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Bidirectional AC/DC converter connecting AC and DC microgrids for smart grids

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ABSTRACT

This paper proposes a converter connecting two independent AC and DC microgrids in a flexible microgrid and smart grid system. With this converter, basic DC/DC converter types such as Flyback are used to develop the power circuit and controller for the converter that is capable of integrating the operating functions for the operation between microgrids. The converter uses bidirectional switching locking technology to simplify the control algorithm. The energy is converted in two directions, AC/DC and DC/AC, with different working principles of increasing and decreasing voltage according to the standards of the distribution grid and DC microgrid. The TDH value is significantly limited when using the recovery circuit solution. The converter is designed, simulated based on OrCAD software, and tested with a capacity in the range of 2-10 kW. The DC microgrid output voltage is 400 VDC, voltage is 220 VAC.

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1. INTRODUCTION

Microgrid systems in developed countries, such as Southeast Asia in Asia are currently being formed and have not yet entered the electricity law development system of the countries. Microgrids are naturally formed according to the needs of some components in the distribution grid, such as power sources, loads, supply lines, and storage systems [1], [2]. Therefore, management, operation, and control have many changes, requiring integrated components and adaptation to the above changes for microgrids.

The traditional power system in Vietnam and Asian countries is based on AC distribution grids. Naturally formed grids will have conversion links based on AC grids, including DC microgrids [3], AC microgrids [4], and hybrid grids as electronic transformer technology develops for each specific grid and different power sources. As renewable energy sources (distributed sources) develop naturally, the monitoring and management system is also a problem; in addition, distributed power sources are intermittent. To effectively manage distributed power sources, loads, and possibly energy storage, a systematic view is required. By integrating all these distributed units together, a micropower system is formed from the distribution side, thus being nominated as a microgrid. Current power grids use conventional passive devices to connect the grid components and are therefore no longer suitable for the emergence of many microgrids in the future due to limitations in modular flexibility [5], [6], compatibility of parameters such as voltage, frequency with the grid [7], [8]. In this sense, the need to include power converters in these developing systems is mandatory due to their modularity and decentralized control capabilities [4], [9], [10].

Alternatively, power conversion applications can be performed using various forms, such as stacking multiple single-stage converters, combining converters in parallel or in series to increase or decrease the input value, changing the power value, or performing intermediate stages for one form of power, such as DC, and then further converting it to DC power as required. There are direct converters from an AC power source to a DC power source that have input power factor correction solutions according to standards such as IEC 1000-3-2 [11]. The DC to DC converter type has the ability to adjust the output voltage up or down according to actual load requirements. This research work considers the unidirectional, bidirectional, single-stage, two-stage AC/DC power converters. AC/DC two-stage converters are used for converting AC power to DC power, such as chargers in the form of bidirectional energy conversion, driving DC motors, supplying power to DC loads in AC distribution grids, or AC microgrids [12]. AC/DC two-stage converters have a basic first stage that functions to convert AC power parameters into DC. The second stage, DC/DC has the ability to increase and decrease current and voltage parameters according to output requirements. The two-stage converter has the same limitations as the stacked converter, so the double conversion power of the two stages results in efficiency that is also limited by multiplying the average efficiency across the entire converter. In addition, the two-stage converter also has a limitation that there is a capacitor connection between the two stages to support the power, which makes it bulky and reduces the power density of the converter [13], [14].

Two-stage AC/DC converters can have high power factors, low input current harmonics, and regulated DC link voltages, but they have the problem of many components in the converter, and the control part is complicated because of the two processes in the converter. Some solutions when using a single-stage AC/DC converter with some design considerations for the power circuit, such as low cost, small size [15], [16]. Practical converters all use basic converter types such as flyback, half-bridge, or full-bridge converters, or combine converters together to create a converter according to the requirements to meet the input power and DC or AC output power types. The combination will create flexibility in power type as well as the actual power requirements. AC/DC converters also have basic types aiming at increasing power factor and reducing input harmonics of current and voltage, there are some solutions. The single-stage converter is cheaper, smaller in size, the energy density increases, and the control is simpler while still ensuring the energy conversion process [13]-[17].

In this paper, an AC/DC converter is proposed. The converter performs direct and isolated bidirectional power conversion between two AC and DC grids. The concept of the proposed converter is based on the primary side of the transformer, but without the bridge diode, which further eliminates the line frequency rectification losses. Single-stage converters derived from the basic Flyback and Full-Bridge converters, with the advantages of the basic converters, have introduced some solutions in their internal structure to create isolated AC-DC bidirectional converters. Figure 1 shows the operation and power conversion between two microgrids and the independent internal microgrids. When the grid is unavailable, the battery supplies power to the AC and DC loads. When the grid is available, the AC and DC loads are met along with the battery charging. The paper also includes i) reduction of components due to the use of the same components in both power directions, ii) galvanic isolation, iii) minimum number of active switches, iv) low ripple, v) relatively high efficiency in the energy conversion process, and vi) meet the operational flexibility, and meet the continuity of power supply for two power grids. In DC or AC power grids, there are flexible converters capable of operating internal energy exchange within the grid [18]-[25].

2. PROPOSED AC/DC CONVERTER STRUCTURE

The DC microgrid also includes several components in the power system such as DC loads, distributed energy sources transmitted on a DC line, as shown in Figure 1. The DC microgrid can be connected to a single-phase or three-phase AC microgrid with different conversion forms and can also be directly connected to the distribution grid. In the content of the work, the connection to a single-phase microgrid is implemented. The DC microgrid has now emerged with the demand for loads as well as distributed energy sources with advantages in efficiency during long-distance transmission and energy storage in the power system. Therefore, the connection between the DC microgrid and the AC microgrid will improve efficiency and energy storage during the use of energy combined in a system. It also represents an independent operating mode when the grids are not in demand and support energy exchange with each other.

