

A Soft-Switching Isolated Bidirectional Converter Fed Induction Motor Drive



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Abstract:

This paper proposes a soft switching isolated bidirectional LLC converter fed induction motor drive with a new control scheme. All the switches in the proposed topology can achieve soft switching. Compared with traditional isolated bidirectional dc-dc converters such as dual active bridge converter, the reverse energy and turn-off loss are reduced dramatically, and the conversion efficiency can be much improved. With the proposed new control scheme, the power flow direction and output power of the proposed converter can be changed automatically and continuously, which is attractive for energy storage systems to balance the energy and to keep the dc-bus voltage constant. Proposed circuit is validated by the simulation results.

I. INTRODUCTION:

Most activities in the world depend on the electrical power system so that uninterrupted power supply is needed. In most cases reliable power is stored in batteries. This can be expanded to supply the ac system by the same battery. This can be achieved by the application of power electronics with bidirectional power converters. Isolated bidirectional dc-dc LLC resonant converter is one of the building blocks that enable power to flow in both directions. The converter is static to be used in battery charging and discharging circuits for uninterruptable power supply, hybrid vehicles, space application, telecommunication, hospital etc.

LLC resonant converter is a promising alternative for converters to reduce switching losses and to improve the life time of the MOSFETs. LLC resonant converter reduces or eradicates the energy circulating in the converter by applying zero voltage switching and zero current switching. The converter should be analyzed by simulation to the LLC resonant tank in the isolated bidirectional converter and also the efficiency of the bidirectional converter should be tested in the laboratory. Develop the automatic controller, small signal analysis and minimize the loss by selecting the proper resonant value. If time, the converter should be developed and tested on laboratory. The goal of the thesis is to minimize the switching loss of the MOSFETs by adding the LLC resonant tank on the isolated bi-directional dc-dc converter and also improve the lifetime efficiency of the converter.

In addition to develop LLC resonant tank in the isolated bidirectional converter also develop automatic bi-directional controller. Since electronic devices are driven by DC, commercial AC is converted to DC before use. However, as power conversion generates loss, reducing the number of conversions leads to energy conservation. Therefore, the introduction of DC power supply systems that supply DC power instead of conventional commercial AC is being considered for smart grids. In a DC power supply system, DC power between 300 and 400V is supplied to a building, factory or house through a DC bus, and power generated by solar power generation or wind power generation is supplied to the DC bus through a power

conditioner. Surplus power is sent to the energy storage system, using lithium ion batteries or other types of batteries. The EZA series bidirectional DC-DC converter is a power supply unit that exchanges power between the DC bus and energy storage system. Conventionally, when such a power supply is needed, there is no choice but to either develop a special power supply or to switch between 2 DC-DC converters, one for step up conversion and the other for step down conversion. However, the new EZA series converters are state-of-the-art power supplies that realize both step up and step down power conversion in just one DC-DC converter. Most of power converter devices have common unidirectional application with power being supplied from the source to the load. However different types of applications require dual direction; the applications such as motor drives, uninterruptible power supplies (UPS), alternate energy system, telecommunication, space technology, hybrid Automotives, battery charger and discharger etc.

require using another system of conversion which is not similar to unidirectional. Therefore these applications introduce power converter with bi-directional power transfer property. Conventionally, the two independent unidirectional converters can be used together parallel for achieving bi-directional power transfers. Bidirectional DC-DC converters recently gates awareness due to application of bidirectional power transfer between different dc sources buses. The demand for development of complex, compact and efficient power system implementation has encouraged scientists in bi-directional converter development.

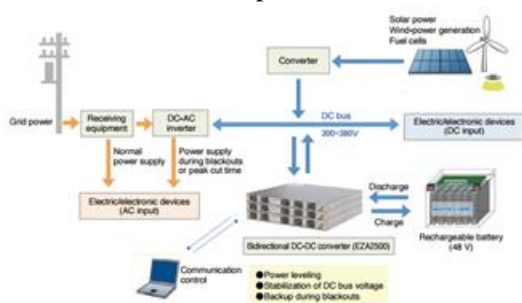


Fig. 1. Typical DG system with ESSs.

