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DESIGN OF A DUAL ACTIVE BRIDGE DC-DC CONVERTER FOR PHOTOVOLTAIC SYSTEM APPLICATION

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Abstract. *This paper focuses on a bidirectional isolated dual active bridge (DAB) based dc/dc converter as one of the potential modules for photovoltaic system applications. The DAB converter possesses the functions of bidirectional power flow transfer, and has some advantages, including electrical isolation, high step-up ratio, and zero voltage switching. It is worthy of applying in renewable source, such as wind power and PV energy based system which combined energy storage unit. For performance analysis, the input side of the converter is connected to the high voltage bus and the output side is connected to the battery. Energy transfer between these two sides is accomplished by the proposed symmetric phase shift control algorithm. It is easy to be implemented by analogous circuits. To verify the feasibility, a system equipped with 12V lead acid battery as an energy storage device with rating about 150W topology is settled to verify the control idea.*

Keywords: Bidirectional power flow, High step-up ratio, Symmetric phase shift control

1. **Introduction.** With the increasing penetration of renewable energy sources like photovoltaic cell (PV), power generation system using DC micro grid has been increased and more visible, while the world's power demand is increasing. For PV applications, since the conversion becomes more and more efficient due to existing technologies, also, the price of the PV modules is continuously decreased, it is gradually suitable for small scale residential applications with a range below 1kW [1,2]. Generally, a PV power system can be divided into stand-alone system and grid-connected system dependent on whether it is parallel with the utility or not. Stand-alone system is mainly used in the place without utility source or sparsely populated areas where the utility cannot supply energy with low cost, and an additional battery bank is usually necessary to support the uncertain renewable energy.

This paper focuses on a bidirectional dual active bridge (DAB) based dc/dc converter to fulfill the required function of regulating the battery bank energy and the DC bus voltage to confirm a stiff energy transfer for stand-alone PV system. DAB is a preferred topology due to its many advantages of zero-voltage switching (ZVS) function without requiring additional active or passive components [3-7]. It has also been gaining popularity for renewable energy applications, particularly used as an interface between the energy storage devices and the dc bus. Phase shift modulation, triangular modulation, and dual phase shift modulation, are the popular modulation schemes [4,5]. A critical disadvantage of these modulation techniques is the complexity which requires large amount of calculations. Even though the conventional phase shift modulation scheme is simple to implement and easy to control since it has only one degree of freedom, it should also be implemented by micro-controller based circuits.

In this paper, an analogous circuit based control algorithm which derived from symmetric phase-shift modulation [8] is adopted to implement the researched system. It has two active full bridges interfaced through a high-frequency transformer and a coupling inductor. One of the active full bridges is connected to the high voltage side which is parallel with the renewable energy source; the other is connected to battery. As the proposed control idea, it can achieve the ZVS switching function with two directions of power flow, and the direction change is smooth. It meets the requirement of stiff energy transfer between PV and the load. The paper is organized as follows. In Section 2, system structure and operation modes are analyzed. The control circuit design is discussed in Section 3, including the proposed symmetric phase shift algorithm. Section 4 shows the experimental results to prove the performance of the proposed control idea. Finally, the conclusions are presented in Section 5.

2. **System Structure.** Figure 1 shows the circuit schematic of the researched PV system with the DAB converter. As the adopted phase shift method, it possesses two square-waves operating in the two active bridges and utilizes the leakage inductance of the transformer as the main current limit element to control the energy transfer between two terminals.