The converter performs isolation conversion using a pulse transformer with two symmetrically connected secondary windings. Based on the Flyback converter, this proposed improvement to the AC/DC converter makes the conversion bidirectionally isolated. Figure 2 shows the power circuit structure of the AC/DC converter. The converter uses high-frequency DC modulation and is capable of bidirectional energy conversion from the AC microgrid to DC and vice versa. The circuit operates on two half-cycles of the 50 Hz alternating current. In the primary part of the transformer, a bidirectional switch S1 and S2 is used. The secondary side of the transformer is connected to the DC microgrid in the form of a half-bridge with bidirectional switches S3-S6. The combination of the boost inductor and the half-bridge contributes to shaping the current input and the required output voltage with a larger amplitude. The coil is changed as the primary coil if the terminal is input, if the transformer coil is secondary when the terminal is output, the primary coil working in boost mode will work in continuous conduction mode (CCM) connected to the micro-AC grid to shape the input signal stably.

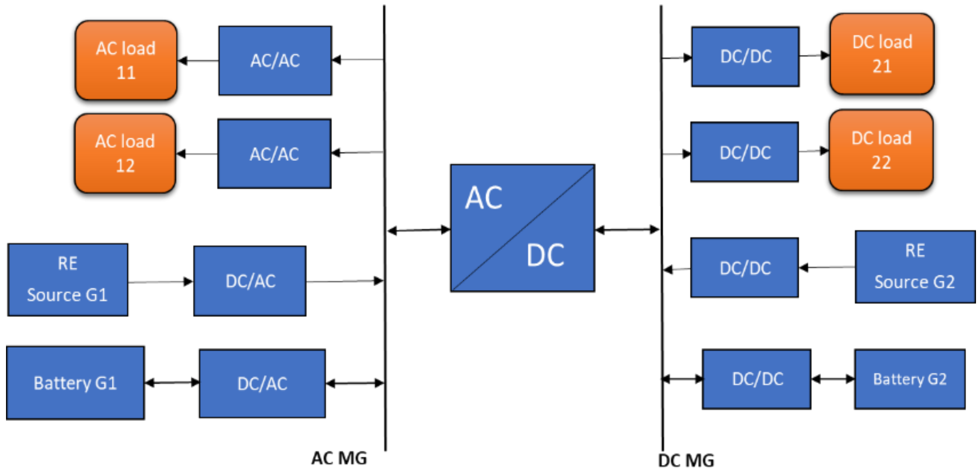


Figure 1. System connecting two AC and DC microgrids using AC/DC bidirectional converter

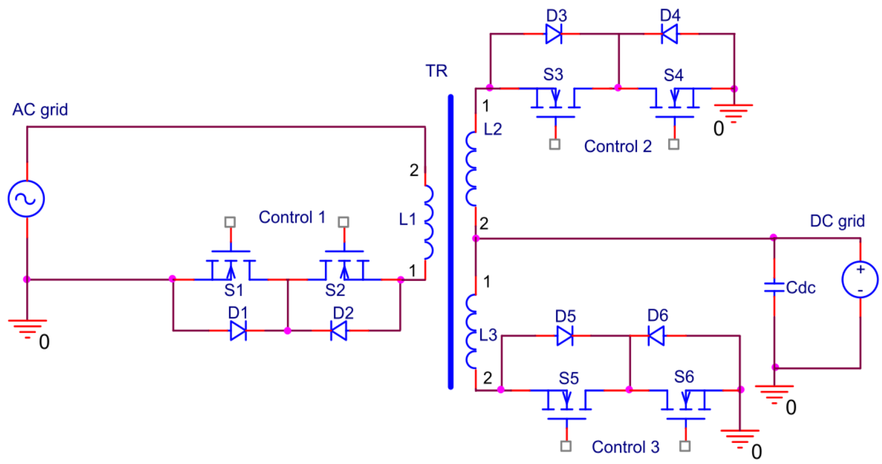


Figure 2. Schematic diagram of the proposed system

2.1. Operating principle of the converter

Energy is converted in the direction from the AC microgrid to the DC grid. The operating mode of the converter is shown in two main modes as follows:

- Mode 1: Half-cycle positive AC current and voltage time period from (0-pi) the power switch S1 and D2 open to let the current flow from the AC source through the coil L1 to ground. Energy is converted through the two coils L2 and L3 when the switches S3 and S5 open respectively, diodes D6 and D8 open to let the current flow to the DC grid. Mode 1 operation is described in Figure 3. The case in mode 1 operates specifically as described in Figure 3(a). The case in mode 1 is described in Figure 3(b). In this case, we have given the control method of the switches and the condition that the opening time of the switches S3 and S5 in this case is less than half of the control time to open the switch S1 as in (1).

$$d3 = d5 = d < 1/2d1 \quad (1)$$

Where: i) *d3*: duty cycle of switch S3; ii) *d5*: duty cycle of switch S5; and iii) *d1*: duty cycle of switch S1.

(a)

(b)

