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A Bidirectional Series-Resonant Converter For Energy Storage System in DC Microgrids

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Abstract: *A bidirectional series-resonant (BSR) converter is proposed for energy storage system in DC micro-grid. The bidirectional converters are mainly used in electric vehicles. To determine the voltage gain of the converter, the effective duty cycles of switches are used. Thus the amplitude and direction of the transferred power is not involved, which is an improvement compared with the existing resonant converters. The proposed converter operates as buck and boost converter so that the normalized voltage gain can be regulated from zero to infinity. The direction of power flow and the operation mode can be changed automatically with the simple PWM control. In the entire operation range, ZVS turn-on is achieved for all the active switches. The current flowing through the primary and secondary side of the converter is controlled using current limit control techniques.*
Keywords: *Bidirectional converter, PWM control, series resonant converter, wide voltage gain, zero-voltage switching*

I. Introduction

Energy storage system such as batteries and super capacitors capable of long-term or short-term energy buffering has been a critical part in various DC micro grids. A bidirectional DC-DC converter (BDC) is the key equipment to interface storage batteries or super-capacitors with a DC voltage bus in a DC micro grid. An isolated BDC can be seen as an improved version of a unidirectional DC-DC converter. Various types of isolated BDCs, including PWM controlled BDCs, phase-shift controlled dual-active-bridge (DAB) BDCs, and resonant BDCs etc., have been proposed in the last decades. Among these BDCs, the DAB BDC has attracted a lot of research interests because of its advantages of zero-voltage switching (ZVS), low voltage stresses on switches, flexible control and Buck-Boost voltage conversion capability . However, it is not suitable for wide voltage range applications due to limited ZVS range, high turn-off losses, and high root-mean-square currents through the transformer and semiconductor devices because of high circulating current. The turn-off current associated loss can be reduced by using a resonant BDC, because a nearly sinusoidal current is obtained by using a resonant tank, which enables low turn-on/off current. Similar to the traditional DAB BDC, the phase-shift angle between the primary and secondary switching-bridges can be employed as the control variable to regulate the amplitude and direction of power flows. In comparison with the phase-shift control, variable-frequency control is more popular for resonant converters. In order to achieve wider and higher voltage conversion ratio, improved resonant tanks, such as LLC resonant tank , LCLC resonant tank and CLC resonant tank etc., were proposed. But, it is difficult to optimize the parameters of the resonant tank and transformer under variable frequency control. If the switching frequency is fixed at the resonant frequency of the resonant tank, high efficiency can be achieved easily with a resonant BDC but the voltage regulation capability of the resonant BDC is lost . Besides, accurate synchronous driving of bidirectional resonant converters is much more difficult than that in a PWM controlled BDC . Furthermore, automatic and smooth mode transition between forward and backward modes is another issue to be solved for most of the existing resonant BDCs because the control strategies in the two modes are different. On the other hand, the voltage gain of almost all the existing resonant converters is highly dependent on the amplitude and direction of transferred power, which complicates the control, design and implementation of resonant converters.

The major purpose of this paper is to propose a novel bidirectional series-resonant (BSR) converter. Close observation indicates that the proposed converter has the following features:1) The voltage gain of the converter is only determined by the effective duty cycles and has nothing to do with the amplitude and direction of transferred power, which is a major improvement and innovation of the proposed BSR converter. 2) Theoretically, the normalized voltage gain can be regulated from zero to infinite, which makes the proposed converter suitable for wide voltage range applications. 3) ZVS of all the active switches have been achieved within the entire operation range with the help of an auxiliary inductor. 4) Automatic and smooth mode transition between forward and backward modes is achieved due to the unique voltage gain characteristics of the proposed converter. 5) The switching frequency is fixed at the resonant frequency of the series-resonant tank, and the duty cycles of primary and secondary-side switches are employed as the control variables. Therefore, the control is simple and easy to implement.

The major contribution of this paper is to design a feed back loop to set the charging current and control the primary and secondary side duty cycle for automatic buck and boost mode transition. And also to design a feed back loop to set the maximum temperature in the battery so that the battery will cut off automatically when it exceeds the limit.

II. Proposed Bsr Converter

II.1 Circuit Diagram:

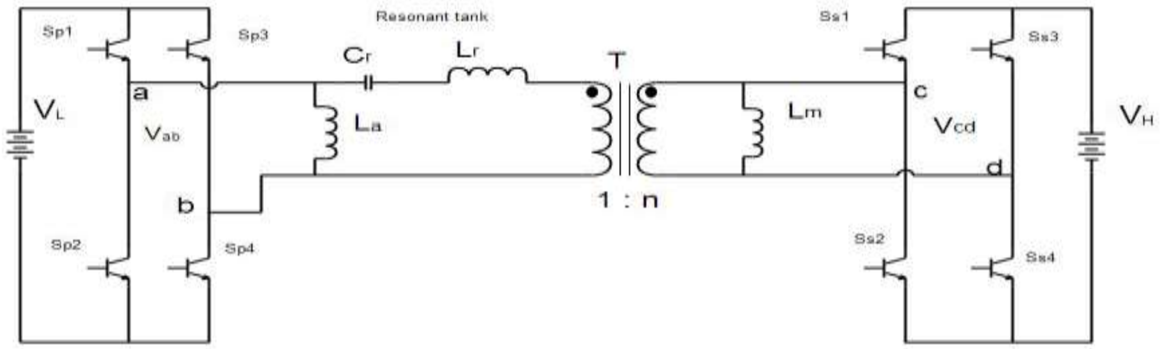

Fig 1: Proposed Resonant Bidirectional DC-DC Converter.

