Bidirectional Converter Connecting the Energy Storage System to the DC and AC Grid

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ABSTRACT

A new built-in DC/DC/AC converter has the structure and function of linking between the DC and AC microgrid including renewable source and load, and the storage system for the microgrid system. Electrical energy consumption is increasing, as does the need to increase the power supply. The microgrid is studied with the necessary objective of the energy security of the country in the near future and increases operational flexibility, minimizing loss during conversion and investment in the microgrids. In this proposal, a multi-function converter is used to convert un-bidirectional and bidirectional energy, it connects storage system, DC/AC converter connects to AC load, DC and AC microgrid. The proposed converter is modified from a SEPIC converter with a pulse transformer, combined with the Buck-Boost and full bridge converter. The converter has many advantages such as high voltage gain, non-inverting output, constant input current, high efficiency and lower voltage stress on the switches. The hybrid converter connected to the microgrid can flexibly provide power loads from DC and AC grid, therefore, system reliability is likely to be improved alternative sources of supply. System expansion is simpler. The results of the converter were carried out by OrCAD and experiment in the laboratory.

1. INTRODUCTION

Currently, power sources have a rapidly increasing share of renewable energy, both in developed and developing countries. Furthermore, many countries have ambitious goals to convert their electricity sector to 100% renewable energy [1]-[4]. To achieve these goals, the structure and operation of existing grid infrastructure will need to be planned to ensure that renewables increase in a localized or evenly distributed manner. There are four important characteristics to provide specific methods and solutions to integrate technologies into the existing power system of renewable energy sources (highly distributed energy sources): (1) sources with changing power capacity values; (2) fluctuations in the capacity of large sources such as solar energy; (3) renewable technology requires less maintenance; and (4) renewable technology efficiency remains low.

The transition to a high-rate renewable energy source system requires readjustments to the design, operation, and planning of the future power system from an economic and technical point of view. In such a system, supply and demand would be matched in a different and much more flexible way. On the technical front, renewable energy systems that can be distributed and delivered are ideally combined with smart grids, energy storage, and more flexible power generation technologies.

The biggest disadvantage is the instability of the power supply and the discontinuity in the use and operation of the power system with renewable energy sources [5]-[9]. To address these issues, the research proposes solutions such as energy storage systems (battery, supercapacitor, water storage lake for hydroelectricity), flexible conversion systems for the power grid, such as adjusting distribution based on load characteristics to improve reliability. In power systems with large capacity and the most difficult conditions for renewable energy sources (large capacity fluctuations), devices are put into use to improve reliability through analysis [5], [10].

Therefore, the power system can be off-grid or grid-connected, combining distributed energy sources with storage systems is one of the good solutions for power systems in developing countries and undeveloped countries as well. Power systems in developed countries, especially power grids and distribution grids, will be supplemented with increasingly micro-hybrid renewable energy sources, leading to the introduction of different concepts and forms microgrid (MG) [10]-[12]. Therefore, the analysis of different microgrid architectures of distributed energy sources is a useful solution for automating loads in islands and remote areas, such as rural areas described in the literature [13]-[16]. Technological solutions for microgrid structures will improve reliability, stability, energy and cost savings, and will help to ensure energy security and

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environmental sustainability [13]. An independent electrical system has an operating range and provides electricity for an area (many load households), or a household can be like a microgrid [12]. There are several points, such as: power quality, voltage quality, AC load output frequency, and grid connection, that need to be considered for project planning for an MG power system [13]-[16]. Countries bordering the equator have the advantage of available renewable energy sources, so it is necessary to exploit and take advantage of these resources as a solution for the supply and operation of useful electrical energy in the regions' mountainous and remote areas [12]-[15]. Energy conversion systems such as photovoltaics and wind turbines can be used in combination by creating hybrid energy system structures, especially the MG system or the hybrid renewable energy microgrids (HRES). A hybrid micro-renewable energy system (such as photovoltaic, wind power) combined with a storage system for batteries. Regardless of power supply, the critical electrical equipment in the loads almost always operates steadily, efficiently, and continuously. In addition, it also reduces oscillations during energy conversion at the converters [14], [15]. Reducing dependence on the grid: When fully charged, the storage battery will be a backup power source for the system, thus minimizing dependence on the national grid. Therefore, when there are problems with the power supply, a power failure, voltage drop [17]-[21]. Integrating storage systems in HRES reduces overall costs and improves system resiliency [19], [21]. Furthermore, hybrid energy systems combined with storage provide uninterruptible power to the load [21], [22]. One more solution for increasing the continuity of power supply to the load is to use a diesel generator. The system is further configured with a charge/discharge function based on actual time and demand, allowing storage batteries to be charged during normal hours and emitted during peak hours, saving electricity costs for customers who use electricity at different rates depending on the time frame (peak, normal, off-peak). Alternatives to generators, safe for the environment: A hybrid solar power system operates automatically, quietly, without making noise like generators, does not use gasoline or oil, and has no emissions. The reduce CO2 emissions to the environment for renewable power plants [22]-[29]. Some DC/AC bi-directional converters have made the conversion from storage to the AC grid but are not really flexible to connect between DC and AC microgrids [30], [31]. The bidirectional DC/DC converter with magnetic coupling to increase the port terminals to connect multiple distributed power sources for the DC microgrid as analyzed [32]-[35] it will be a solution for the operation optimize energy from sources. Some Totem pole-linked bidirectional DC/AC converters use MOSFET, Thysitor or Triac bidirectional switches, which have the advantage of reducing control components and reducing the operational complexity of the converter [36], [37]. Therefore, hybrid micro-energy systems that combine renewable energy sources and storage systems will be a better choice to meet the power of central loads. This paper presents a flexible operation strategy for supplying and storing power to two DC and AC microgrids using a bidirectional DC/DC/AC converter structure. This converter is combined according to DC/DC and DC/AC conversion stage operation or only one of them. The main contribution of this study is the design of the principal circuit, the size of the component ropes and the initial experimentation of the DC/DC/AC converter with the strategy of connecting the two DC and AC microgrids.