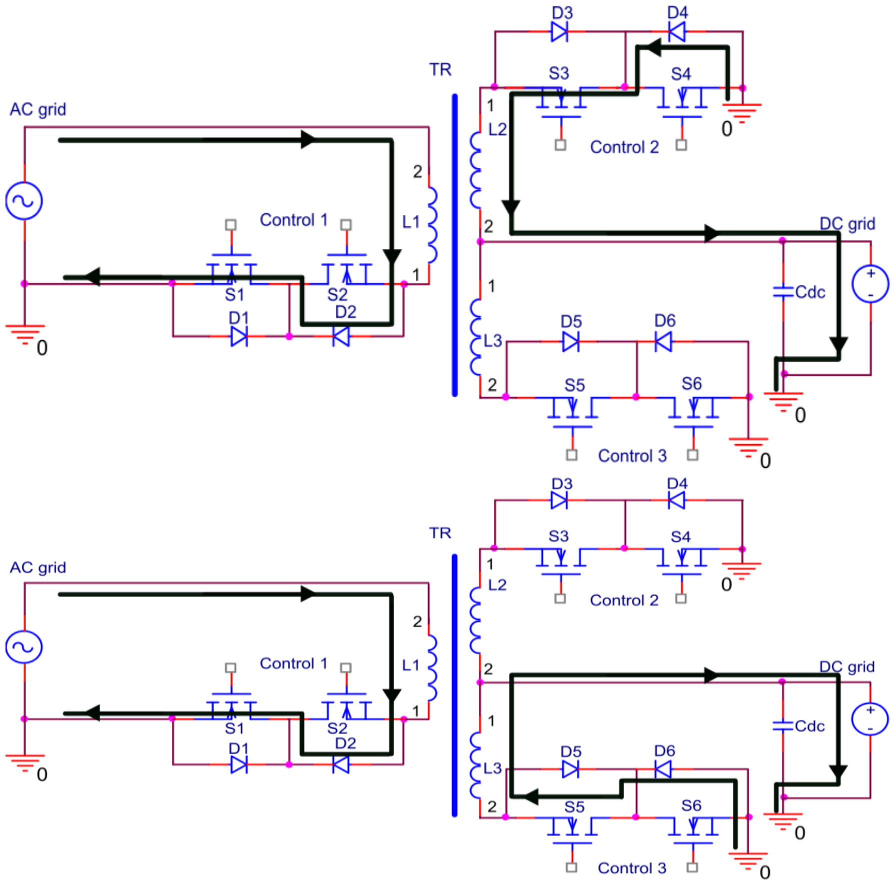


Figure 3. Mode 1 operation diagram: (a) case 1 in mode 1 and (b) case 2 in mode 1

- Mode 2: Half-cycle negative AC voltage period from π-2π power switches S2 and D1 open to let current flow from the negative AC source through coil L1. Energy is converted through two coils, L2 and L3, when switches S3 and S5 open, respectively, and diodes D4 and D6 open to let current flow into the DC grid. Mode 2 operation is described in Figure 4. Rectified voltage on the DC grid side can be increased by controlling switches S1 and transformer ratio Tr. Operation 1 in mode 2 is described in Figure 4(a). Operation 2 in mode 2 is described in Figure 4(b). In this case, we have given the control method of the switches and the condition that the opening time of the switches S3 and S5 in this case is less than half of the control time to open the switch S1, as in (2).

$$d3 = d5 \text{ or } d4 = d6 = d < 1/2d1 \tag{2}$$

The rectifier voltage calculation expression is as (3) according to the flyback with 2 secondary windings.

$$V_{outDC} = V_{AC}\frac{N2}{N1}\frac{d1}{1-d1} \tag{3}$$

Where i) *N1* primary coil of transformer TR; ii) *N2* secondary coil L2 or L3; and iii) *d1* duty cycle of switch S1 or S2. Figure 4(c) shows the current and voltage signal on the switch S1 when operating with a peak voltage value of more than 200 V. The voltage at the DC microgrid reaches 400 VDC. The power transmitted from the AC to the DC microgrid is nearly 3 kW.
- Mode 3: In the case of energy conversion from a DC microgrid to an AC grid. The converter operates in the following modes: In mode 3 of the converter operation, switches S4 and S6 are active, diodes D3 and D5 conduct the energy flow from the DC grid supplied through the transformer TR through the coils L2 and L3. The operation process is in the negative cycle period. Switch S1 and diode D2 operate according to the SPWM modulation control through the coil L1, as shown in Figure 5. Figures 5 (a) and 5(b) describe the operation of case 1 and case 2 in mode 3.

(a)

(b)

(c)