The topology of the proposed BSR converter is shown in Fig 1. A full bridge network comprising of four MOSFETs, Sp1-Sp4, is employed on the primary side of the proposed converter, while another full-bridge network comprising of Ss1-Ss4 is used on the secondary-side. The two full-bridges are connected by a high frequency transformer T, and a series-resonant tank comprising of Lr and Cr**.** An auxiliary inductor, La, is employed on the primary side and connected to the midpoints of the full-bridge to achieve ZVS for the four primary-side switches Sp1-Sp4, whereas the magnetizing inductance, Lm, of the transformer is functioned as another auxiliary inductor to realize ZVS of the four secondary switches Ss1 - Ss4. VP and VS are the voltage sources on primary and secondary sides respectively, and n is the secondary to primary turns ratio of the transformer T. In the proposed BSR converter, the resonant capacitor Cr only resonates with Lr, and never resonates with the two auxiliary inductors La and Lm, because the voltages across La and Lm are always clamped by the full-bridge networks on the primary and secondary-side.

II.2 Control Strategy

In this bidirectional converter, a simple PWM control strategy is proposed and applied to regulate the power flows in a wide voltage range and achieve an attractive load-independent voltage-gain characteristic. The switching frequency, fs, of the converter is fixed at the resonant frequency, fr, of the series-resonant tank. The switches in the same switching-leg are driven complementary. The two switching-legs in the same full-bridge are operated in an interleaved fashion with 180 degree phase shift. In both the primary and secondary-side full-bridges, the two upper switches, Sp1 and Sp3 or Ss1 and Ss3, share the same duty cycle, while the two lower switches, Sp2 and Sp4 or Ss2 and Ss4, have the same duty cycle. The driving signals of Sp1, Sp4, Ss1 and Ss4 are always center-aligned. A square or quasi-square wave high frequency voltage Vab is produced by the primary side full-bridge, while a another high frequency voltage Vcd is generated by the secondary side full-bridge. The two voltages Vab and Vcd are center-aligned as well. The control of the BSR converter is achieved only by regulating the pulse-width of the two voltages Vab and Vcd. It is obvious that the pulse-width of Vab and Vcd can be regulated by the duty cycle of either the two upper switches or the two lower switches in the corresponding full-bridge network. Without loss of generality, the duty cycle Dp of the two upper switches Sp1 and Sp3 and the duty cycle Ds of the two upper switches Ss1 and Ss3 are employed as the two control variables. The following analysis will indicate that the voltage gain of the converter is only determined by the two duty cycles, Dp and Ds, and has nothing to do with the amplitude and direction of the transferred power. The normalized voltage gain Gb is defined as:

$$Gb = Vs/nVp \quad (1)$$

The proposed BSR can work in the Buck mode with Gb<1 or in the Boost mode with Gb>1. In the Buck mode, the duty cycle Dp < 0.5 and is used to regulate the power flow while the duty cycle Ds is fixed at its maximum value 0.5. In contrary, in the Boost mode, the duty cycle Ds < 0.5 and is used to regulate the power flow while the duty cycle Dp is fixed at its maximum value 0.5.

III. Principle Of Operation

III.1) Buck mode with $G_b < 1$, $D_p < 0.5$ and D_s=0.5

The key waveforms of the proposed converter in the buck mode are illustrated in Fig 2 where Fig 2 is the waveforms of the forward mode, i.e. the energy is transferred from V_L to $V_{H.}$, but in backward mode, the energy is transferred from V_H to V_L. The switching sequence and waveforms of the two modes are exactly the same due to the symmetry of the circuit and operation of the proposed converter, the only difference is that the direction of i_{Lr} and v_{Cr} is reversed.

