. 3.11 Output voltage and current waveforms.

IV. STEP – DOWN MODE.

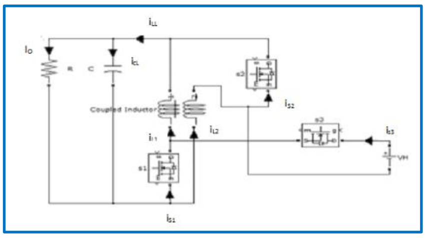


Fig. 4.1 Proposed converter in step-down mode.

The proposed converter in step-down mode[1] is shown in Fig. 4.1.The pulse width modulation (PWM) technique is used to control the switches S_1, S_2 and S_3. The operating principles and steady state analysis of continuous conduction mode is described as follows.

1) Mode 1: During this time interval (DTs), Switch S_3 is ON and switches S_1, $S_2$are OFF. The current flow path is shown in Fig. 4.2(a). The high voltage side V_H energy is transferred to the primary and secondary of the coupled inductor, the capacitor C_L and the resistive load. At this time the primary and secondary windings of the coupled inductor are in series. The current through the primary and secondary are equal and are given as:

$I_{L1} = I_{L2}$ (12)

$V_{L1} + V_{L2} = V_H – V_L$. (13)

Substituting (3), (4), (12) into (13), get

$$\frac{di_{L1}}{dt} = \frac{di_{L2}}{dt} = \frac{V_H - V_L}{2(1+K)L} \text{For the period DTs.} \quad (14)$$

2) Mode 2: During this time interval (1-DTs), switch S_3 is turned OFF and switches S_1, S_2 are ON. The current flow path is shown in Fig. 4.2(b). The energy stored in the primary and secondary windings of the coupled inductor will flow to the capacitor C_L and the resistive load. The primary and secondary windings of the coupled inductor are coming in parallel. The voltage across the primary and secondary windings are

$V_{L1} = V_{L2} = -V_L$. (15)

Substituting (3) and (4) into (15),

$$\frac{di_{L1}}{dt} = \frac{di_{L2}}{dt} = -\frac{V_L}{(1+K)L}\text{, For the period (1-D) Ts.} \quad (16)$$

From (14) and (16):

$$\frac{D(V_H - V_L)}{2(1+K)L} - \frac{(1-D)V_L}{(1+K)L} = 0. \tag{17}$$

Simplifying (17), the voltage gain is

$$G_{CCM(step-down)} = \frac{V_L}{V_H} = \frac{D}{2-D}. \tag{18}$$

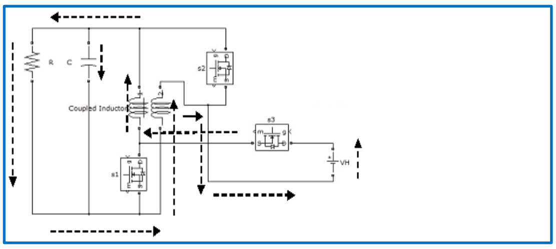


Fig. 4.2(a) current flow path in mode 1.

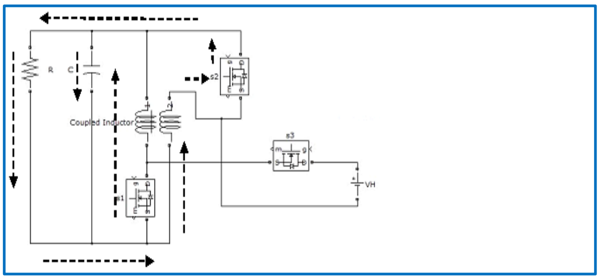


Fig. 4.2(b) current flow path in mode 2.

a) SIMULINK Model.