2. STRUCTURE OF MICROGRID

2.1 Block Diagram

As seen in Figure 1, the microgrid consists of a source of solar photovoltaic (PV) panels, an energy storage unit, a link converter between the DC and AC grids, which also integrates a DC/DC power converter connected to a renewable energy source and features bidirectional energy conversion to the storage system and to the DC and AC grids of the microgrid system. The output DC voltage of the solar generator is boosted by a DC/DC/AC unit to convert the DC power into AC power to feed into the grid or supply DC and AC loads. To charge or discharge the storage, a bidirectional DC/DC/AC conversion is used. In this circuit, the power conversion stages between DC/DC, DC/AC, and AC/DC are integrated into a converter linking the two DC and AC grids.

An MG hybrid system is studied for performance and features in this work, consists of a DC and AC microgrid linked together by a bidirectional link converter. In the AC and DC grid systems, there are components such as renewable energy sources, generators using natural resources (gas, oil), energy storage systems, and grid-based loads. The MG hybrid can run independently of the grid or connected to the grid by large-capacity electronic locks.

This is a parallel hybrid system configuration, the renewable energy source and AC microgrid components can directly supply the load to the grid itself. This system can be arranged in a sequence of components in the system, which can meet the optimal energy generation, optimize fossil fuel sources. Thus, it is possible to reduce the capacity of storage systems to store energy.

Grid systems may or may not be centralized in AC microgrids and DC microgrids. In this work the coupled hybrid system centralizes all the connected components into the AC microgrid. AC power converters connected directly to the AC bus or via a recommended DC/AC converter. The proposed converter aims to help control the flow of energy inside and outside microgrids.

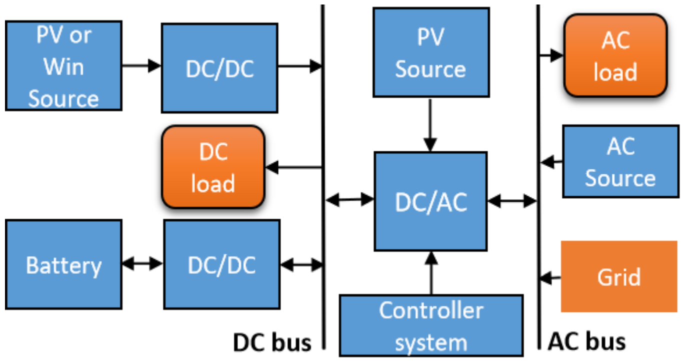


Fig. 1. Block diagram of microgrid.

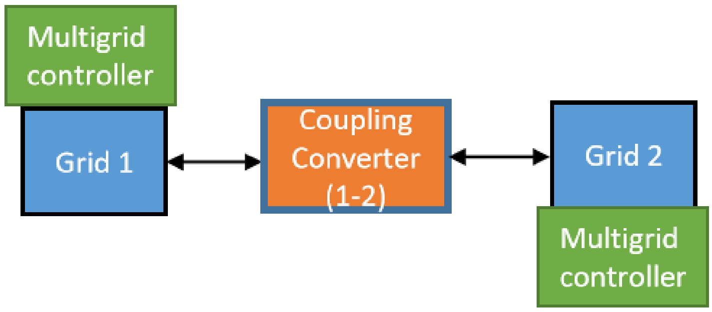


Fig. 2. Decentralized control system of a multi-microgrid.

There is a growing need to integrate multiple microgrids to enhance stability and improve energy management. The control and monitoring system in the converter in this paper uses the proposed decentralized approach to the multi-microgrid approach described in Figure 2. In Figure 2, the converters link between the microgrids, such as two 1-2 grids. Multiple independent systems can be coordinated by decentralized control [38]-[41]. An integrated control system will be proposed based on the structure and coordination properties of the microgrids in the microgrid system.

2.2 Converter Proposed

Figure 3 describes the schematic diagram of the proposed DC/DC/AC converter. In the circuit, there are three bidirectional power switches corresponding to three control signals for the connection of switch nodes with components of each converter for ports connected to the DC microgrid (including DC loads and renewable energy sources), the AC microgrid (including AC loads and sources and connected to the grid through an automatic control breaker), and storage systems. S3 and S4 are two circuits, such as IGBT/MOSFET transistors, that connect to form a bidirectional switch between the storage system buck-boost converter switch node and the DC microgrid, as shown in Figure 3. The connection diagrams of S3 and S4 allow a single control signal to be sufficient for control. Similarly, S2 and S7 form a second switch that connects the storage circuit converter's switch node and the DC/AC converter circuit input connected to the load and the AC grid. S5 and S6 from the third bidirectional power switch that connects the DC and AC microgrids via an H-bridge DC/AC converter. The circuits both perform independent conversion and perform in several modes at the same time as buffer circuits for the SEPIC DC/DC main converter.

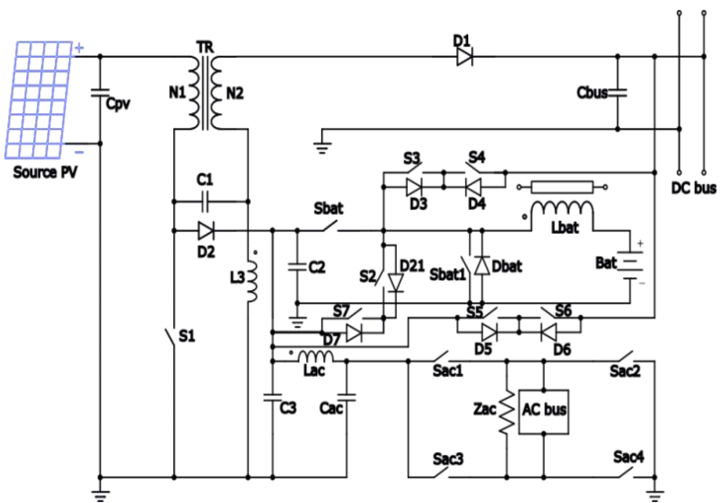


Fig. 3. The schematic diagram of the DC/DC/AC converter.

