Review and Analysis of a Coupled Inductor Based Bidirectional DC-DC Converter

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ABSTRACT

In this paper, a bidirectional DC-DC converter has been presented and analysed. Bidirectional DC-DC converters are used for transferring the power, between any two DC sources in any forward or reverse direction. This bi-directional dc-dc converter, is capable of bilateral power flow, providing the functionality of two uni-directional converters in a single converter unit. These type of converters are widely used in applications like Hybrid Electric Vehicle energy systems, fuel-cell hybrid power systems, Uninterrupted Power Supply systems, Photo-Voltaic hybrid power systems, and battery chargers. Different topologies of bidirectional dc-dc converters are studied for reference and finally the selected topology is analysed here. This paper describes the operating principles and steady-state analysis for the step-up and step-down modes of such bidirectional dc-dc converter. This converter has higher step-up and step-down voltage gains than the conventional bidirectional DC-DC boost/buck converter. The special element of such a bidirectional dc-dc converter is the coupled inductor employed here which has same number of winding turns at the primary and secondary sides. In order to analyze the steady-state characteristics of such proposed converter, some conditions are assumed as: 1) The ON-state resistance RDS(ON) of the switches and the equivalent series resistances of the coupled inductor and capacitors are ignored. 2) The capacitor is sufficiently large, and the voltages across the capacitor can be treated as constant.

Keywords: Bidirectional DC-DC Converter, Step-up Mode, Step-down Mode, Coupled Inductor.

1. INTRODUCTION

The dc-dc converters mean the input is dc and the output is also dc. The two basic dc-dc converters are buck converter and boost converter. Based on these two converters, all other converters are derived. These converters can be classified based on various categories. The aim of developing these kind of converters are high efficiency and high gain with fast response. One such type of converter is bidirectional buck-boost converter. In this type of converter, one direction is used to step-up the voltage and another direction is used to step-down the voltage. It is just like the charging and discharging of the converter [1].

Applications that require exchange of power from the source to the load and vice versa have conventionally been implemented with two uni-directional converters, each processing the power in one direction. With growing emphasis on compact, smaller and efficient power systems, there is increasing interest in the possibility of using bidirectional converters, especially in DC power based applications like space, telecommunication and computer systems[2]. This paper presents a bi-directional dc-dc converter topology for low power applications like DC UPS systems, battery chargers, etc.

1.1 Applications of BDC

Bidirectional DC - DC converters play an important role in applications where conversion of DC to DC is involved. These applications include hybrid electric vehicles, switching mode power supplies, battery chargers, PV hybrid power systems and un-interruptible power supplies.

1.1.1 Application in battery charger circuits

A battery charger/discharger circuit is shown in the figure 1 where such a bidirectional converter can be implemented. The battery charger/ discharger circuit can be used as part of a DC UPS system. Conventional battery charger/discharger circuits comprised of two converters; one for the charging the battery from a DC bus and the other to provide power to the DC bus from the battery. The adopted bi-directional converter provides both functions of battery charging and discharging in a single conversion unit with its bidirectional power flow capability [2].

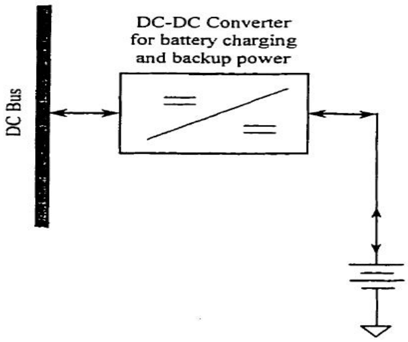


Figure 1 Battery charger/discharger circuit

To realize the double sided power flow in bidirectional dc-dc converters, the switch cell should carry the current on both directions. It is usually implemented with a uni-directional semiconductor power switch such as power MOSFET or IGBT in parallel with a diode, because the double sided current flow power switch is not available. For the buck and boost dc-dc type converters, the bidirectional power flow is realized by replacing the switch and diode with the double sided current switch cell.

1.1.2 Application in PV energy systems

Using clean energy resources like photovoltaic arrays and wind turbines in renewable electric power generation systems, the bidirectional dc-dc converter is used to transfer the solar energy to the capacitive energy source during the sunny time, while to deliver energy to the load when the dc bus voltage is low. A PV power system with bidirectional converter is shown in figure 2. The bidirectional dc-dc converter is regulated by the solar array photovoltaic level, thus to maintain a stable load bus voltage and make fully usage of the solar array and the storage battery.