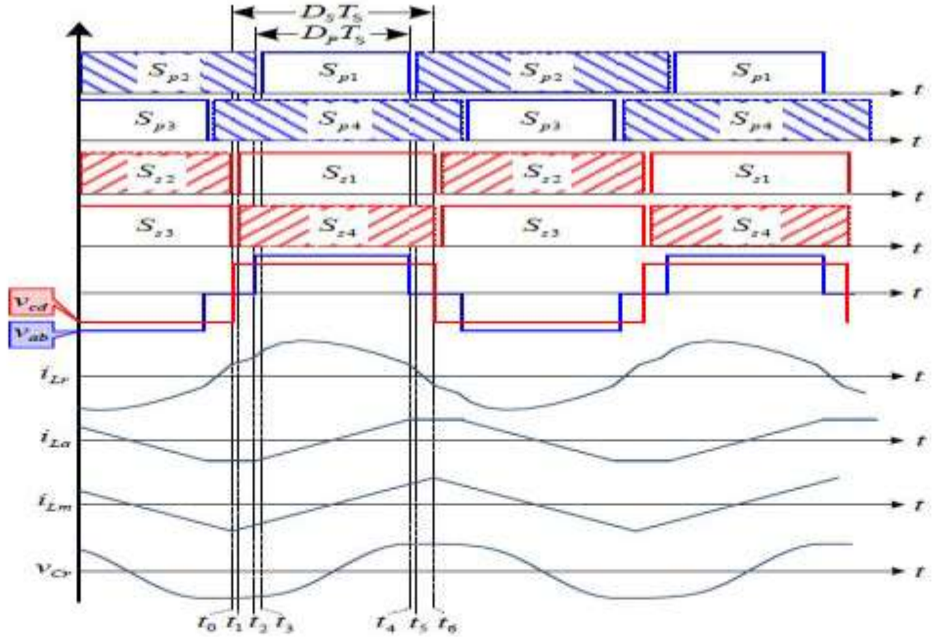

Fig 2: Waveforms of proposed converter in buck forward mode.

III.1.1) Modes Of Operation:

1) Mode 1:[t_0 to t_1]

The circuit diagram of mode 1 is shown in the Fig 3. Before t_0, S_{p2}, S_{p4}, S_{s2} and S_{s3} are ON, the voltage V_{ab} of the primary-side bridge is clamped to zero while the voltage V_{cd} of the secondary side bridge is -V_H. At t_0, S_{s2} and S_{s3} are turned-OFF. The body-diodes of S_{s1} and S_{S4} begin to conduct and V_{cd} commutates to V_s due to the negative current of i_{Lm}.

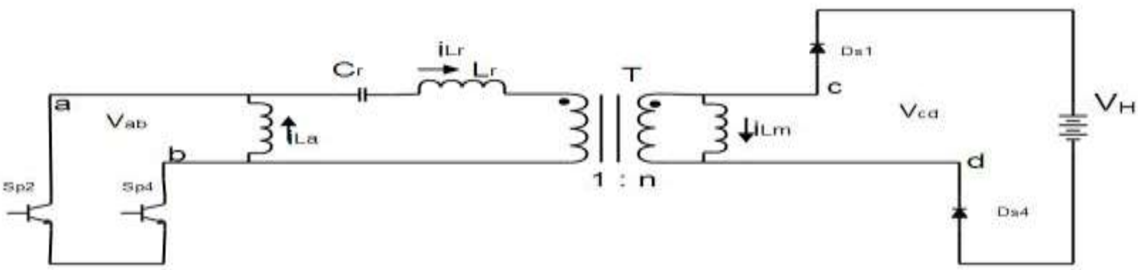

Fig 3: Mode 1

2) Mode 2:[t_1 to t_2]

The circuit diagram for mode 2 is shown in the Fig 4. At t_1, the switches S_{s1} and S_{s4} are turned ON with zero voltage. The operation of the mode 1 and 2 is similar to the freewheeling stage of a traditional Buck converter. The primary side voltage V_{ab} is clamped to zero while $V_{cd}=V_H$. Therefore, the current of the series resonant tank and the auxiliary inductor L_a, i_{La}, freewheels through S_{p2} and S_{p4}. Meanwhile, the magnetizing current i_{Lm} increases linearly due to the positive voltage V_H and assume $V_H = V_s$:

$di_{Lm}/dt = V_s/L_m$ (2)

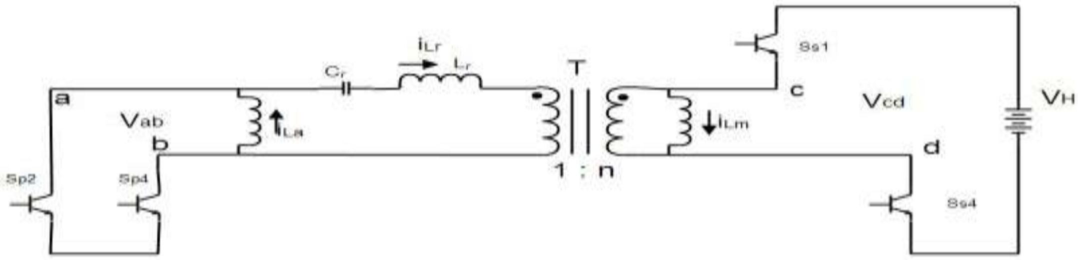

Fig 4: Mode 2

During the two Stages, the resonant inductor resonates with C_r. Assuming the voltage on C_r and current of L_r at the time t_0 is V_0 and I_0, respectively, the current $i_{Lr}(t)$ and voltage $v_{Cr}(t)$ can be calculated as:
$i_{Lr}(t) = I_0 \cos w_r t -((V_s+nV_0)/nZ_r)\sin w_r t$ (3)
$V_{Cr}(t) = -Vs/n+I_0Z_r \sin w_r t +(V_0+(V_s/n))\cos w_r t$ (4)

3) Mode 3:[t_2 to t_3]