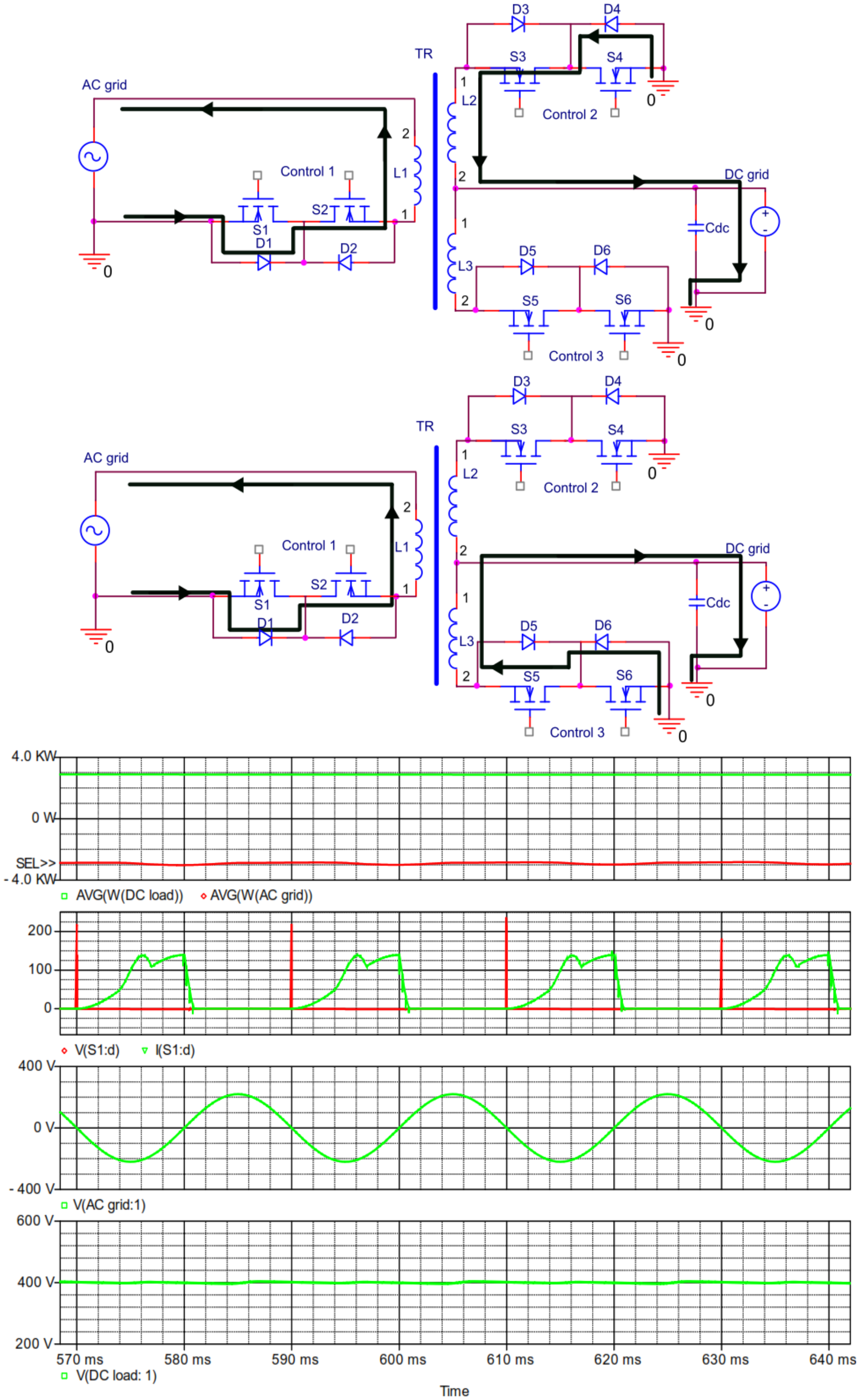


Figure 4. Operation mode of the proposed converter mode 2 and simulation graph: (a) operation 1 in mode 2, (b) operation 2 in mode 2, and (c) simulation graph of modes 1 and 2

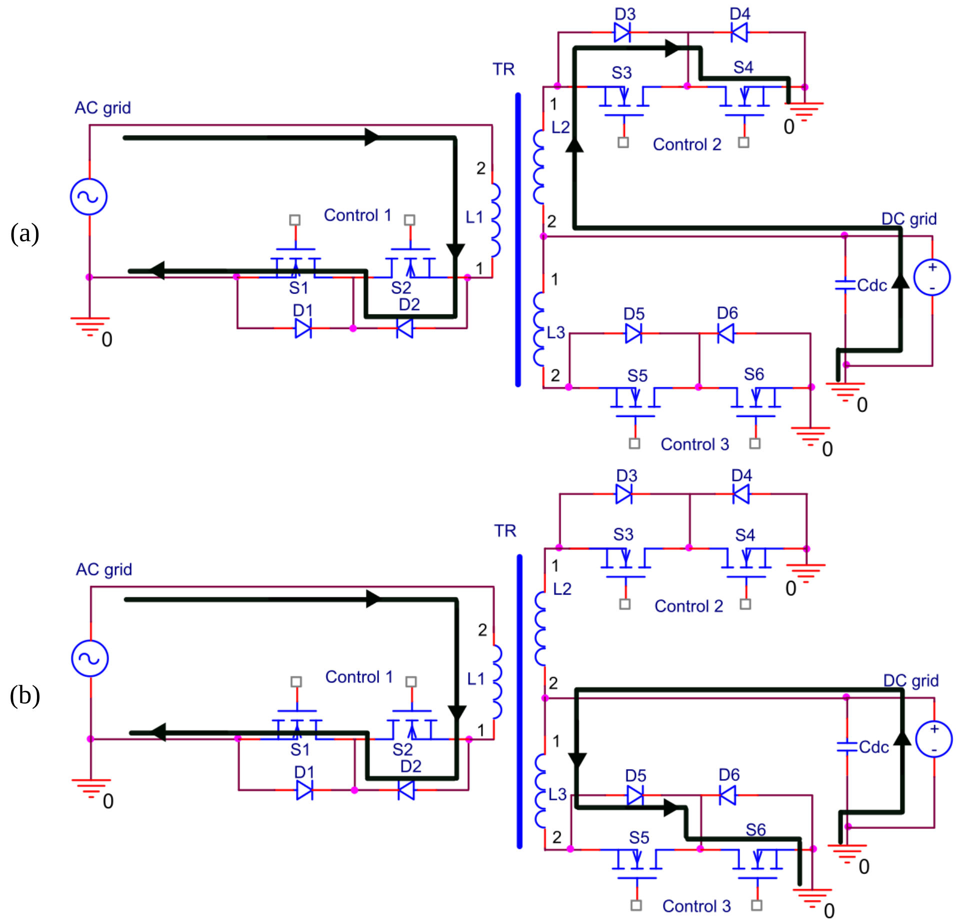


Figure 5. Operation diagram of mode 3 converter: (a) operation 1 in mode 3 and (b) operation 2 in mode 3

- Mode 4 switches S4 and S6 operate for current to pass through, diodes D3 and D5 conduct energy flow from the DC power grid supplied through transformer TR through coils L2 and L3. The operation process is during the negative cycle of the AC power source. Switches S1 and S2, diodes D1 and D2 operate according to SPWM modulation control through coil L1 as described in Figure 6 (see Appendix). In this case, the voltage will decrease in amplitude to the value connected to the distribution grid, as shown in (4). Figures 6(a) and 6(b) describe the operating principle of operation 1 and operation 2 in mode 4.

$$V_{outAC} = \sqrt{2}V_{DC}sin\omega t\frac{N1}{N2}d \quad (4)$$

d duty cycle of switch S4 or S6

Figure 6 (c) shows the current and voltage patterns of the DC microgrid and AC microgrid, the operating current of switch S2, and the operating current of the primary winding of transformer TR. They transmitted and received power in the case of energy from the DC grid to AC.

3. CONTROL TECHNIQUES AND SIMULATION RESULTS

The control technique for the converter is implemented by SPWM modulation for the switches S1, S2, and PWM S3-S6. The SPWM control is implemented in rectifier and inverter modes. The rectification mode (main operation is mode 1, mode 2 in the proposed converter operation analysis) of the converter is implemented with the switches S1 and S2, the switches on the DC microgrid connection side are S3 and S5; S4, S6 under the conditions of (1) and (2) the DC output voltage is feedback by the conventional PID control loop to regulate the voltage stably shows in Figure 7.

The inverter mode of the proposed converter with the main switch S3-S6 by SPWM and S1, S2 by PWM is similarly controlled under the conditions of (4), the opening time of the two rectification and inverter modes is guaranteed to be less than 50% so the loss on the switches is improved. Feedback parameters are current, voltage, and power when the conversion direction is corresponding, for example, the energy is converted from an AC microgrid to a DC microgrid, the feedback signal from the DC microgrid is as described in Figure 7.