The turn-off power loss is related to the turn-off current, which can be reduced by operating the DAB topology in res-onant mode with an extra resonant capacitor, i.e., dual bridge series resonant converter. However, it can only oper-ate under buck mode which is not suitable for wide input/output range applications like ESSs. A new bidirectional SRC for wide voltage range application with clamped capacitor was studied , but the topology itself is complex due to the complex auxiliary circuits.

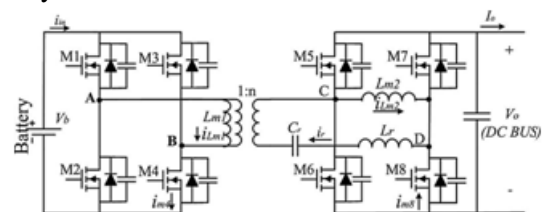


Fig. 2. Proposed bidirectional LLC resonant converter.

Among the resonant converters, the LLC resonant converter has superior performance compared to the series resonant converter (SRC), especially for buck/boost operation capability, narrow switching frequency variation range, and higher efficiency [29]–[32]. Most of the researches on LLC resonant converter are focused on unidirectional dc–dc applications, and very little research work on bidirectional LLC resonant converter was reported in the literature. A bidirectional LLC resonant topology for vehicular applications was proposed in [33].

The topology was still a traditional SRC during backward operation, which is not preferred for wide voltage range application. In [34], a bidirectional CLLC resonant converter with two resonant tanks in the transformer primary side and secondary side, respectively, was proposed. The extra resonant tank increased both the cost and volume of the converter, and the voltage gain was reduced compared with the traditional LLC converter.

INDUCTION MOTOR:



An asynchronous motor type of an induction motor is an AC electric motor in which the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding. An induction motor can therefore be made without electrical connections to the rotor as are found in universal, DC and synchronous motors. An asynchronous motor's rotor can be either wound type or squirrel-cage type. Three-phase squirrel-cage asynchronous motors are widely used in industrial drives because they are rugged, reliable and economical.

Single-phase induction motors are used extensively for smaller loads, such as household appliances like fans. Although traditionally used in fixed-speed service, induction motors are increasingly being used with variable-frequency drives (VFDs) in variable-speed service. VFDs offer especially important energy savings opportunities for existing and prospective induction motors in variable-torque centrifugal fan, pump and compressor load applications. Squirrel cage induction motors are very widely used in both fixed-speed and variable-frequency drive (VFD) applications.

Variable voltage and variable frequency drives are also used in variable-speed service. This paper proposes a new bidirectional LLC resonant converter with a new control scheme for ESSs applications. The circuit diagram is shown in Fig. 2. The detailed operating principle is presented in Section II. The theoretical analysis of the proposed topology is given in Section III. Section IV presents the experimental results from a 1-kW prototype with 75 V– 130 V input and 400-V output.

Main Features:

- Input/output isolated type, which is safe and provides a good noise countermeasure.
- Achieves bidirectional conversion efficiency of 94% through digitally controlled optimization.
- Capable of autonomous operation and can automatically change conversion direction to stabilize input or output voltage.
- Capable of changing the conversion direction at high speed (15 ms or less), without stopping the converter.
- Serial communication (RS485) enables control of current, voltage and conversion direction, and status monitoring.
- Compact, space saving type.

II. PRINCIPLE OF OPERATION:

The proposed bidirectional LLC resonant converter is shown in Fig. 2. The energy storage element is in the transformer primary side and the dc bus is in the secondary side. For bidirectional power flow, two active bridges are adopted in the proposed topology. It should be noted that a half-bridge structure can also be used. An extra inductor L_{m2} is added between point C and point D.

In this paper, the forward mode means the battery delivers energy to the dc bus, which is a discharging mode. And the backward mode is a charging mode. The voltage gain G is the ratio of dc-bus voltage referred to the primary side to the battery voltage, which is equal to V_o / nV_b , where n is the transformer turns ratio as shown in Fig. 2.