The circuit diagram for mode 3 is shown in the Fig 5. At t_2, the switch S_{p2} is turned OFF. Then, the body diode of S_{p1} begins to conduct because of the negative current of i_{La}. The voltage V_{ab} commutates to V_L, and the current i_{La} begins to increase linearly and assumes $V_L = V_P$:
$di_{La}/dt = V_p/L_a$ (5)
Meanwhile, L_r continues to resonate with C_r, $i_{Lr}(t)$ and $v_{Cr}(t)$ are expressed as follows:
$i_{Lr}(t) = I_{Lr}(t_2)\cos w_r(t -t_2)+((n[V_p-V_{Cr}(t_2)]-Vs)/nZr)\sin w_r(t-t_2)$ (6)
$V_{Cr}(t) =V_p-V_s/n+I_{Lr}(t_2)Z_r \sin w_r(t-t2)+[V_{Cr}(t_2)+(V_s/n)-V_p)\cos w_r(t-t_2)$ (7)

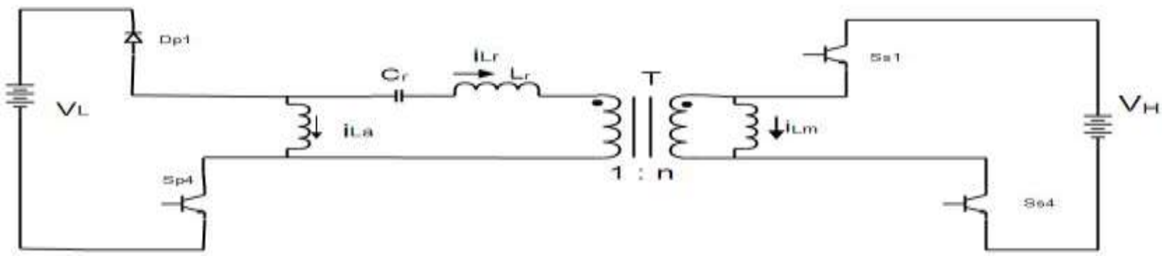

Fig 5: Mode 3

4) Mode 4:[t_3 to t_4]

The circuit diagram of Mode 4 is shown in the Fig 6. At t_3 , the switch S_{p1} is turned ON with zero voltage. This mode ends when S_{p1} is turned OFF at t_4.

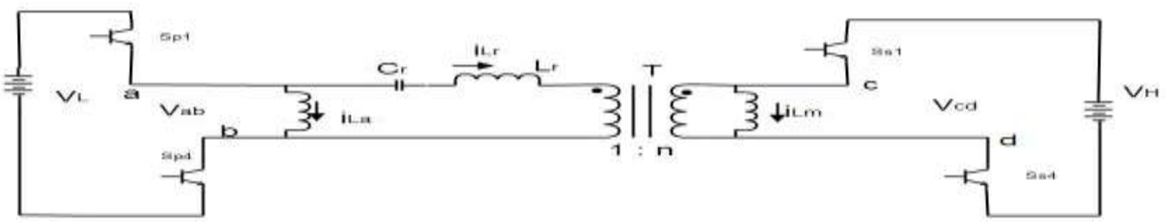

Fig 6: Mode 4

5) Mode 5:[t_4 to t_5]

The circuit diagram of mode 5 is shown in the Fig 7. At t_4 , S_{p1} is turned OFF. The body diode of S_{p2} begins to conduct because of the positive current of i_{Lr} and i_{La}, and the voltage V_{ab} commutates to zero again. It means the lower switch S_{p2} is easier to achieve ZVS than the upper switch S_{p1}.

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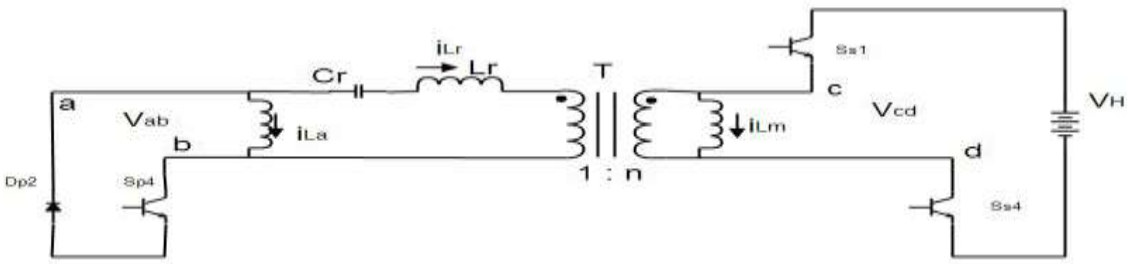

Fig 7: Mode 5

6) Mode 6:[t_5 to t_6]

The circuit diagram of mode 6 is shown in the Fig 8. At t_5 , the switch S_{p2} is turned ON with zero voltage. During the mode V and VI, V_{ab} is clamped to zero by S_{p2} and S_{p4}. Therefore, the current of the resonant tank and the auxiliary inductor L_a freewheels through S_{p2} and S_{p4}. Meanwhile, L_r continues to resonate with C_r, and the current $i_{Lr}(t)$ and $v_{Cr}(t)$ can be calculated as follows:

$i_{Lr}(t) = I_{Lr}(t_4)\cos w_r(t - t_4)-([nVs+V_{Cr}(t_4)])/nZr)\sin w_r(t-t4)$ (8)