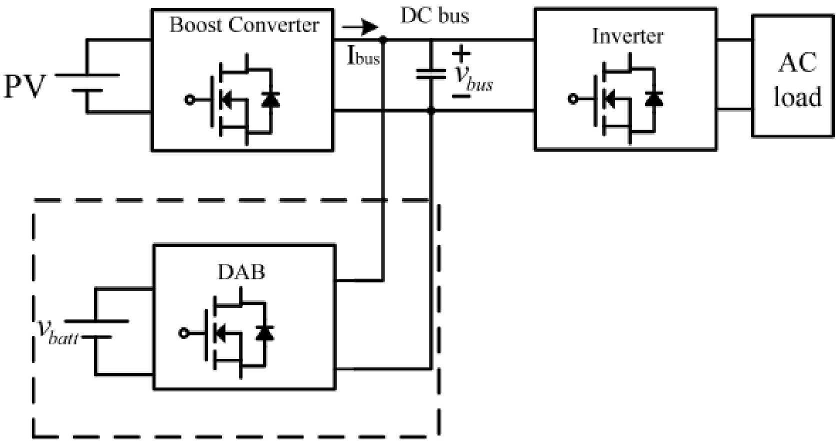


FIGURE 1. The researched PV system

The DAB structure is shown as Figure 2. In the full-bridge converter at the high voltage side, the switching devices, Q_1 and Q_4, are simultaneously turned on and off, and Q_2 and Q_3 are also simultaneously turned on and off. In the battery side, the other full-bridge converter is also operated in a similar manner, where switching devices, Q_5 and Q_8, are simultaneously turned on and off, so as to the switching devices of Q_6 and Q_7. Two full-bridge switches are 50% duty cycle to generate positive and negative voltages between the transformer primary and secondary. This paper adopts the symmetric phase shift algorithm to replace the conventional phase shift method to achieve bilateral power flow control function. The power transmission direction is determined from the leading square wave side to the lagging side.

The transmission power P_D can be expressed as (1), where L_{eq} is the sum of the transformer leakage inductance plus the auxiliary inductor, d defined the phase shift angle between both sides, and ω defined the angular frequency [6,7].

$$P_D = \frac{V_{bus} V_{batt} n}{\omega L_{eq}} \left(d - \frac{d^2}{\pi} \right) \tag{1}$$

Assuming there is no switching loss, then we have

$$\frac{V_{bus} V_{batt} n}{\omega L_{eq}} \left(d - \frac{d^2}{\pi} \right) = V_{batt} I_o \tag{2}$$

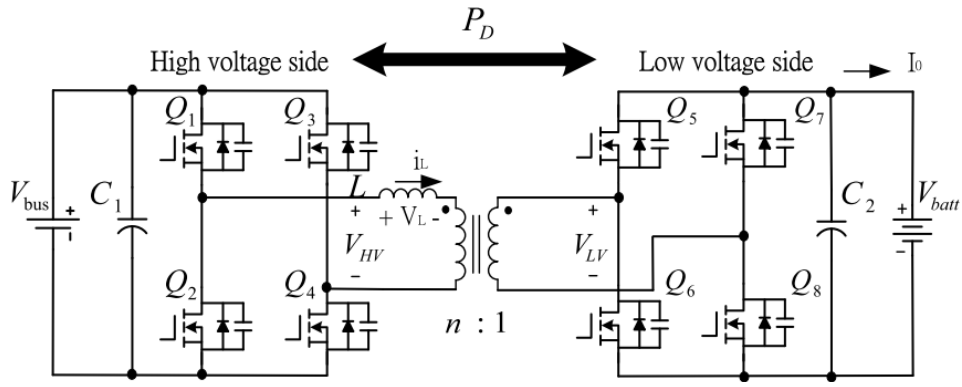


FIGURE 2. The researched DAB structure

And the following equation can be obtained

$$\frac{V_{bus}n}{\omega L_{eq}}\left(d-\frac{d^2}{\pi}\right)=I_o \tag{3}$$

As V_{bus}, n, ω and L_{eq} are all the constants, (3) can be rewrited as follows:

$$I_o \propto \left(d-\frac{d^2}{\pi}\right) \tag{4}$$

The above equation shows that if the phase shift angle d can be controlled, then the battery input current, I_o, can be regulated. When the researched DAB circuit operated in the charging mode, the corresponding waveforms are shown as Figure 3, where the related waveforms between transformer primary and secondary in a switching period, T_s, has been presented.

For the discharge mode, the corresponding waveforms are similar to the charging mode, and thus it is omitted in this paper.