For $G \geq 1$, the auxiliary inductor L_{m2} , resonant inductor L_r and resonant capacitor C_r form the LLC resonant tank, and the transformer magnetizing inductor L_{m1} is used to help to

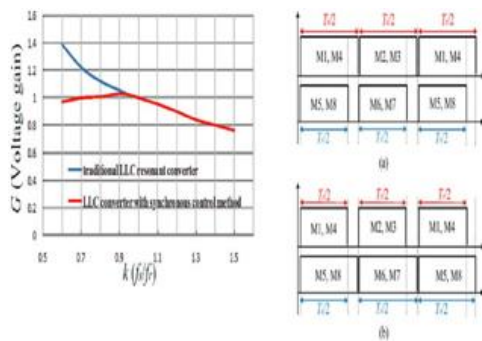


Fig. 3. Voltage gain with $k = 4$, $Q = 0.4$. Gate drive signals of the proposed control schemes

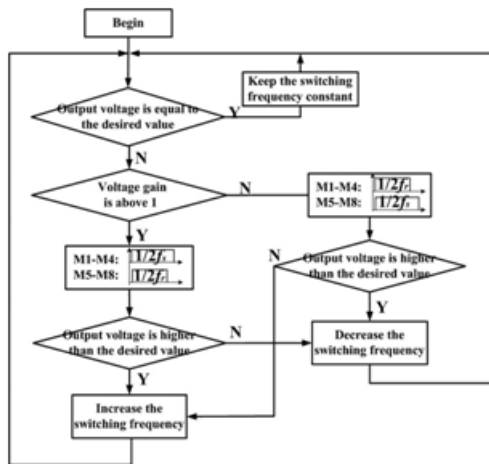


Fig. 6. Output regulating method using the proposed control scheme.

Generally, for a typical DG system, the dc-bus voltage should be regulated to a constant value. And the converter should automatically switch between the discharging mode and charging mode according to the energy consumed by the load and generated by the generators. Also, it is preferred that the bidi-rectional dc-dc converter can operate in buck/boost mode due to the large terminal voltage variation of the ESS. To meet these requirements, this paper proposes a new control scheme for the proposed bidirectional LLC topology. With the proposed control method, the converter is always operating below the resonant frequency f_r . All the MOSFETs in the converter are switching with same frequency, but the pulse width of gate drive signals for primary side MOSFETs and secondary side MOSFETs are different according to the voltage gain G .

Achieve ZVS for MOSFETs in the primary side. For $G < 1$, the resonant inductor L_r , resonant capacitor C_r and transformer magnetizing inductor L_{m1} form the LLC resonant tank, and the auxiliary inductor L_{m2} is used to help to achieve ZVS for secondary side switches. If L_{m2} (referred to the primary side) is equal to L_{m1} , the parameters of resonant tank are exactly the same, and the converter is symmetrical, which means the operation is also the same. The control scheme is very important to achieve the desired characteristics of the proposed topology. The most straight forward control scheme is turning ON and OFF the primary side switches and secondary side switches with same switching frequency [35]. The diagonal switches M1/M4 and M2/M3 in the input bridge are switching with 50% duty cycle and complementarily without considering the dead time. The gate drive signals for M5/M8 and M6/M7 in the output bridge are the same as those for M1/M4 and M2/M3, respectively, which can be regarded as the synchronous control. The switching frequency is used to control output power as traditional LLC resonant converter. Thus, the high conduction loss and poor reverse recovery problem of MOSFET body diodes in the output side can be avoided. And the current in the output side is always in continuous conduction mode (CCM) even when the switching frequency is below the resonant frequency, which is different from traditional unidirectional LLC converter. Moreover, the output characteristic such as voltage gain is also different.

For $G < 1$, the switching frequency should decrease to reduce the energy delivered to the output, and vice versa. The reason is that a decreased switching frequency leads to an increased reverse energy and the output power will decrease correspondingly. There is also a critical switching frequency for a given voltage gain G , at which the average output current is zero. If the switching frequency is below this critical value, the converter will operate in backward mode. The operation of the proposed topology along with the control scheme is symmetrical for forward mode with $G > 1$ and backward mode with $G < 1$ by simply swapping the input and output side.