The SEPIC converter uses a transformer circuit and thus has the advantage of a high boost voltage when connecting the regenerative power source and the DC grid, as shown in equations (1) and (2). The composite converter can perform DC/AC conversion when it is operating a voltage source inverter normally and can also perform both DC/DC and DC/AC conversion simultaneously. In the converter structure, which has evolved for both grid-connected and off-grid operation modes, are control systems such as power balance between source and demand, DC link voltage control and frequency control, AC link voltage, and charging and discharging of energy storage systems

$$V_{DC\,bus} = V_{PV} \cdot \frac{1+n}{1-D} \tag{1}$$

Where

n: the inductor windings turns ratio. $n = \frac{N2}{N1}$

D: Duty ratio of the S1

$$V_{C3} = V_{input\,AC} = V_{PV}\,\frac{1}{1-D} \tag{2}$$

$V_{input\ AC}$: is the H-bridge converter input voltage connected to the AC load.

The operation of the converter, as shown in Figure 4, realizes the concept of optimal use of energy from renewable sources in the DC grid and in the supply system for DC and AC loads. Currently, the AC load system accounts for the majority of energy consumption, so the operating modes will give priority to the conversions that respond to the AC loads on the AC grid.

The converter operation proposed to implement eight modes follows the grid-connected and off-grid operation modes. Off-grid mode can be performed in modes 1 through 7. Mode 8 in the operation of the switch can be connected to the grid.

Figure 4(a) depicts Mode 1: The PV source provides energy to DC on the DC microgrid and AC load, and to the Battery (battery energy storage system). AC and DC load capacity can be received more extended from the power sources from the DC microgrid supply. In this case, if the AC load increases the power, it is performed with priority as an operation in mode 2. The battery charge may not be full.

The power equation:

$$\begin{aligned} P_{PV} &= P_{acload} + P_{DCload} + P_{Bat} \\ &+ P_{loss(S1+Sbat+Sbat1+Sac1\text{-}4)} \\ &+ P_{loss(D1+D2)} \end{aligned} \tag{3}$$

Mode 2 shown in Figure 4(b): PV source supply for DC load and AC load for the following reasons: (1) increased power on the DC and AC loads; (2) power surge at either DC or AC load; (3) sufficient power supply for DC and AC loads. In this mode the converter performs step-up DC/DC functions using a SEPIC converter with a transformer connected to the DC microgrid and DC/DC/AC Boost converter combines an H-bridge connected to an AC load. This case can switch to mode 1 when the load changes in the downward direction or remove the load on the DC or AC microgrid.

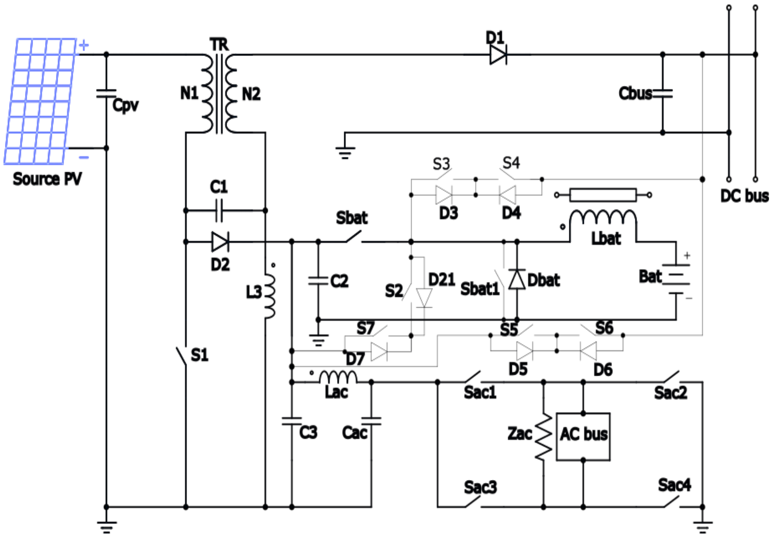
The power balance equation of this mode:

$$\begin{aligned} P_{PV} &= P_{DCload} + P_{acload} + P_{loss(S1+Sac14)} \\ &+ P_{loss(D1+D2)} \end{aligned} \tag{4}$$

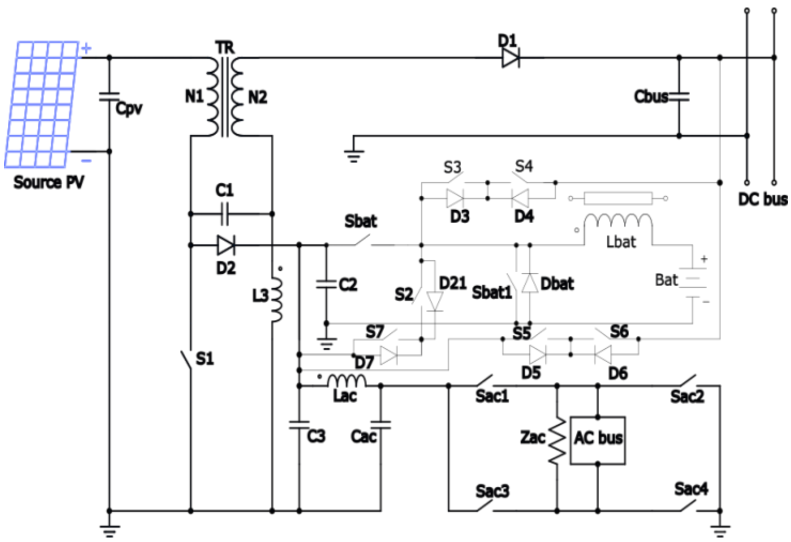
Mode 3: When the DC and AC load power increases compared to the PV source. The converter will perform the power conversion from the PV sources and the storage system to the loads, the converter will function as DC/DC and DC/DC/AC is shown in Figure 4(c). Assume the case that the power from the DC grid is stable for a certain period of time. Nonpreferred loads from DC or AC microgrids will be removed according to the storage system's capacity loss characteristics over the steady time of the PV source. This mode will switch to operate as mode 2.