3. **The Control Circuit Design.** The proposed control is dependent on the bus voltage in high voltage side. If the PV energy is larger than the required load, then the bus voltage will be higher than the regulated level, which results in the DAB to operate in charging mode; otherwise, the DAB will be operated in the discharge mode. Figure 4 shows the proposed controller to meet the desired function. It includes a voltage controller, PI_V, and a current controller, PI_I, where V_{busfb} noted the detected bus voltage, V_{busset} noted the desired bus voltage value, $I_{bat}*$ noted the current command, and I_{fb} noted the detected load current. The current controller output V_C adjusts the phase shift angle, and controls the DAB's power switching devices to get the desired power flow. In this paper, the symmetric phase shift algorithm is adopted to implement the control idea. Based on the algorithm, V_C will determine the direction of the energy transfer.

Figure 5 shows the control block diagram of the algorithm, where the control signal V_C is coming from the current controller's output. When V_C is negative, it shows the the phase angle presented in the transformer secondary is lagging to the primary, and the power flow is from the dc bus, passing through the transformer to charge the battery; in contrast, a positive control signal V_C results in a leading phase for the transformer secondary to the primary, and the power flow is from the battery to dc bus. Thus, the energy transfer can be directly controlled by adjusting the control signal V_C, and the proposed idea is easy to implement by analogy circuit.

Figure 6 shows a case of the corresponding symmetric phase shift modulation waveforms in the discharging mode, where the phase angle presented in the transformer primary is lagging to the secondary by ($d = 180° - \alpha$). As shown in Figure 6, V_C is compared with a triangular wave to determine the Q_1 state, and it is turned on if the triangular wave is