So, only the operating principle for $G > 1$ is analyzed in this paper. A. $i_o > 0$ When energy generated in the distributed system is not sufficient, the ESS (battery) is discharged to deliver energy to the load, so the output current of the bidirectional converter is positive. In this discharging mode, the auxiliary inductor $L_m 2$ is part of the LLC resonant tank and the transformer magnetizing inductor $L_m 1$ helps to achieve ZVS for M1 to M4. This operating mode is similar to the traditional unidirectional LLC resonant converter when $f_s < f_r$, and there are three operating modes in a half switching cycle, which are shown in Fig. 9(a), (b), and (d).

Mode 1 ($t_0 - t_1$): The equivalent circuit of this mode is shown in Fig. 9(a). M1, M4, M5, and M8 turn ON at t_0 with ZVS. The voltage across the auxiliary inductor $L_m 2$ is equal to V_o , so $i_{L m 2}$ increases linearly. Voltage across the transformer magnetizing inductor $L_m 1$ is equal to V_b , and its current increases linearly, too. In this mode, L_r resonant with C_r and i_r is always larger than $i_{L m 2}$. This mode ends when M5 and M8 turn OFF at t_1 when i_r is equal to $i_{L m 2}$, so M5 and M8 turn OFF with ZCS.

Mode 2 ($t_1 - t_2$): The equivalent circuit is shown in Fig. 9(b). The output is disconnected from the resonant tank, and energy to the load is supplied by the output capacitor. In this mode, C_r , L_r , and $L_m 2$ form the resonant tank, so $i_{L m 2}$ and i_r are the same. As the resonant period is quite long, i_r will increase very slowly due to large inductance of $L_m 2$.

Mode 3 ($t_2 - t_3$): The equivalent circuit is shown in Fig. 9(d). M1 and M4 turn OFF at t_2 . i_r plus $i_{L m 1}$ charge the parasitic capacitors of M1 and M4, and discharge the parasitic capacitors of M2 and M3 until the voltage across M1 and M4 reaches the input voltage, then current in the primary side begins to flow through the body diodes of M2 and M3. Then, current in the secondary side begins to flow through the body diodes of M6 and M7, so they will turn ON with ZVS. B. $i_o = 0$

When energy generated in distributed system exactly matches the load power, the energy transferred between the battery and the dc bus will be zero. And the steady state waveforms are shown in Fig. 7(b). There are also three operating modes in a half switching cycle, which are shown in Fig. 9(a), (c), and (d).

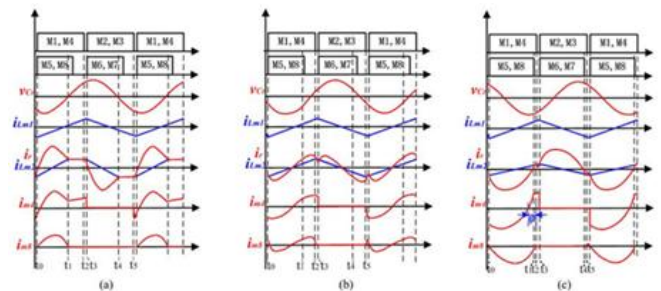


Fig. 7. Steady-state waveforms when $G \geq 1$. (a) $i_o > 0$. (b) $i_o = 0$. (c) $i_o < 0$.

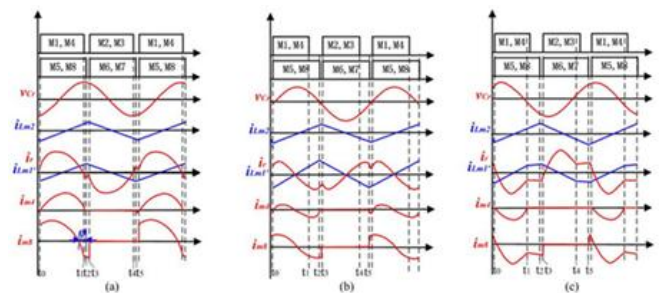


Fig. 8. Steady-state waveforms when $G < 1$. (a) $i_o > 0$. (b) $i_o = 0$. (c) $i_o < 0$.