The power balance equation:

$$\begin{aligned} P_{PV} + P_{Bat} &= P_{DCload} + P_{acload} \\ &+ P_{loss(S1+S4+S7+Sbat1+Sac1\text{-}4)} \\ &+ P_{loss(D1+D2+D3+D21)} \end{aligned} \tag{5}$$


Source PV
Cpv
TR
N1
N2
D1
Cbus
DC bus
C1
D2
L3
S1
Sbat
C2
S2
D21
S3
S4
D3
D4
Lbat
Sbat1
Dbat
Bat
S7
D7
S5
S6
D5
D6
Lac
C3
Cac
Sac1
Sac2
Zac
AC bus
Sac3
Sac4

(a)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S4
D3
D4
Lbat
Sbat1
Dbat
Bat
S7
D7
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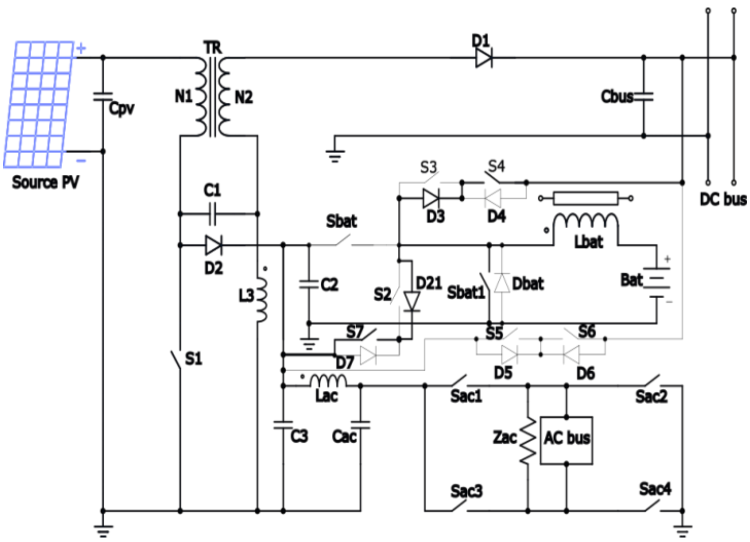
(b)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S4
D3
D4
Lbat
Sbat1
Dbat
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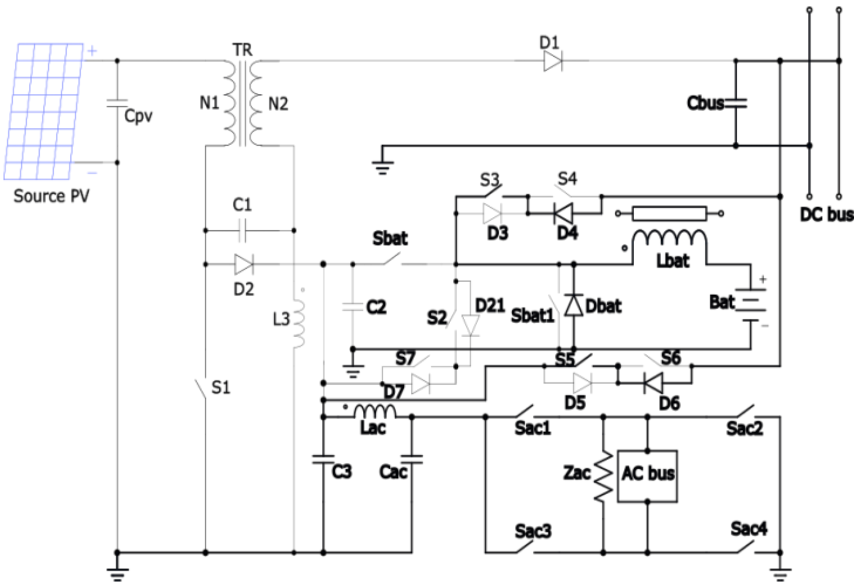
(c)



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D21
Sbat1
Dbat
Bat
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S7
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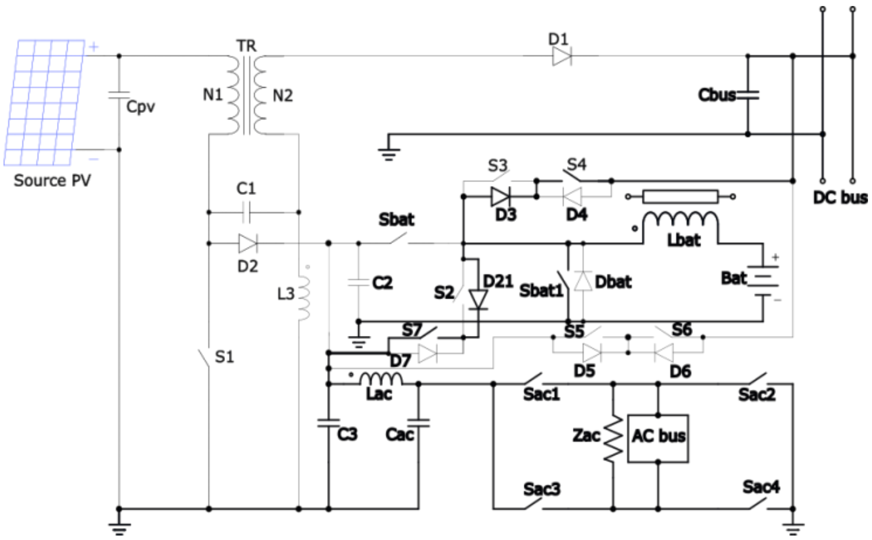
(d)