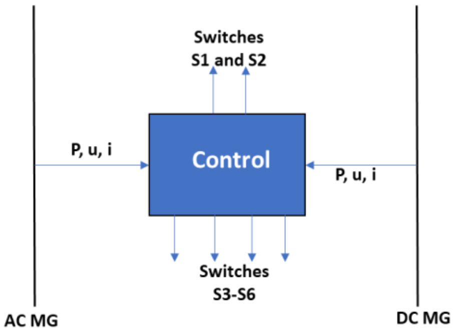


Figure 7. Feedback control signals of the proposed converter: (a) energy conversion from AC grid to DC grid and (b) energy conversion from DC grid to AC grid

In Figures 8(a) and 8(b), we see the bidirectional conversion energy corresponding to the voltage gain and loss factors of the converter and the load power value corresponding to each grid. In Figure 8(a), we see that the proportional efficiency is reduced compared to the increasing voltage gain factor; the proportional efficiency decreases with the increasing load power value. In Figure 8(b), the load power with the largest efficiency is 7 kW corresponding to the pressure drop factor of 0.7, the converter efficiency changes significantly according to the pressure drop factor in the range of 93-96%, the efficiency changes according to the load power value in the range of 93-96%, this result shows that when the load power changes, it will affect almost the pressure drop factor in the energy conversion process in this proposed converter.

In Figure 9 (a), we see that the average efficiency of the AC/DC converter power transmission tends to decrease gradually as the power value increases from the receiving side, in the efficiency range from more than 96% to nearly 93.3%. The average efficiency of the DC/AC converter power transmission tends to increase with the power value in the range of 2-7 kW and then gradually decreases; the efficiency fluctuates in the range of 93.3-94.8%. Figure 9(a) shows the average efficiency of the entire conversion for the cases and modes oscillating in a small range close to the value of 95%. Correspondingly, the power loss in the main elements in the converter, such as the MOSTFET switching switch and diode, is shown in Figure 9(b). In Figure 9(b), it is shown that the power loss value when performing inverter mode will be higher because more main switches are used than in rectifier mode.

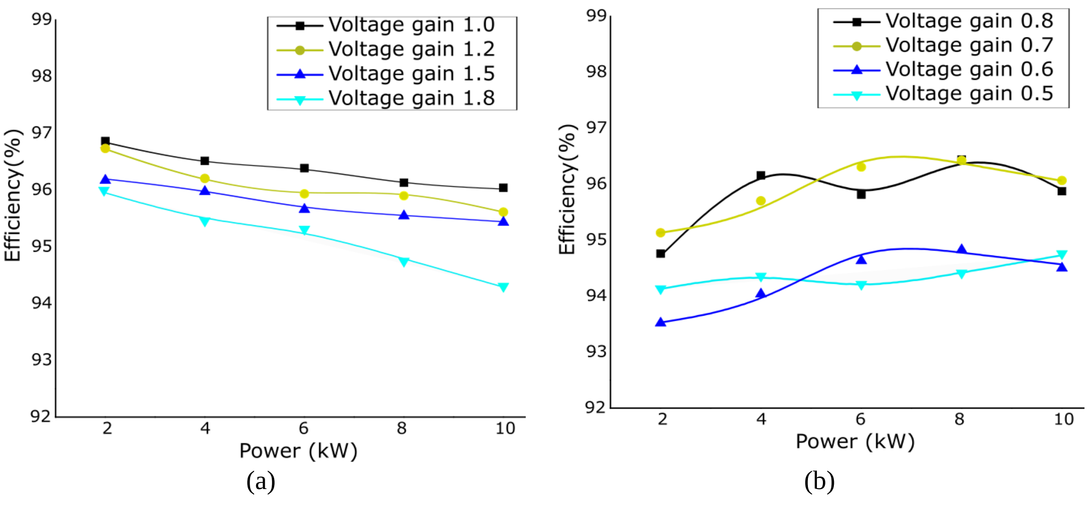


Figure 8. Efficiency characteristics of the proposed bidirectional converter: (a) energy conversion from AC grid to DC grid and (b) energy conversion from DC grid to AC grid

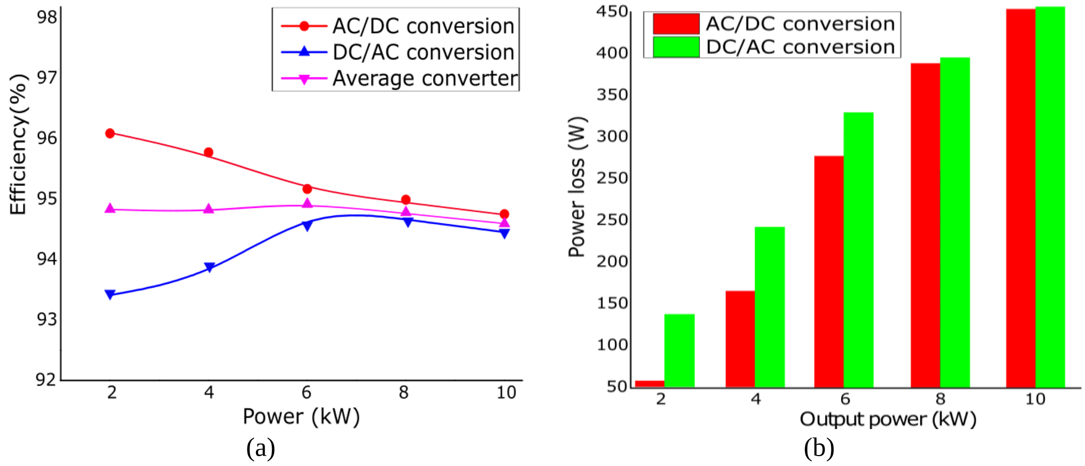


Figure 9. Average efficiency and loss of the proposed converter: (a) average efficiency and (b) average loss

Figure 10(a) shows the voltage harmonics and input voltage in the case of energy conversion from AC power source from AC microgrid to DC microgrid. The DC power grid voltage is concentrated at 0 Hz frequency, and the harmonic steps are concentrated at 50 Hz and 100 Hz frequency. The AC voltage is concentrated at 50 Hz frequency. Ensure the quality of the output voltage. The conversion Figure 10(b) shows the energy conversion process from DC microgrid to AC, the AC output voltage has harmonic steps concentrated at 100 Hz and 150 Hz frequency.