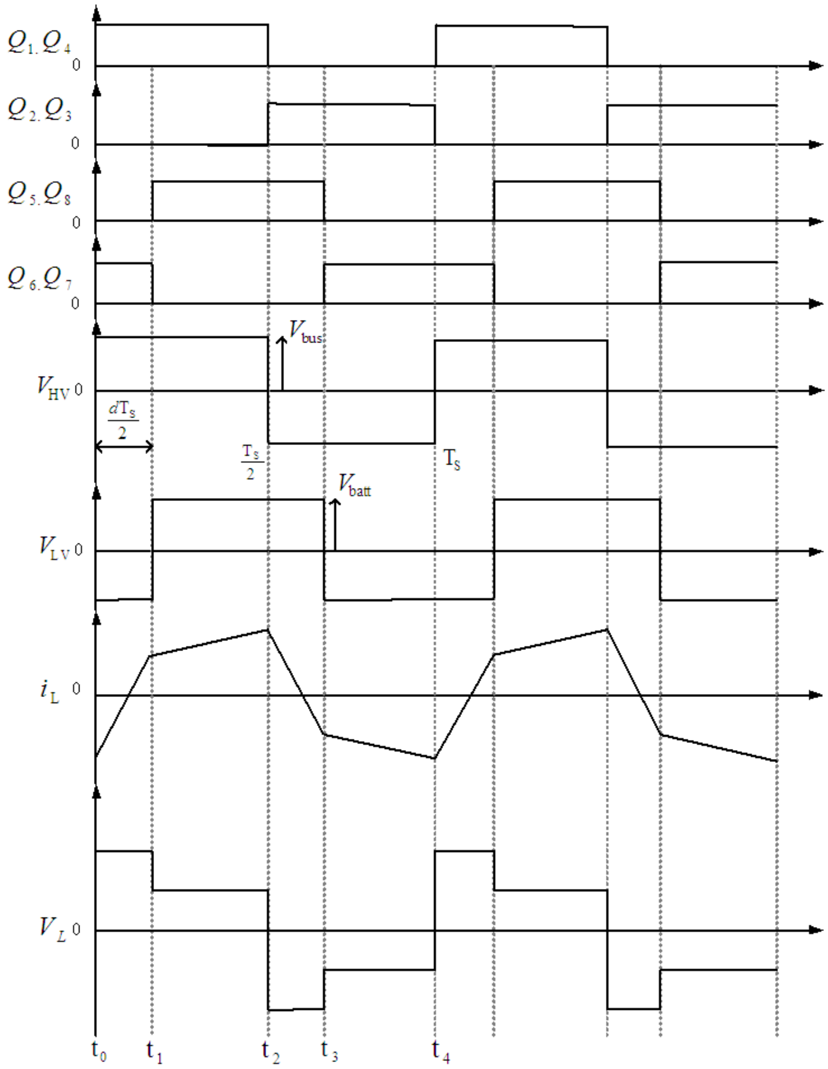


FIGURE 3. The corresponding waveforms for charging mode control

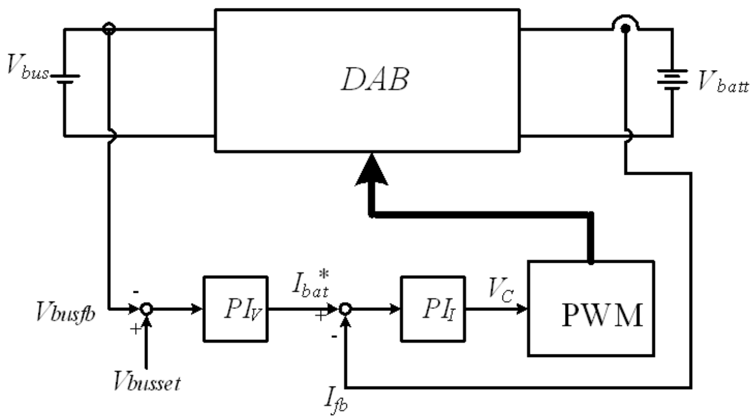


FIGURE 4. The proposed control block diagram

lower than V_C in its positive slope or lower than $-V_C$ in its negative slope. The Q_5 state is determined in a similar condition, and it is turned on if the triangular wave is lower than V_C in its negative slope, or lower than $-V_C$ in its positive.

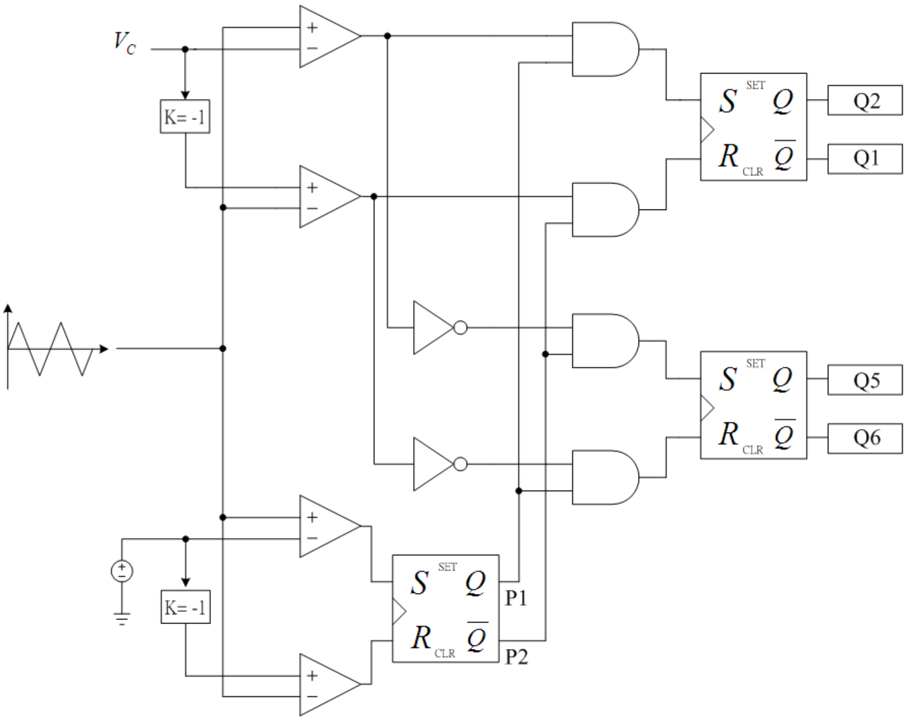


FIGURE 5. The control block diagram of the proposed symmetric phase shift algorithm