TR
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Cbus
Source PV
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DC bus
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D3
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Sbat
Lbat
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C2
S2
D21
Sbat1
Dbat
Bat
L3
S7
S5
S6
S1
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C3
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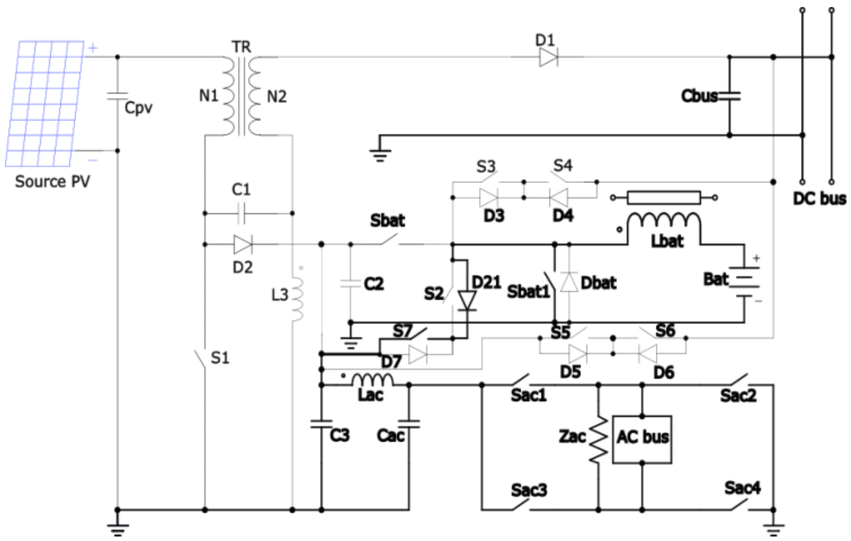
AC bus
Sac3
Sac4

(e)



TR
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Source PV
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DC bus
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C2
S2
D21
Sbat1
Dbat
Bat
L3
S7
S5
S6
S1
D7
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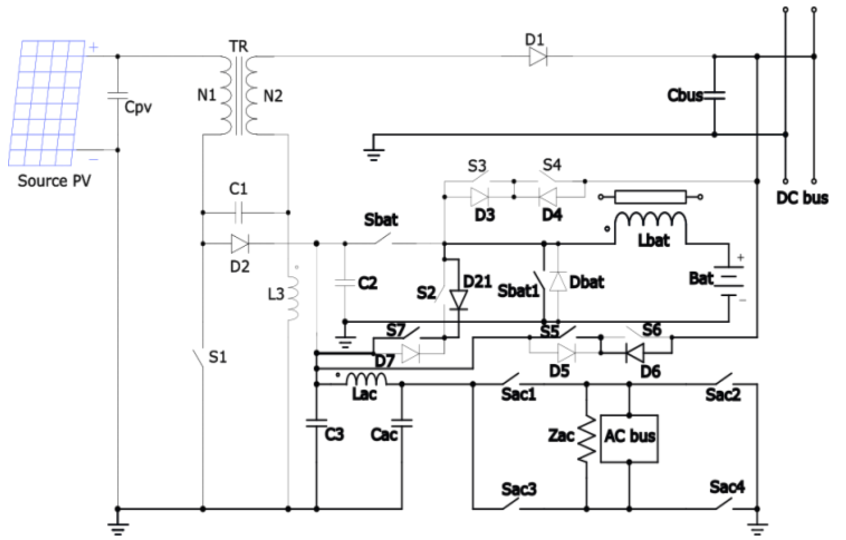
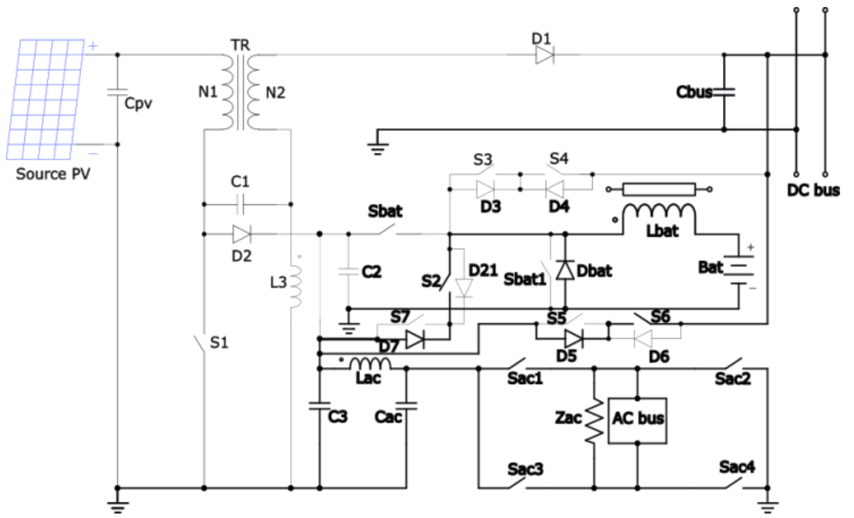
Zac
AC bus
Sac3
Sac4

(f)



(g)



(h)

Fig. 4. The operations of the proposed converter (a) mode 1; (b) mode 2; (c) mode 3; (d) Mode 4; (e) Mode 5; (f) Mode 6; (g) Mode 7; (h) Mode 8.