Mode 1 ($t_0 - t_1$): M1 and M4 turn ON with ZVS at t_0 . The equivalent circuit of this mode is also shown in Fig. 9(a). The secondary side current is positive at t_0 , and then the resonant begins. This mode ends when M5 and M8 turn OFF at t_1 , which is also the end of the half resonant cycle.

Mode 2 ($t_1 - t_2$): i_r is still larger than $i_{L m 2}$ in this mode, so current in the secondary side will flow through the body diodes of M5 and M8, and the equivalent circuit is shown in Fig. 9(c). This mode ends when M1 and M4 turn OFF at t_2 .

Mode 3 ($t_2 - t_3$): The equivalent circuit is shown in Fig. 9(d). In the primary side, the parasitic capacitors of M2 and M3 are discharged, and the current will flow through their body diodes once the voltage across M1/M4 reaches zero, so M2 and M3 can turn ON with ZVS in the next half switching cycle. In the secondary side, current begins to flow through the body diodes of M6 and M7. $i_o < 0$

When there is excess energy generated by the generators in the distributed system, the feedback loop will increase the switching frequency to reduce the energy from ESS to the load. If the switching frequency is above the critical value, the average output current is negative and the converter automatically operating in backward mode. The steady-state waveforms are shown in Fig. 7(c). There are also three operating modes in a half switching cycle, and the equivalent circuits are the same as those for $i_o > 0$, which are also shown in Fig. 9(a), (b), and (d).

Mode 1 ($t_0 - t_1$): The equivalent circuit and operation is the same as that describe in Mode 1 when $i_o > 0$, the difference is that i_r is always lower than i_{Lm2} in this mode. According to (4), the current of M5 and M8 is always negative and energy flows from the secondary side to the primary side. This mode ends when M5 and M8 turn OFF at t_1 .

Mode 2 ($t_1 - t_2$): The equivalent circuit is shown in Fig 9(b). When M5 and M8 turn OFF at t_1 , current flows through them is negative, so it will charge the parasitic capacitors of M5/M8 and discharge the parasitic capacitors of M6/M7. When M5 and M8 have turned OFF, L_{m2} will be resonant with L_r and C_r . This mode ends when M1 and M4 turn OFF at t_2 .

Mode 3 ($t_2 - t_3$): The voltage across M5/M8 reaches V_o , the body diodes of M6 and M7 conduct, so M6 and M7 will turn ON with ZVS in the next half switching cycle. This mode is almost the same as Mode 3 when $i_o > 0$, and only the current direction is reversed, which will not be repeated here. According to the analysis of operation mode for $G \geq 1$, it is clear that the converter can operate automatically from forward mode to backward mode. With the proposed gate drive pattern, the switching frequency modulation can be used to control the output power and its direction. The operation of the proposed converter under $G < 1$ is a dual to that with $G \geq 1$, which will not be elaborated here.

III. CONVERTER CHARACTERISTICS ANALYSIS

Since energy generated in DG system like PV or wind power always changes, and the load condition may also vary with time, the bidirectional converter in ESS has to regulate the out-put power to keep the dc-bus voltage constant. A typical DG system with ESS (battery) is shown in Fig. 10. The proposed bidirectional dc-dc converter is used as the interface between the battery and the dc bus. V_p is the equivalent output voltage of the renewable energy resources, such as PV panels. The resistor r_1 is used to simulate the output characteristics of the renewable energy resources, the cable resistance of dc bus and parasitic resistance. D1 is used to simulate the unidirectional energy flow of the renewable energy resources. V_b is the battery terminal voltage and V_o is the dc-bus voltage which is also the output voltage of the bidirectional dc-dc converter.