$V_{Cr}(t) = -Vs/n+I_{Lr}(t_4)Z_r\sin w_r(t-t4)+[V_{Cr}(t_4)+(Vs/n)\cos w_r(t-t4)$ (9)

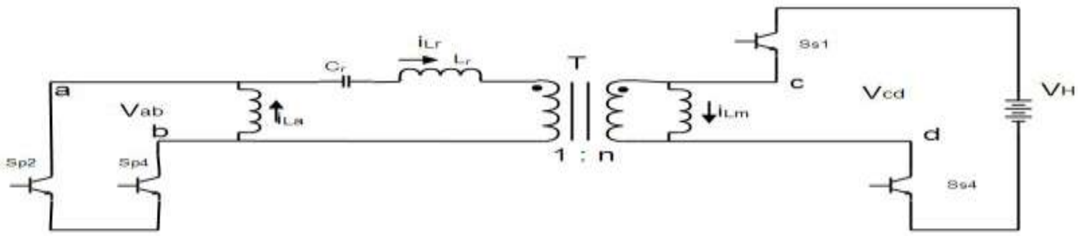

Fig 8: Mode 6

IV. Simulation

IV.1) Simulation Parameters

Components	Parameters
Primary side Voltage	320V-480V
Secondary side Voltage	400V
Rated output Power	1600W
Switching frequency	100kHz
Magnetising Inductance	500 µH
Auxillary Inductor	500 µH
Resonant Capacitor	16.9nF
Resonant Inductor	50 µH

IV.2) Simulation Diagram

The simulation circuit for boost forward mode is shown in Fig 10. The primary side voltage is varied from 320V to 480V. The secondary side voltage is fixed at 400V. The primary side is connected to a full bridge inverter. The output of the inverter is given to the primary side of the high frequency transformer using a series resonant tank circuit. The secondary side of the transformer is connected to the full bridge rectifier.

In the boost forward mode, the duty cycle of the secondary side is controlled and the duty cycle of the primary side is fixed. To limit the current flowing through the secondary side, a current limit control technique is used. In the current control method, a PI controller is used.

In the simulation results, the boost forward mode flows power from left to right. Thus the average current measured in primary and secondary side should be negative. But in the boost backward mode, the power flows from right to left. Thus the current measured from primary and secondary side should be negative.

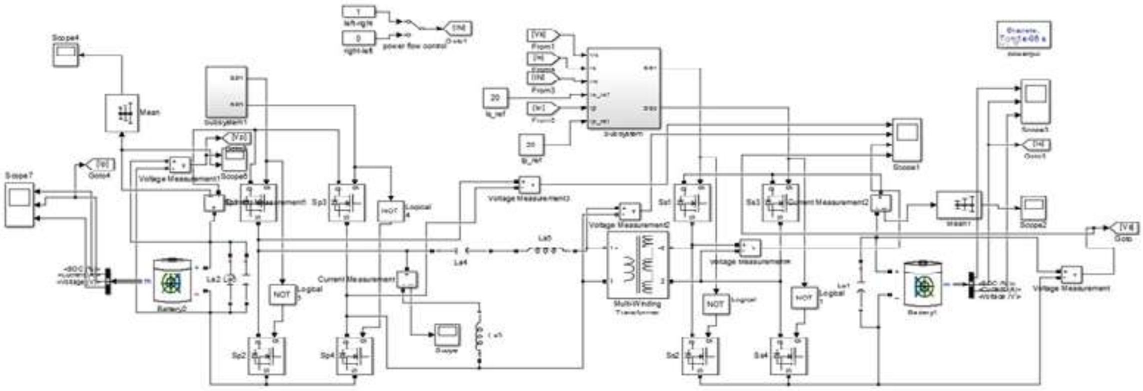

Fig 10: Simulation circuit for boost forward mode

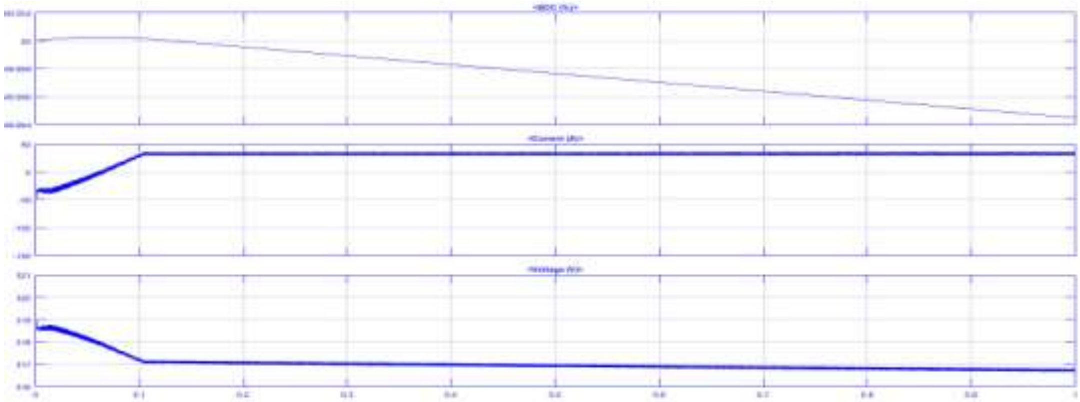

Fig 11: Simulation result for battery parameters on left side.