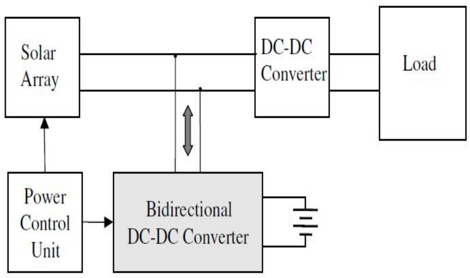


Figure 2 Solar cell PV energy system

1.1.3 Application in HEV systems

In the electric vehicle applications also, an auxiliary energy storage battery absorbs the regenerated energy fed back by the electric machine. So a bidirectional dc-dc converter is required to draw power from the auxiliary battery to boost the high-voltage bus during vehicle starting, acceleration and hill climbing [3].

1.2 Classification of BDC

We can classify bidirectional dc-dc converters as isolated and non-isolated dc-dc converters. The isolated bidirectional dc-dc converters include the half-bridge types and full-bridge types. These converters can provide high step-up and step-down voltage gain by adjusting the turns ratio of the transformer [4]. But these mechanisms with isolated transformers have high conduction losses because four to nine power switches are required. Also the switching losses are increased.

For non-isolated applications, the non-isolated bidirectional DC-DC converters include the conventional boost/buck type, multi-level type, three-level type, sepic/zetatype, switched-capacitor type, and coupled-inductor type. The multi-level type is a magnetic-less converter, but 12 switches are used in this converter. If higher step-up and step-down voltage gains are required, more switches are needed. Thus control circuit becomes more complicated. In the three-level type, the voltage stress across the switches on the three-level type is only half of the conventional type. However, the step-up and step-down voltage gains are low. Since the sepic/zeta type is combined of two power stages, the conversion efficiency will be decreased. The switched capacitor and coupled-inductor types can provide high step-up and step-down voltage gains [5]. However in switched capacitor type, increased switching loss and current stress are the critical drawbacks.

2. BDC USING COUPLED INDUCTOR

The coupled inductor is the main energy transfer element in the converter. In each switching cycle it is charged through source side active switches for the duration of T_{on}=DT, where T=1/f_{sw} is the switching period and D is the duty cycle. This energy is then discharged to load during T_{off} =(1-D)T. A coupled inductor is the inductor with same winding turns in the primary and secondary sides as shown in figure 3.

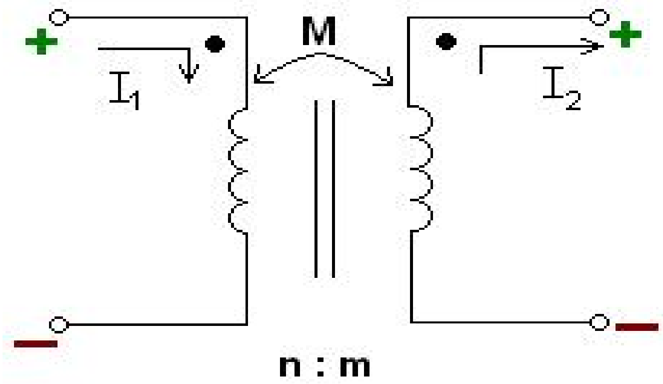


Figure 3 A coupled inductor

The pair of coupled coils shown in figure 3 has currents, voltages and polarity dots indicated and M_{12} = M_{21} = M where M is the mutual inductance.

3. CIRCUIT AND ANALYSIS

The basic elements of the converter and their functionality are described in this section. The circuit topology and its different modes of operation of the bi-directional dc-dc converter are explained in detail here. In the converter, the semiconductor devices are used as switching devices due to which the converters can operate at high frequencies. The different arrangement of inductors and capacitors in the converters operates as a filter circuit. The resistance act as a load in the circuit which can be varied to study the behaviour during light load and heavy load. The different types of input dc sources which are used are like battery, renewable energy sources etc.

A bidirectional dc-dc converter using a coupled inductor is adopted here consisting of three switches as shown in figure 4. This adopted converter employs a coupled inductor with same winding turns in the primary and secondary sides. The power MOSFETs S_1, S_2, S_3 are the primary switching devices of the adopted converter. They are gated at a constant frequency with variable on time to provide the necessary regulated output voltage.

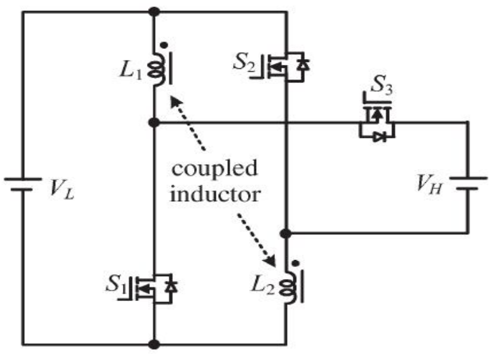


Figure 4 Bidirectional DC-DC converter with coupled inductor

The pulse-width modulation (PWM) technique is used to control the switches here.