Mode 4: DC microgrid to Battery, the AC and DC loads, converters act as DC/DC and DC/DC/AC converters. When the PV source doesn't supply (doesn't emit electrical energy) as shown in Figure 4(d). Energy is provided from other renewable energy sources connected on the DC microgrid.

Equation power of this mode:

$$P_{DCbus} = P_{Bat} + P_{DCload} + P_{acload} + P_{loss(S3+S5+Sac1\text{-}4)} + P_{loss(D4+D6)} \quad (6)$$

Mode 5 shown in Figure 4(e): The storage system (Battery) to AC and DC loads, the case when the capacity of renewable sources does not generate energy. This situation rarely occurs in the connection system between two off-grid DC and AC grids.

Equation power of this mode:

$$P_{Bat} = P_{DCload} + P_{acload} + P_{loss(S4+S7+Sbat1+Sac1\text{-}4)} + P_{loss(D3+D21)} \quad (7)$$

Mode 6: The storage system supplies power to the AC load. This mode of the converter operates as DC/DC/AC by boost combined with H-bridge by the principle of priority for AC load shown in Figure 4(f). In this case, priority is given to the AC load in the power system.

Equation power of this mode:

$$P_{Bat} = P_{acload} + P_{loss(S7+Sbat+Sac1\text{-}4)} + P_{loss(D12)} \quad (8)$$

Mode 7: DC microgrid and battery to AC and DC load shown in figure 4(g). This case also prioritizes the load principle for the whole system.

Equation power of this mode:

$$P_{DCbus} + P_{Bat} = P_{DCload} + P_{acload} + P_{loss(S6+S7+Sbat1+Sac1\text{-}4)} + P_{loss(D6+D12)} \quad (9)$$

Figure 4(h) depicts mode 8, which allows the system to connect to the grid when the power of AC microgrid sources does not meet enough energy for the loads. The goal of optimal use of renewable energy, the flexible distribution of energy in the microgrids is described operating in the modes in the above converter. In the system of microgrids, all sources are connected but will focus on priority use of energy from renewable sources from sources connected through converters in the system and renewable energy sources in the DC and AC microgrids.

3. SIMULATION AND EXPERIMENTAL RESULTS

3.1 Simulation Results

Simulation results are performed by the OrCAD software to show the operation process and functional forms of the DC/DC/AC converter in the system connecting the two AC and DC microgrids. The battery pack is charged according to the principle of constant current, and the combined voltage gradually increases to the rated value of the battery. The charging current will decrease gradually when the voltage of the battery equals the rated value. The value of the mode 1 charging current is 5.5A and the charging voltage is 57V at 2.8s as shown in Figure 5. Figure 5 shows the simulation results during the mode 1 energy conversion. The required AC load capacity is 700 W, 1.2kW of solar power output, 400W of battery capacity, and 140W of DC microgrid load capacity. The required capacity of the battery is less than the amount of solar energy generated. Load power is supplied by a PV source.

The simulation results of mode 2 as shown in Figure 6. The AC load power required 900W, DC load power 230W on the DC microgrid and PV source 1.2kW. The battery in this mode is disconnected from the inactive state. Operation of the converter switches from mode 1 to mode 2.

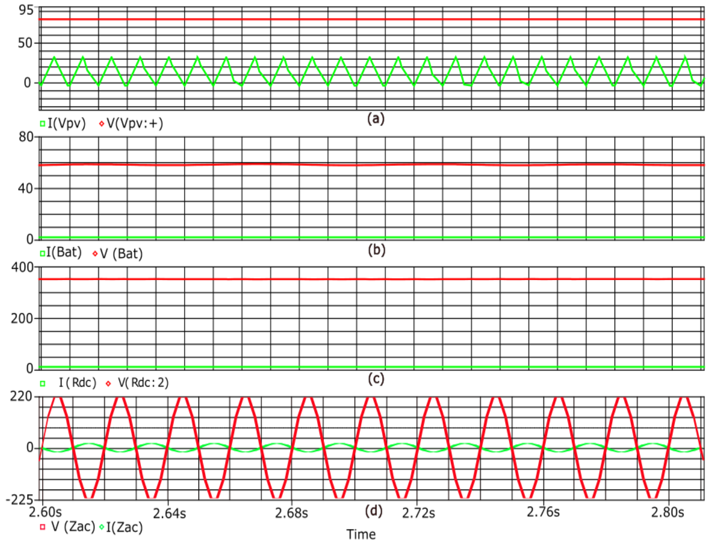


Fig. 5. Simulation waveforms of Mode 1: (a) PV source voltage and current; (b) battery charge current and voltage; (c) DC grid voltage and current; (e) Voltage waveform and AC load current.

Figure 7 illustrates the mode 2 to mode 3 operation of the converter. Load power requires 1.8 kW of AC and DC microgrids supplied from the PV source and accumulated energy from a battery. In this case, after a period of time, the battery power will decrease and the total energy of the power supply and the battery will be less than the load capacity due to the measurement, it will switch to an operating state that gives priority to the AC load only. The DC load will be regulated supply from the DC microgrid in the system.

Figure 8 shows the voltage, current signal waveforms of the battery outputs with a power value of 800W and the required power of a 740W DC and AC load in mode 5. In this case, the microgrid is deployed in off-grid mode as well as modes 1 to 7.