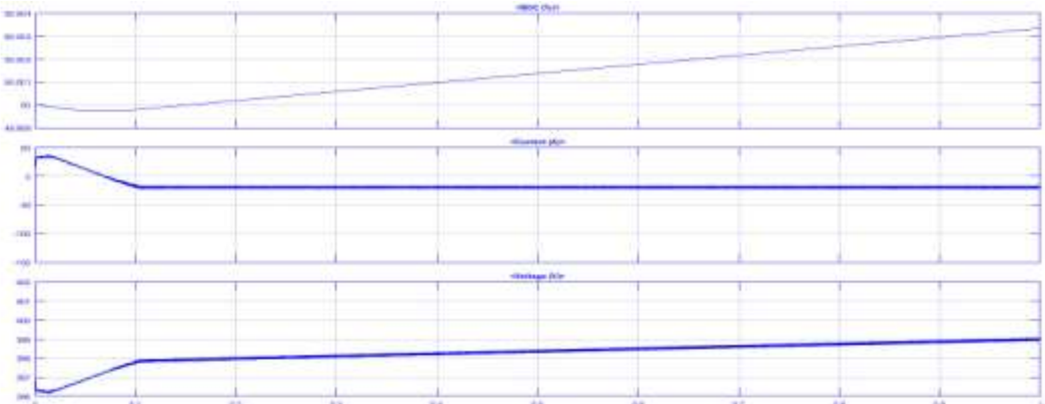

Fig 12: Simulation result for battery parameters on right side.

PRIMARY & SECONDARY CURRENT:(I_p =28A, I_S =17A)

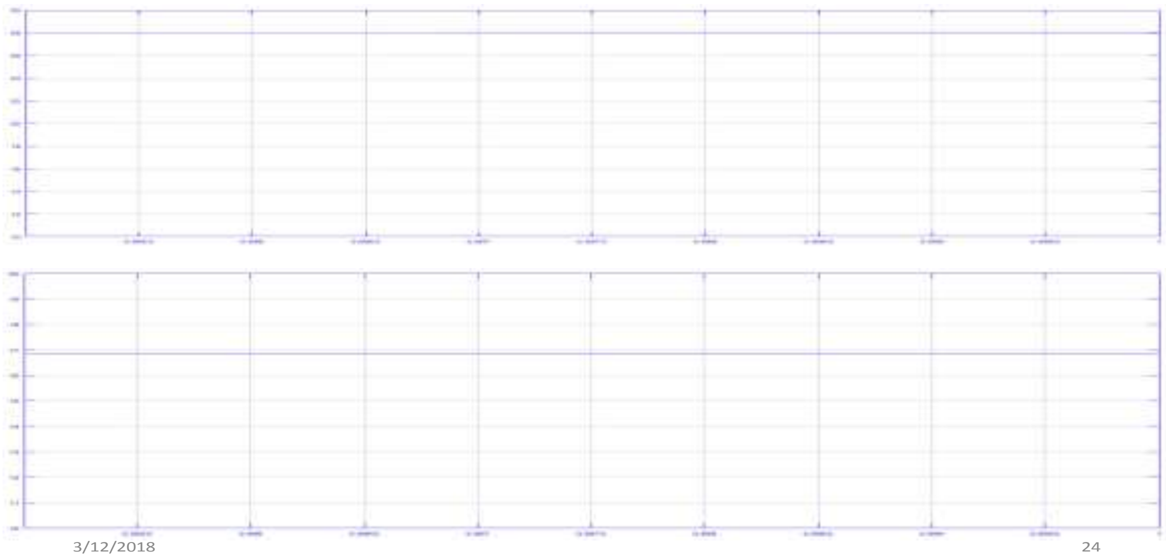

Fig 13: Simulation result for the average current in both primary and secondary conditions.

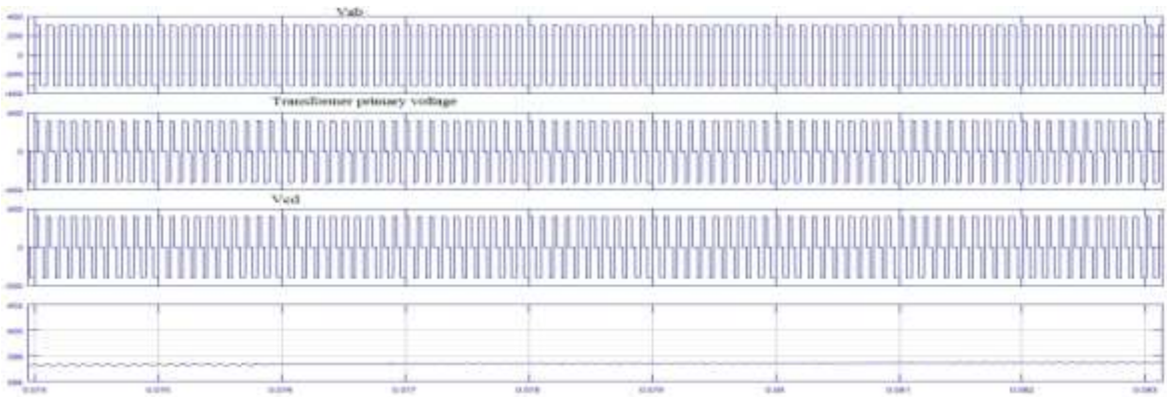

Fig 14: Simulation result for different voltages in boost forward mode.