3.1 Step-up mode of Bidirectional DC-DC Converter

The adopted converter in step-up mode is shown in Figure 5.[5] The pulse-width modulation (PWM) technique is used to control the switches S_1 and S_2 simultaneously. The switch S_3 is the synchronous rectifier [5].

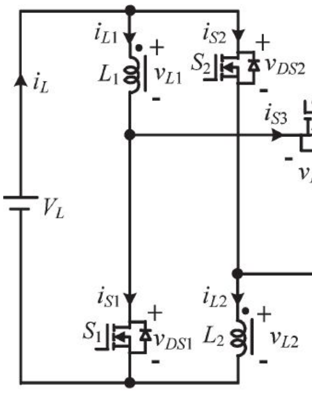


Figure 5 Bidirectional dc-dc converter in step-up mode

Since the primary and secondary winding turns of the coupled inductor is same, the inductance of the coupled inductor in the primary and secondary sides are expressed as

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

Thus, 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 coefficient of the coupled inductor. The voltages across the primary and secondary windings of the coupled inductor are as follows:

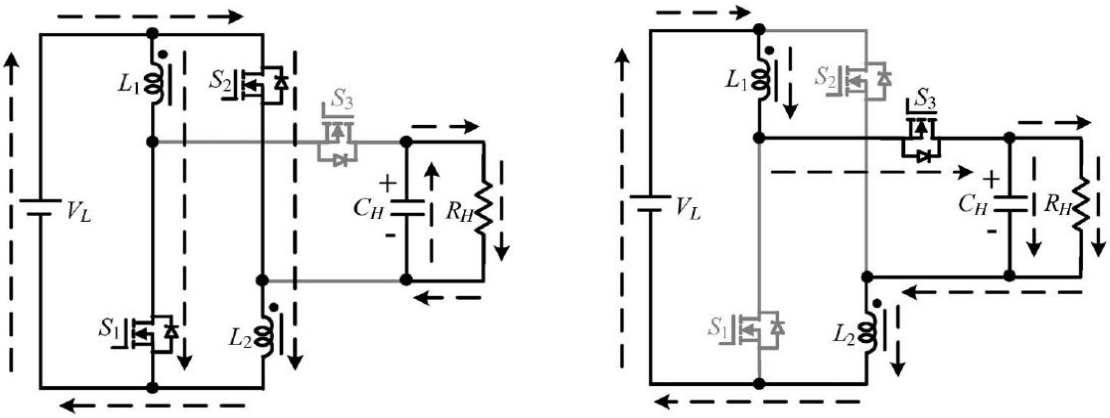
$$V_{L1} = L_1\frac{di_{L1}}{dt} + M\frac{di_{L2}}{dt} = L\frac{di_{L1}}{dt} + kL\frac{di_{L2}}{dt} \tag{3}$$

$$V_{L2} = M\frac{di_{L1}}{dt} + L_2\frac{di_{L2}}{dt} = kL\frac{di_{L1}}{dt} + L\frac{di_{L2}}{dt} \tag{4}$$

The operating principle and steady-state analysis of the converter in Continuous Conduction Mode (CCM) of operation is described as follows:

3.1.1 Mode 1

During this time interval [t_0; t_1], S_1 and S_2 are turned on and S_3 is turned off. The current flow path is shown in figure 6.(a). The energy of the low-voltage side V_L is transferred to the coupled inductor. Meanwhile, the primary and secondary windings of the coupled inductor are in parallel. The energy stored in the capacitor C_H is discharged to the load.



(a) **(b)**

Figure 6 Current flow path in step-up mode: (a) Mode 1 (b) Mode 2

Thus, the voltages across L_1 and L_2 are obtained as

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

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

$$\frac{di_{L1}(t)}{dt} = \frac{di_{L2}(t)}{dt} = \frac{V_L}{(1+k)L}, t_0 \le t \le t_1 \quad (6)$$

3.1.2 Mode 2

During this time interval [t_1; t_2], S_1 and S_2 are turned off and S_3 is turned on. The current flow path is shown in figure 6.(b). The low-voltage side V_L and the coupled inductor are in series to transfer their energies to the capacitor C_H and the load. Meanwhile, the primary and secondary windings of the coupled inductor are in series. Thus, the following equations are found to be

$$i_{L1} = i_{L2} \quad (7)$$

$$v_{L1} + v_{L2} = V_L - V_H \quad (8)$$

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

$$\frac{di_{L1}(t)}{dt} = \frac{di_{L2}(t)}{dt} = \frac{V_L - V_H}{2(1+k)L}, t_1 \le t \le t_2 \quad (9)$$

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

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

Simplifying (10), the voltage gain is given as

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

3.2 Step-down mode of Bidirectional DC-DC Converter

Following figure 7 shows the adopted converter in step-down mode. The PWM technique is used to control the switch S_3. The switches S_1 and S_2 are the synchronous rectifiers.