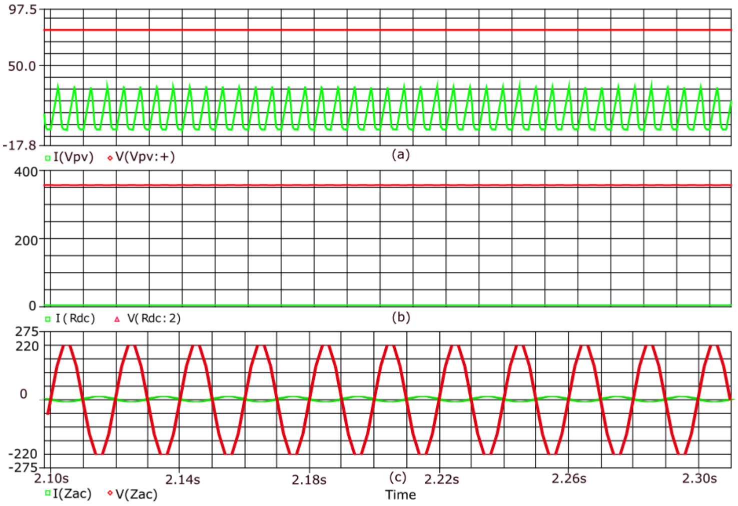


Fig. 6. Simulation waveforms of Mode 2: (a) PV source voltage and current; (b) DC grid voltage and current; (c) Voltage waveform and AC load current.

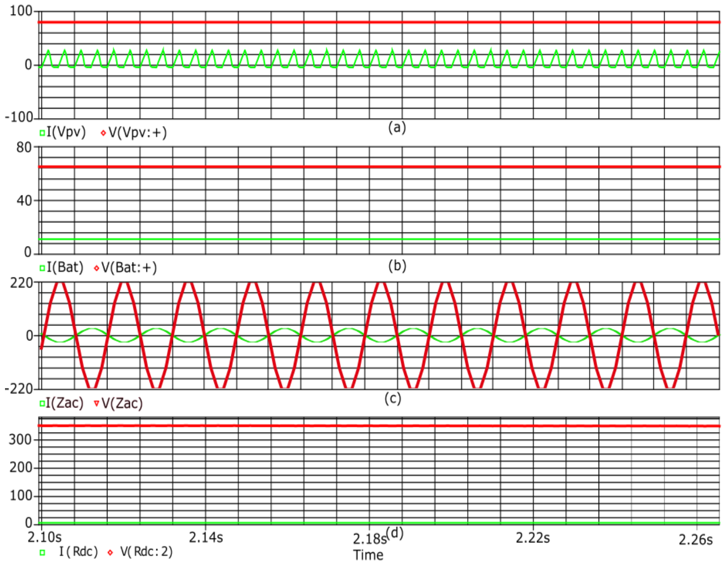


Fig. 7. Simulation waveforms of Mode 3 (a) PV source voltage and current (b) battery discharge current and voltage (c) Voltage waveform and AC load current (e) DC grid voltage and current.

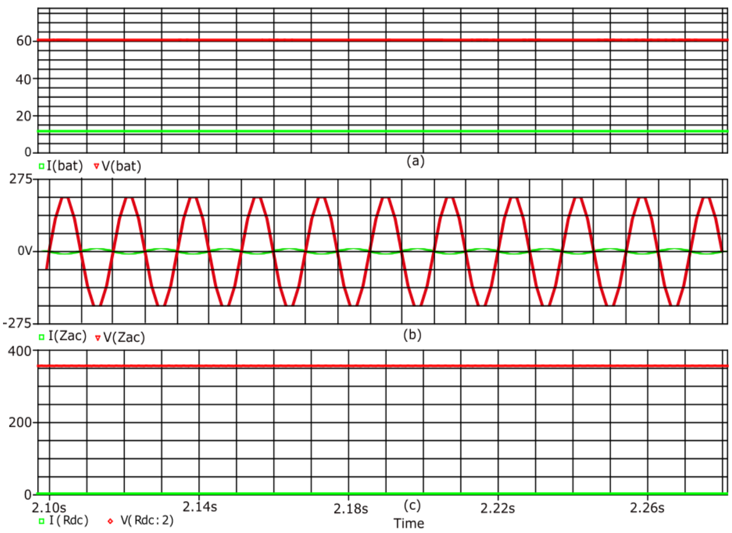


Fig. 8. Simulation waveforms of Mode 5: (a) battery discharge current and voltage; (b) Voltage waveform and AC load current; (c) DC grid voltage and current.

The work for the simulation results basically shows the overall performance modes of the proposed converter. In addition, mode 4 is similar to mode 1, mode 6 simulates operation like mode 3 and 5, mode 7 is similar to mode 3, mode 8 simulates operation like mode 4.

3.2 *Experimental Results*

Experiment results, as shown in Figure 9, equipment used as Table 1, to demonstrate the operational feasibility of the proposed converter, and experimental results from the converter are also observed. Figure 9 shows during testing of the proposed converter connected to components such as a PV source, an AC load, a DC bus, an AC grid, and a storage system (battery). The voltage across the AC and DC main ports is shown in Figure 10 in mode 1. The experimental waveform is consistent with the theoretical simulation waveform.

Table 1. Experimental set up parameters.

Parameter	Values
Input voltage DC/DC SEPIC converter	(20-80)V DC
Output voltage DC/DC SEPIC converter	350V DC
Transformer in DC/DC SEPIC converter	L1(N1): 100µH, L2(N2): 450µH
Inductance L3	1mH
Inductance Lbat	2mH
Inductance Lac	2mH
Capacitance C1, C2, C3 and Cac	10µF
MOSFET Switch S1 to S7, Sbat, Sac1 to Sac4	IRF740, IRFP640N, IRF340
DC load	500Ω
Output AC voltage	220V±3%
Input AC voltage	200-350V DC
Frequency of AC output	50Hz±0.5%
AC load	(58-250)Ω

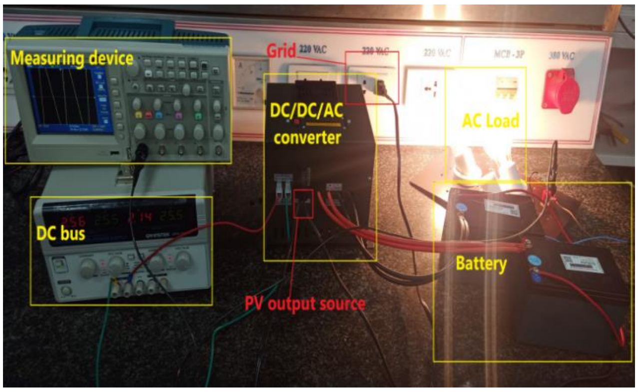


Fig. 9. Image of the experimental converter circuit in the laboratory.