The simulation circuit for boost forward mode is shown in Fig 16. The closed loop circuit to limit the current flowing through the converter using PI controller . The battery parameters such as state of charge, voltage and current is shown in Fig 11. The state of charge is 50% and the voltage is set as 320V. The average current is obtained as 28A. The primary and secondary side average current is shown in Fig 13. The secondary side battery parameters are shown in Fig 12. The state of charge is 50% and battery voltage is set as 400V. The secondary side average current is obtained as 17 A. The transformer primary and secondary voltages and the voltages V_{ab} and V_{cd} are shown in Fig 14.

The simulation circuit for boost backward mode is shown in Fig 15. The battery parameters for left side such as state of charge, voltage and current is shown in Fig 16. The state of charge is 50% and the secondary side voltage is 400V. The battery parameters for right side is shown in Fig 17. The average primary and secondary currents are shown in Fig 18 and 19. The average current is obtained as -20.3A and -20.78 A respectively.

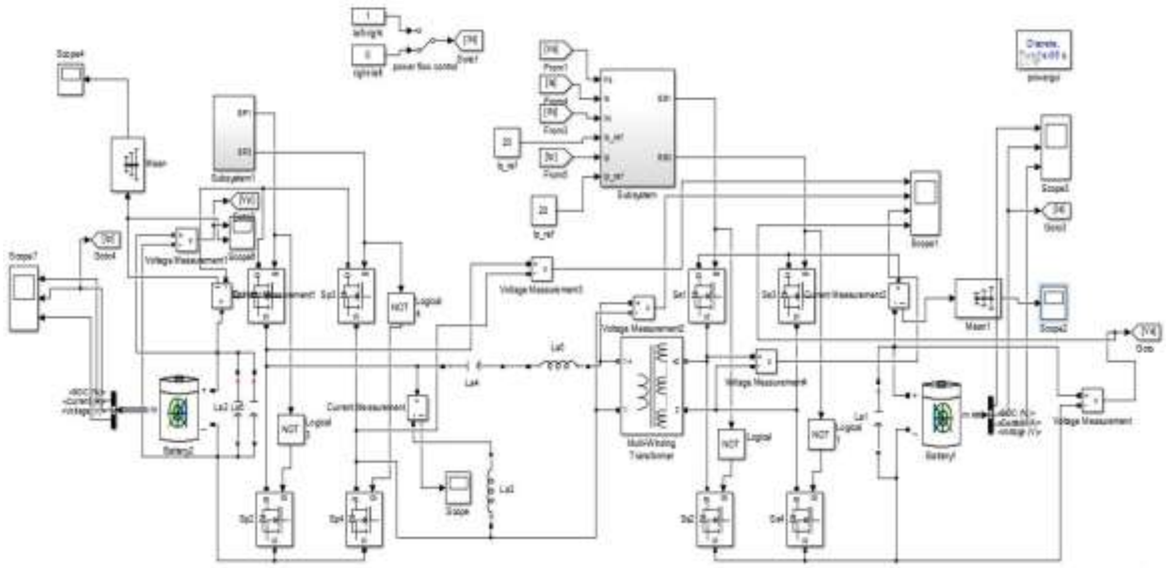

Fig 15: Simulation circuit for boost backward mode

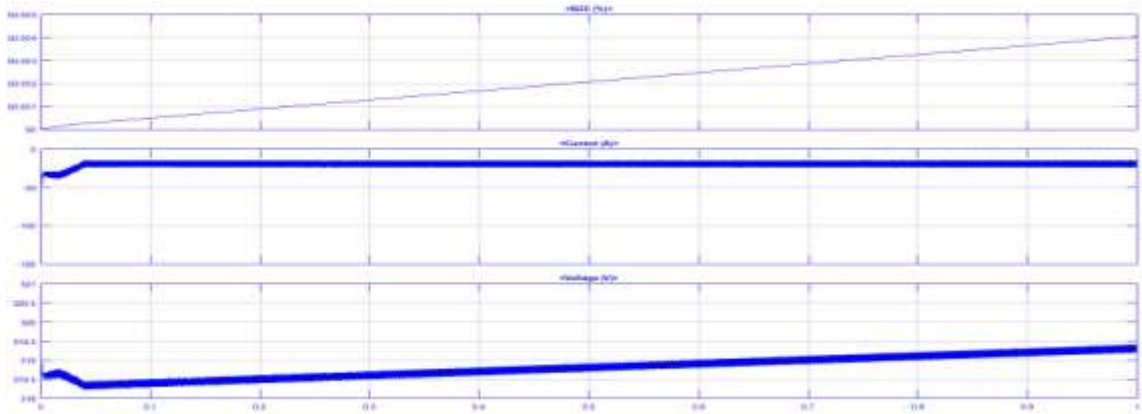

Fig 16: Simulation result for battery parameters on left side.