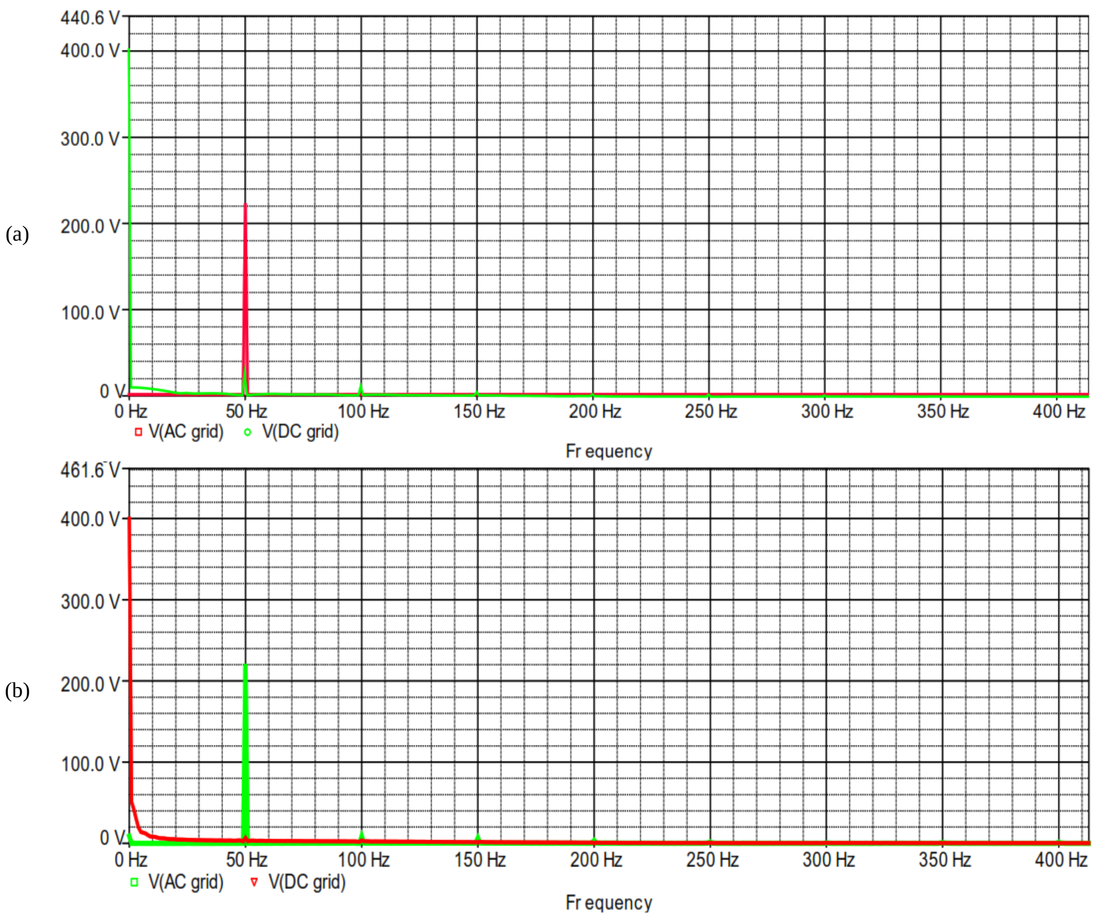


Figure 10. Harmonic voltage of the AC and DC microgrid: (a) harmonic voltage during AC/DC conversion and (b) harmonic voltage during DC/AC conversion

4. EXPERIMENTAL RESULTS

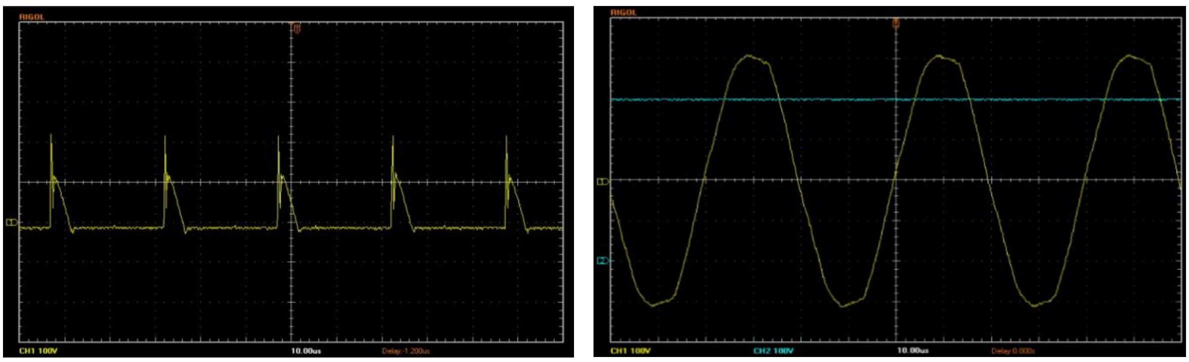
The converter is implemented in the laboratory with the input parameters as shown in Table 1. The experimental converter is illustrated in Figure 10. In the converter, the components are given from the actual requirements on the AC and DC power grids. The converter converts energy in two flexible directions, which is tested as described in the picture in Figure 11. In the experiment, the converter is performed according to the cases, such as simulation, and shows some power values of the load at the AC and DC microgrid in the system.