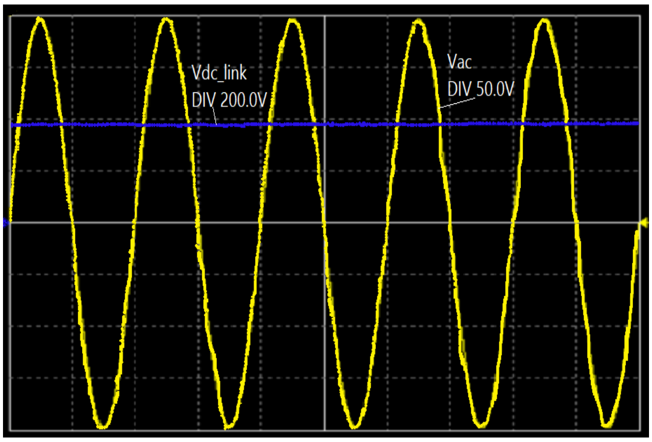


Fig. 10. Show experimental waveform of AC load and DC grid, mode 1.

The typical experimental results for a mode in the proposed converter signal forms for mode 1 of the converter are depicted in Figures 10 and 11. Figure 10 shows the resulting waveform of the voltage measurement at the AC load show the yellow line and the voltage on the DC microgrid show the blue line. Figure 11 shows the results of measuring the output voltage of the PV source show the blue line, the battery voltage show blue, and the voltage (yellow line) on the switch power S1 performing the step-up process of the SEPIC converter in combination with the transformer. The stress voltage on the switch S1 is reduced by the output voltage limited by the battery charge buffer circuit or the voltage on the recovery circuit diode D2, and C3 is connected to the AC load compared to the basic SEPIC.

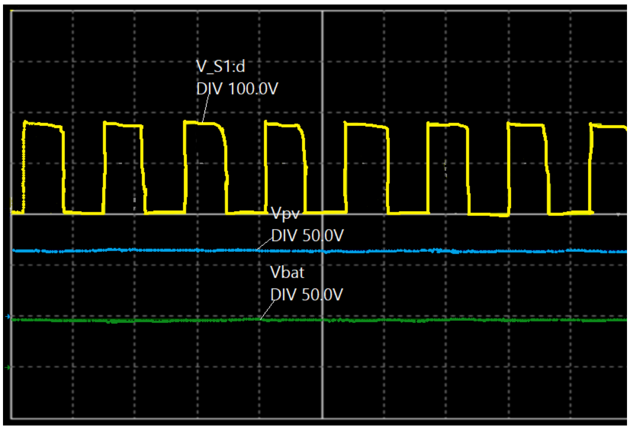


Fig. 11. Show experimental waveform of voltage across switch S1, PV and Battery, mode 1.

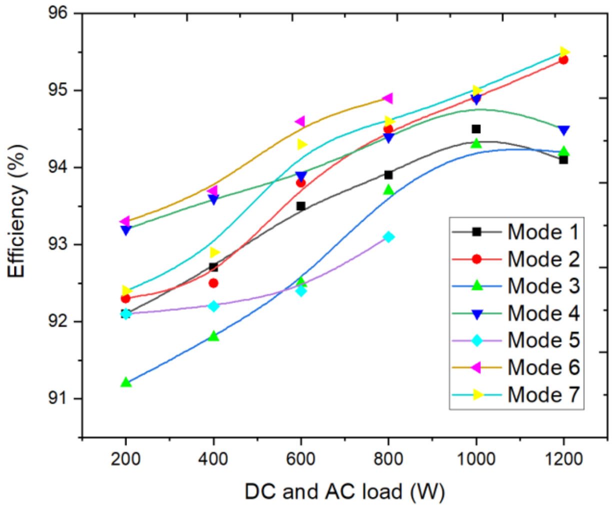


Fig. 12. Efficiency for power AC and DC load at the different modes.

In this work, the article analyzes in detail some typical modes among the eight proposed converter operating modes to help calculate the total system loss. The efficiency was then determined in different power ranges, as shown in Figure 12. It has been studied in different load capacities and operation modes with different functions of the proposed converter. The average efficiency when powered from a PV power source (modes 1, 2 and 3) is more than 93%. The average efficiency when powered from the storage system (modes 5 and 6) is 93.8%. The average efficiency from the DC microgrid (modes 4 and 7) is around 94.5%. Thus, showing what the performance of a multi-conversion bidirectional DC/DC/AC converter connected to two microgrids, renewable energy sources and storage systems will be difficult to achieve when the architecture Integrated DC/DC and DC/AC conversion stages. Although there is only one stage, such as DC/DC (up to 98% [32]-[35]) and DC/AC (over 96% efficiency [30], [31]). As the measured results from this proposed converter is a work to develop this study for the application of the microgrids in the power system, as well as comparisons with other structures discussed in the literature.

4. CONCLUSIONS

This paper presents a proposed hybrid-link converter for flexibly and efficiently converting the hybrid microgrid between DC and AC grids in all eight operating modes. Energy is continuously converted and flexible between the sources renewable and the DC and AC microgrids from the necessary energy generators provided by the link converter. Power sources, energy storage systems, regulated loads, supply, operate more efficiently and stably between microgrids. Moreover, excess energy can be utilized when the system is the grid connected. This converter supports bi-directional DC/AC voltage between two microgrids in off-grid operation, which reduces the need for additional voltage sources. The integrated control converter allows for grid connection and off-grid operation.

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