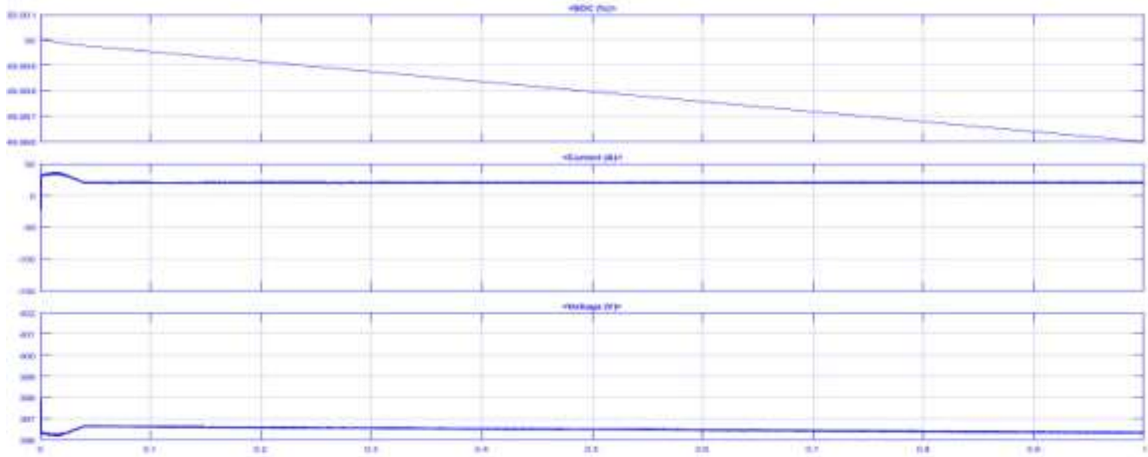

Fig 17: Simulation result for battery parameter on right side.

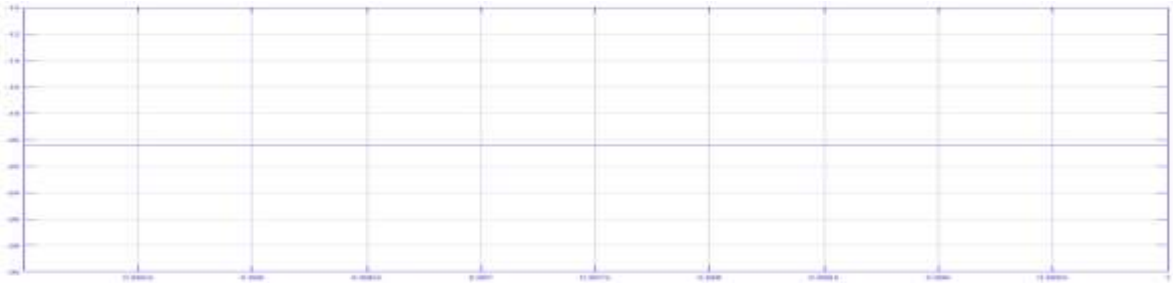

Fig 18: Simulation result for average current in primary side.

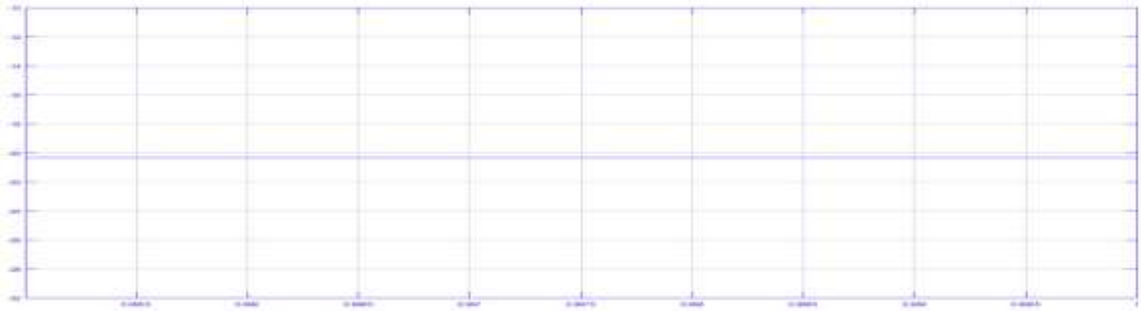

Fig 19: Simulation result for average current in secondary side

V. Conclusion

A novel bidirectional series-resonant (BSR) converter and its control strategies have been proposed in this paper. Bidirectional voltage and power flow regulation with a fixed-frequency PWM control strategy, which makes the implementation and control of the BSR converter easily. The normalized voltage gain is only determined by the effective duty cycles of the primary and secondary switches and has nothing to do with the amplitude and direction of the transferred power. Buck and Boost voltage conversion capabilities in both forward and backward modes, which makes the proposed converter a promising candidate for bidirectional power conversion applications with wide voltage range. Smooth and automatic mode transition has been achieved easily because of the simple control and unique voltage gain characteristics of the proposed BSR converter. Zero-voltage-switching of all the active switches within the entire voltage and load ranges with the help of an auxiliary inductor. The circulating energy for soft-switching is low because the converter always operates at the series resonant frequency. All of these key features combine to result in a high-efficiency isolated bidirectional DC-DC converter for DC microgrid applications.

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