Figure 12(a) shows the voltage profile across switch S1 in the case of AC grid power being supplied to the DC grid; the applied voltage is more than 200 volts. Figure 12(b) shows the rectified voltage measurement to the DC microgrid in blue is approximately 400 VDC, and the input voltage measurement to the converter in yellow is 220 VAC, frequency 50 Hz. Figure 13(a) shows the different current, voltage, and power values from the AC microgrid power supply to the DC microgrid measured schematically from the variable converter test input; the value chart changes from 2 kW to more than 5kW. In this rectification mode, the required output voltage from the AC microgrid to the DC microgrid meets the requirement within 400 VDC, and similarly, the measurement results from the DC microgrid supplying power to the AC microgrid (inverter mode), the converter works normally, and the measurement parameters are as shown in Figure 13(b). The experimental results show that the signal results, as shown in Figure 12(b), demonstrate the assurance of the input and output signal forms of the converter during the energy conversion process, transmitting energy in two directions in reality.

Table 1. Experimental device and component parameters of the proposed converter

Equipment	Parameters
AC microgrid	50 Hz, 220 V
DC microgrid	400 VDC
Transformer TR	L1:1mH; L2 = L3 = 10 mH; f = 10-100 kHz; 6 kVA
Switch S1-S6	IPW60R041P6
Diode D1-D6	VS-60EPU04-N3
Capacitor Cdc	10 µF, 500 VDC
DC or AC load	10 kW

Figure 11. Photograph of the experimental converter in the laboratory, experimental measurement of the operating parameters of the proposed AC/DC converter



(a) (b)

Figure 12. Experimental measurement signals during AC/DC conversion: (a) voltage across switch S1 and (b) rectified DC voltage and AC input waveform

(a)

(b)

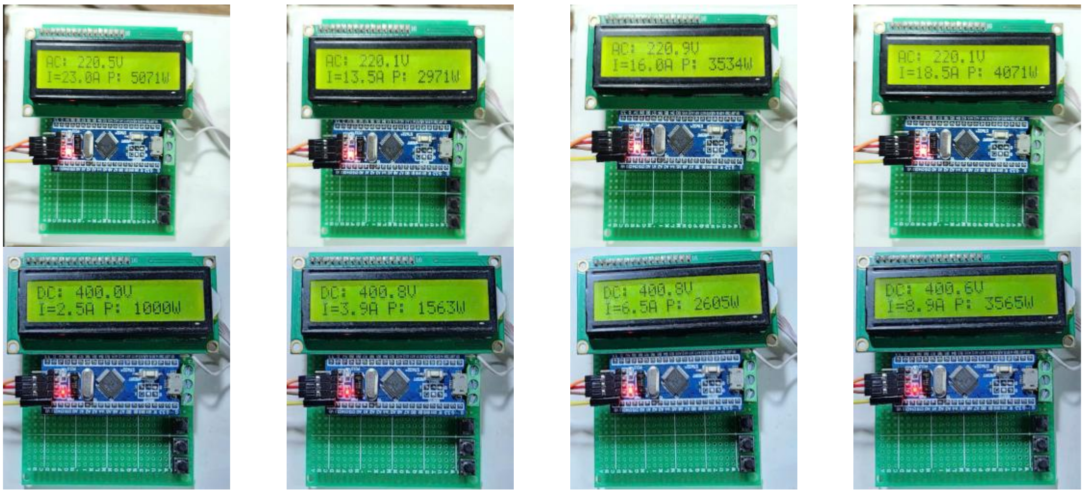


Figure 13. Measurement values for different power cases: (a) measurement parameters from the AC microgrid when powering the DC microgrid, and (b) measurement parameters from the DC microgrid when powering an AC microgrid

Figure 14 shows the average power conversion efficiency of the experimental converter. The experimental value in the range of 2-8 kW has an efficiency value smaller than the average simulation efficiency of the converter and larger than the efficiency value of the converter in reference [21]. This shows that the proposed AC/DC bidirectional converter has the potential for interconnection between AC and DC microgrids, applying distributed energy sources.

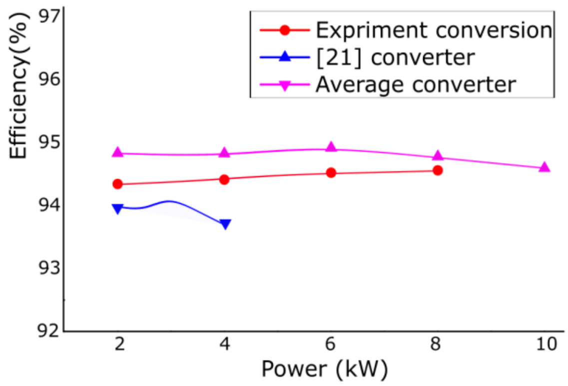


Figure 14. Comparative performance from simulation, reference and experiment of the proposed converter

5. CONCLUSION

The bidirectional converter connecting AC and DC microgrids can be studied to give the above results, the energy can be converted from the energy sources and storage systems of the grids and can be supplied to the required loads through the proposed converter cases with efficiency above 94.2%, total energy conversion harmonics are small. A promising feature of the microgrid is that it can provide uninterrupted power supply during grid outages, often referred to as "seamless" switching during stand-alone operation. For AC microgrid systems, it is difficult to determine when to switch the energy storage converter to stand-alone mode because of the conflict between the potential low-voltage grid code requirement and seamless switching. The reason is that voltage sags due to transmission tend to cause low voltages over a large area of the distribution system, so close-knit microgrids connected to this converter would be a solution to interconnect large areas and increase voltage stability and power quality for the load and the power system as a whole. A possible scenario in the future is that the utility grid operator would require distributed sources or microgrids to be connected for a pre-determined period of time, such as a few hundred milliseconds, before disconnecting when the voltage remains above a small percentage of the nominal value. This would be feasible for systems with flexible bidirectional converters connected to both AC and DC microgrids with high penetration of small to medium-sized renewable energy sources.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Nguyen The Vinh	✓	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
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I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [HTT], upon reasonable request via email: vinhnt@ptit.edu.vn.