Simulation has been carried out to study the performance of a proposed bidirectional dc-dc converter. A high voltage of 42v is given as input voltage. Three switches S_1, S_2 and S_3 are controlled by PWM technique. The voltage and current waveform across the resistive load is simulated for an input voltage of 42v, R = 30Ω, C = 0.1F. With a resistive load the output voltage and current are pulsating.We get an output voltage of 26.7v. Total harmonic distortion is also measured as 4.676 value. The voltage across the switches, current through the switches and coupled inductor are obtained.

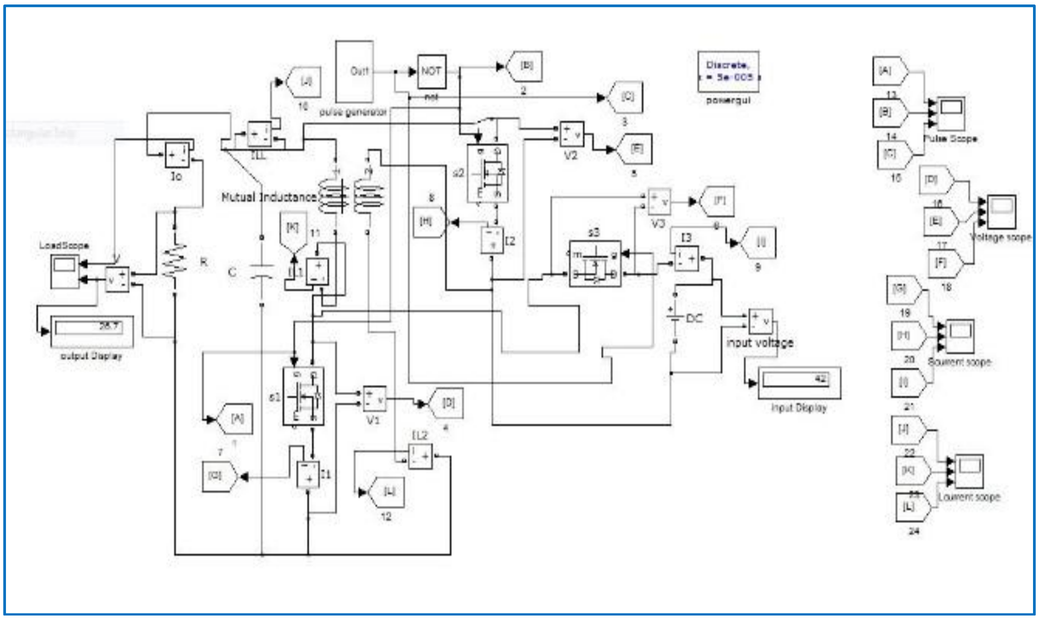


Fig. 4.3 SIMULINK Model.

b) SIMULATION results.

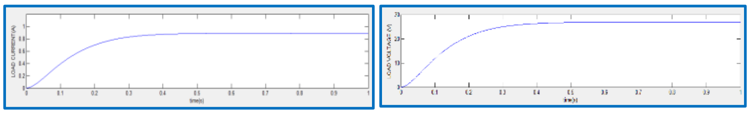


Fig. 4.4 Output current and voltage waveforms.

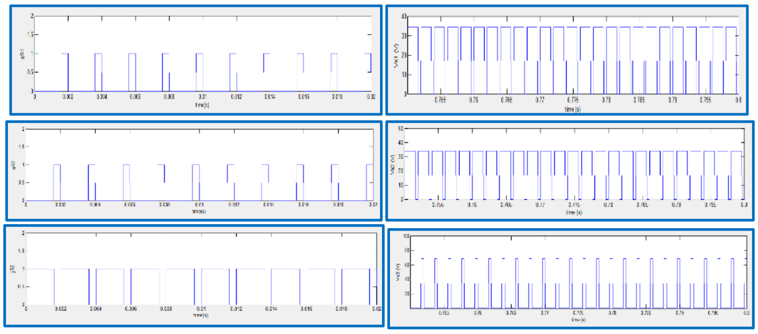


Fig. 4.4 Output current and voltage waveforms.Fig. 4.6 Voltage across switches.