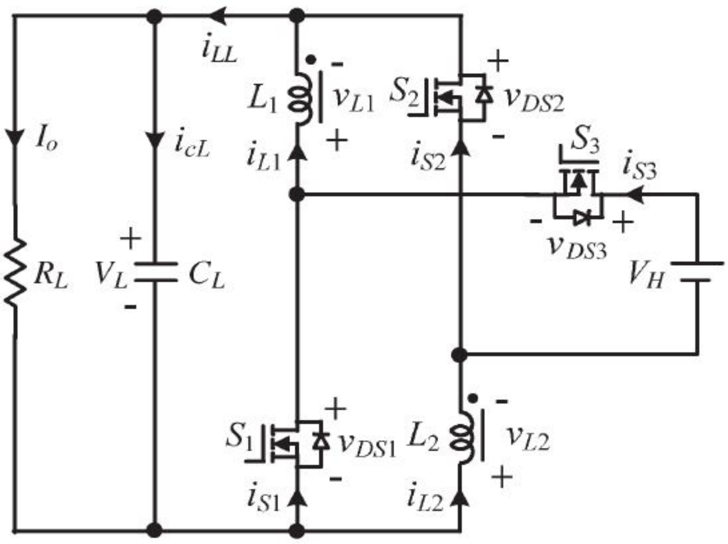
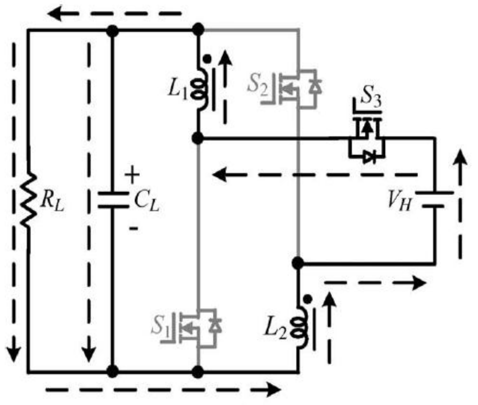


Figure 7 Bidirectional dc-dc converter in step-down mode

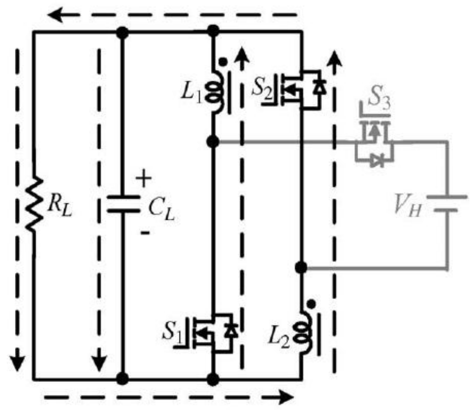
The operating principle and steady-state analysis in CCM mode of operation is described as follows:

3.2.1 Mode 1

During this time interval [t_0; t_1], S_3 is turned on and S_1/S_2 are turned off. The current flow path is shown in figure 8.(a). The energy of the high-voltage side V_H is transferred to the coupled inductor, the capacitor C_L, and the load. Meanwhile, the primary and secondary windings of the coupled inductor are in series.



(a)



(b)

Figure 8 Current flow path in step-down mode: (a) Mode 1 (b) Mode 2

Thus, the following equations are given as

$$i_{L1} = i_{L2} \tag{12}$$

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

Substituting (3), (4), and (12) into (13), gives

$$\frac{di_{L1}(t)}{dt} = \frac{di_{L2}(t)}{dt} = \frac{V_H - V_L}{2(1+k)L}, t_0 \le t \le t_1 \tag{14}$$

3.2.2 Mode 2

During this time interval [t_1; t_2], S_3 is turned off and S_1/S_2 are turned on. The current flow path is shown in figure 8.(b). The energy stored in the coupled inductor is released to the capacitor C_L and the load. Meanwhile, the primary and secondary windings of the coupled inductor are in parallel. Thus, the voltages across L_1 and L_2 are derived as

$$v_{L1} = v_{L2} = -V_L \tag{15}$$

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

$$\frac{di_{L1}(t)}{dt} = \frac{di_{L2}(t)}{dt} = -\frac{V_L}{(1+k)L}, t_1 \le t \le t_2 \tag{16}$$

By using the state-space averaging method, the following equation is obtained 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 found to be

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

4. CONCLUSION

From the above discussion and results it is observed that the selected bidirectional dc-dc converter with minimum number of switches and a coupled inductor has high efficiency and high gain in both the modes of operation. The converter operation is studied and the circuit topology is analysed in the steady state condition for both step-up and step-down modes. Such a bi-directional dc-dc converter is capable of power flow in forward and reverse directions and thus it can be easily implemented for the most required application like battery charger/discharger circuits.

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