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APPENDIX

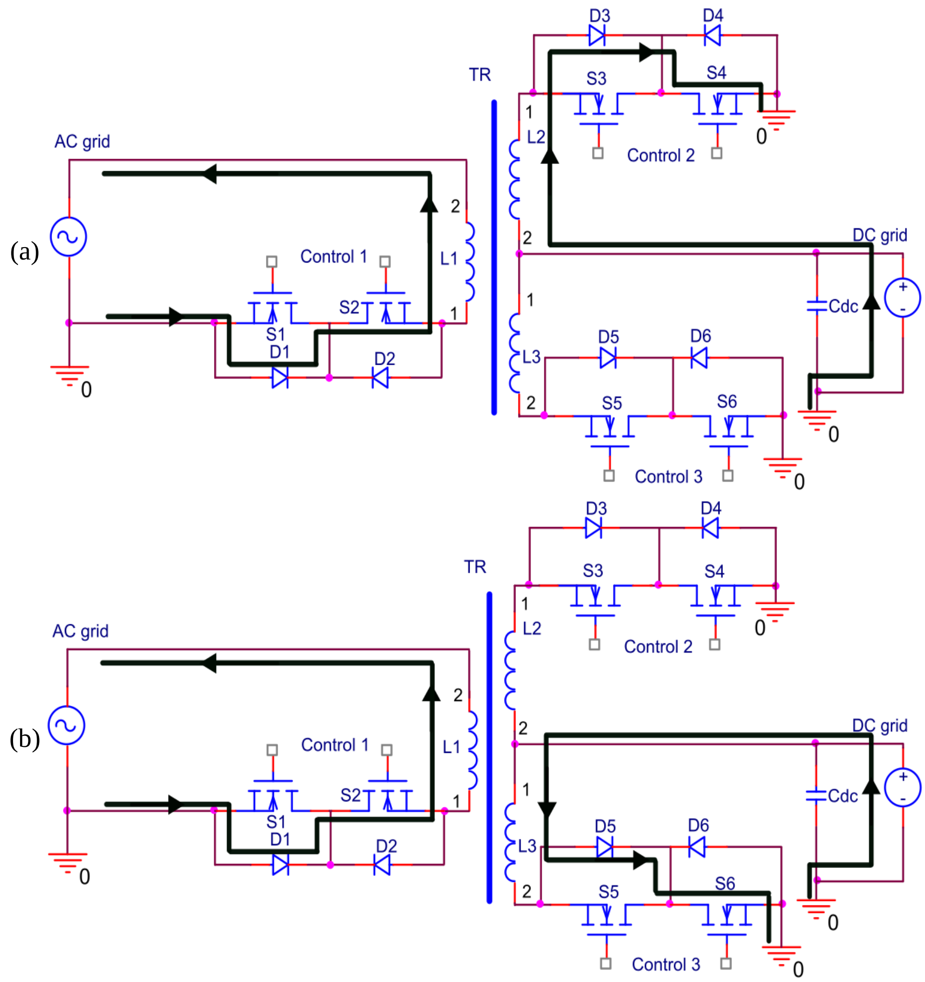

Figure 6. Operation diagram of mode 4 converter: (a) operation 1 in mode 4 and (b) operation 2 in mode 4

(c)

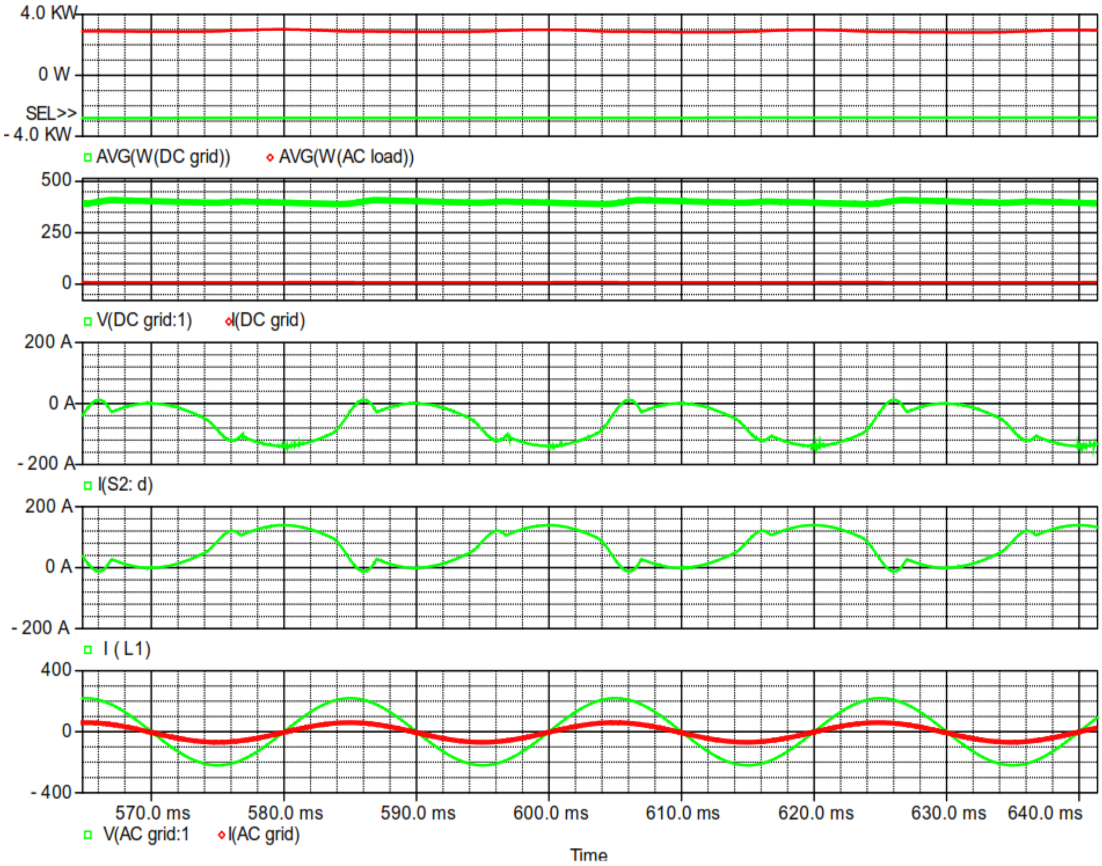

Figure 6. Operation diagram of mode 4 converter: (c) simulated graph of mode 3 and 4 operation (continued)

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