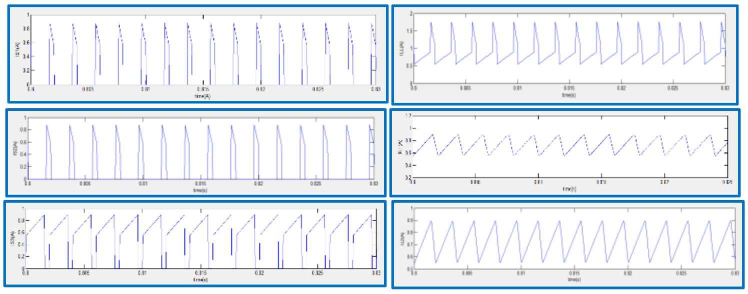


Fig. 4.7 Current through switches. Fig. 4.8 Current through coupled inductor and output current.

c) SIMULINK Model With Feedback

With a resistive load the output voltage will be pulsating. For a constant voltage application, the voltage is to be constant. To achieve this a feedback circuit is given to the Simulink model Fig. 4.9. In the PI controller, the values of Kp is 0.006 and Ki is 36.38 approximately. Here also the total harmonic distortion is measured and it is reduced to 0.0667 value when a filter is given.

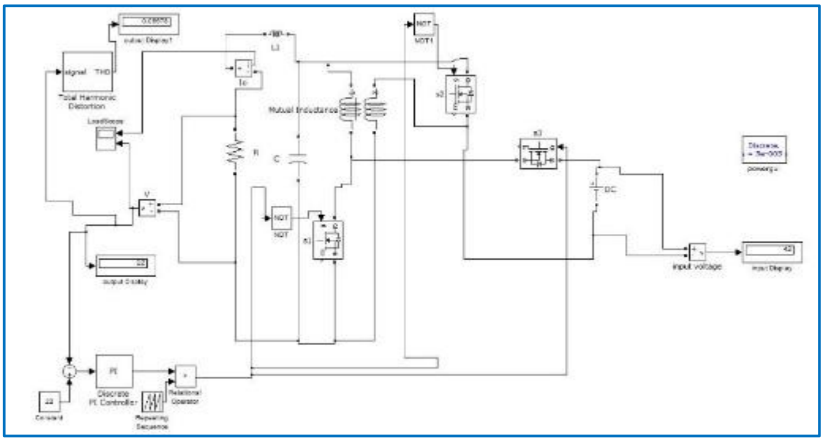


Fig. 4.9 SIMULINK Model with feedback.

d) SIMULATION result with feedback.

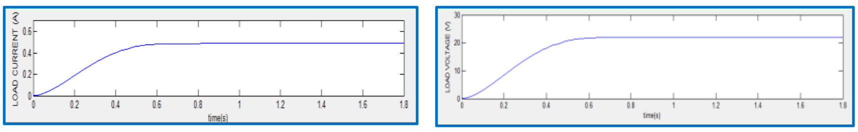
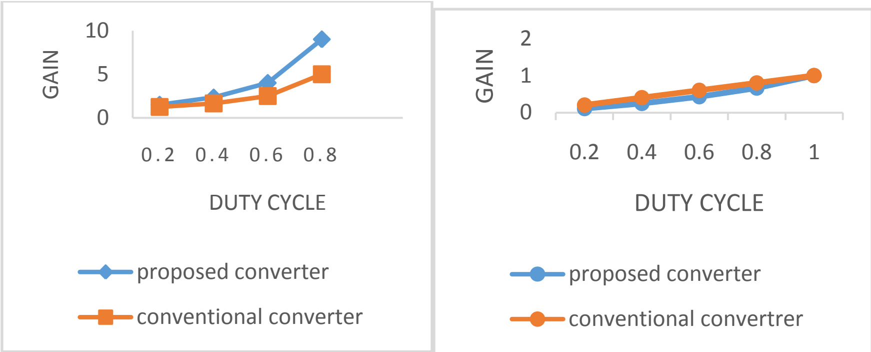


Fig. 4.10 Output current and voltage waveforms.