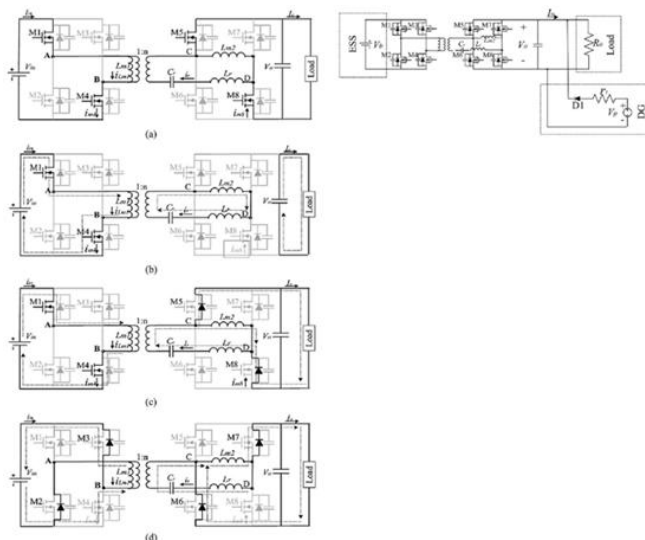


Fig. 9. Operating modes with different voltage gain and output current in half switching cycle.

IV. SIMULATION RESULTS:

Considering $Q_{m\ in}$ and $Q_{m\ ax}$ along with the required resonant frequency, the resonant parameters can be determined, i.e., $C_r = 33\ nF$, $L_r = 77\ \mu H$, and $L_{m\ 1} = L_{m\ 2} = 462\ \mu H$. Taking $x_{m\ in} = 0.6$, $R_{o\ max} = 160\ \Omega$, and $L_m = 462\ \mu H$, the minimum normalized switching frequency at full load can meet the inequality, so soft switching can be achieved in all load range, and the parameters are well designed. The key components are summarized in above. The auxiliary inductor has the same size as the resonant inductor.

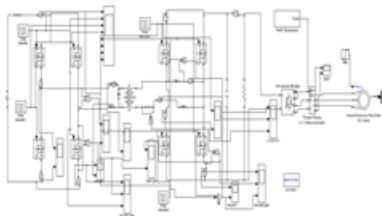


Fig. 10. Simulation model of bidirectional operation.

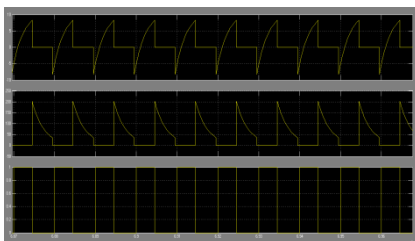


Fig. 11. Vm4, Vds4, Vgs4

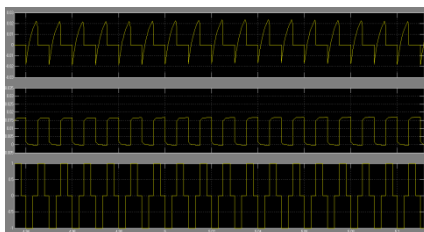


Fig. 12. Vm8, Vds8, Vgs8

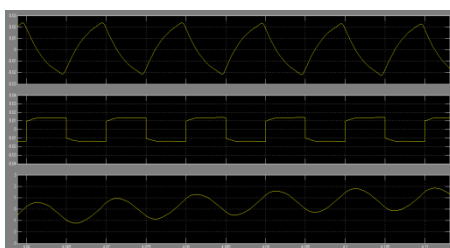


Fig. 13. Ir, Vlm2, Vcr

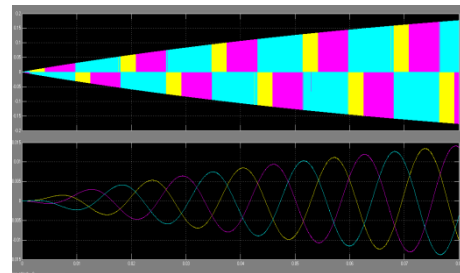


Fig. 14. VSI Output V&I

V. CONCLUSION:

This paper proposes a soft switching isolated bidirectional LLC converter fed induction motor drive with a new control scheme. All the switches in the proposed topology can achieve soft switching. All the switches in the primary side and secondary side turn ON and OFF with the same switching frequency, but the pulse width is different based on the required voltage gain. And the switching frequency is used to regulate the output power and the power flow direction. Therefore, the proposed topology can automatically switch between the forward mode and the backward mode, which is quite attractive for energy storage system and voltage source inverter fed applications. The detailed operation principle and topology characteristics are analyzed. Simulation results verify the theoretical analysis.

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