V. PROPOSED CONVERTER VS CONVENTIONAL BIDIRECTIONAL DC-DC CONVERTER.

A. Voltage Gain

For various values of duty cycle D, calculate voltage gain G and the graph is plotted. The voltage gain curve for proposed converter and conventional converter in continuous conduction mode of operation are plotted[1] in such a way in Fig. 5.1. From the graph we can conclude that the voltage gain in step-up and step-down operations of the proposed converter are higher.



$G_{(proposed)} = \frac{1+D}{1-D}.G_{(conventional)} = \frac{1}{1-D}.G_{(proposed)} = \frac{D}{2-D}.G_{(conventional)} = D.$

Fig. 5.2 Voltage gain of the proposed converter in step-up and down mode.

B. Voltage Stress on the Switches.

From the waveforms Fig. 3.7 and Fig. 4.6, the voltage stresses on switches S_1, S_2 and S_3 in the proposed converter are

$V_{DS1} = V_{DS2} = \frac{V_H+V_L}{2}$ (19)

$V_{DS3} = V_H+V_L$ (20)

In the conventional bidirectional dc-dc converter the voltage stress on switches S_1 and S_2 are

$V_{DS1} = V_{DS2} = V_H.$ (21)

Therefore, the rated voltage of switches S_1 and S_2 can be selected lower in the proposed converter than the conventional converter if the proposed converter is using for an application with high step-up and step-down voltage gain. And the rated voltage of switch S_3 can be selected as same in both proposed and conventional converters.

C. Average value of the Switch- Current

The average value of input current I_L can be found[1] from the Fig. 3.9, when the proposed converter is operated in continuous conduction mode in step-up mode

$$I_{L(proposed)} = \frac{2I_{L1(proposed)}DTs + I_{L1(proposed)}(1-D)Ts}{Ts}$$

$$= (1+D)I_{L1(proposed)}. \quad (22)$$

The average value of the input current IL when the conventional bidirectional converter is operated in step-up modein continuous conduction mode is

$I_{L(conventional)} = I_{L1(conventional)}.$ (23)

The input power for same electric specifications for proposed and conventional converter is given by

$P_{in} = V_L I_{L(conventional)} = V_L I_{L(proposed)}.$ (24)

Substitute (22) and (23) into (24), we get

$I_{L1(proposed)} = \frac{I_{L1(conventional)}}{1+D}.$ (25)

The average value of the current ILL can be found from the Fig. 4.8, when the proposed converter is operated in continuous conduction mode in step-down mode

$$I_{LL(proposed)} = \frac{I_{L1(proposed)}DTs + 2I_{L1(proposed)}(1-D)Ts}{Ts}$$

$$= (2\text{-}D)I_{L1(proposed)}. \quad (26)$$

The output power for both proposed and conventional bidirectional converter under same electric specification is given by

$$P_o = V_L I_{L1(conventional)} = V_L I_{LL(proposed)}. \quad (27)$$

From (26) and (27), get

$$I_{L1(proposed)} = \frac{I_{L1(conventional)}}{2-D}. \quad (28)$$

From (25) and (28), we can understand that the average value of switch current in the proposed converter is less than the conventional bidirectional converter.

VI. CONCLUSION

A bidirectional dc-dc converter with a coupled inductor is presented in this paper. The proposed converter is having a simple circuit configuration. The operating principles and steady state analysis of the proposed converter is also explained in this paper.The proposed converter is having a high voltage gain in step-up and step-down modes than a conventional converter. The average value of switch current in the proposed converter is less than the conventional converter. The rated voltage of the switches in the proposed converter can be selected to be lower in high voltage gain applications also. From the simulation results, it is see that the waveforms agree with the operating principles and steady state analysis.

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