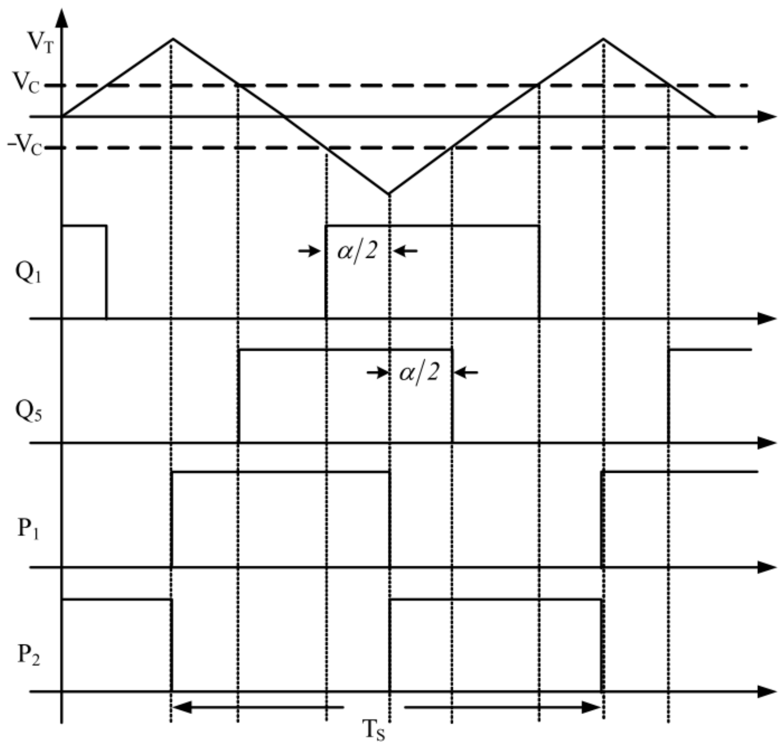


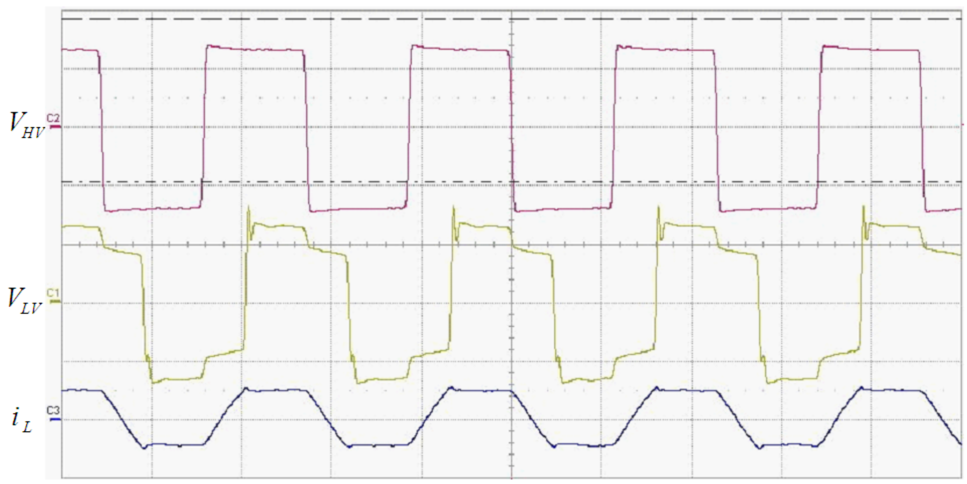
FIGURE 6. The corresponding symmetric phase shift modulation waveforms in the discharging mode

4. **Experimental Results.** According to the foregoing analysis of the structure and principles, a prototype of 150W system is fabricated to verify the control idea. The bus voltage, V_{bus}, in high voltage side is about $70V_{DC}$, and the battery voltage, V_{batt} is around $12V_{DC}$. The other system parameters are shown as Table 1.

TABLE 1. System parameters

Item	Value
Switching frequency	40kHz
L	100μH
C_1, C_2	100mF
High voltage side switching devices	IXTQ 69N30 (300V/69A)
Low voltage side switching devices	IRFB4410 (100V/75A)
Transformer ratio	56:10

When the PV cells produce excess energy, the DAB will be operated in charging mode, the primary voltage V_{HV} of the high frequency transformer has a leading phase angle than the secondary voltage, V_{LV}, and the surplus PV energy passes through the DAB to charge the battery. Figure 7 shows the corresponding waveforms presented in the transformer and inductor, where the charging power is about 150W.



V_{HV} = 50V/div, V_{LV} = 10V/div, i_L = 5A/div, time = 10μs/div

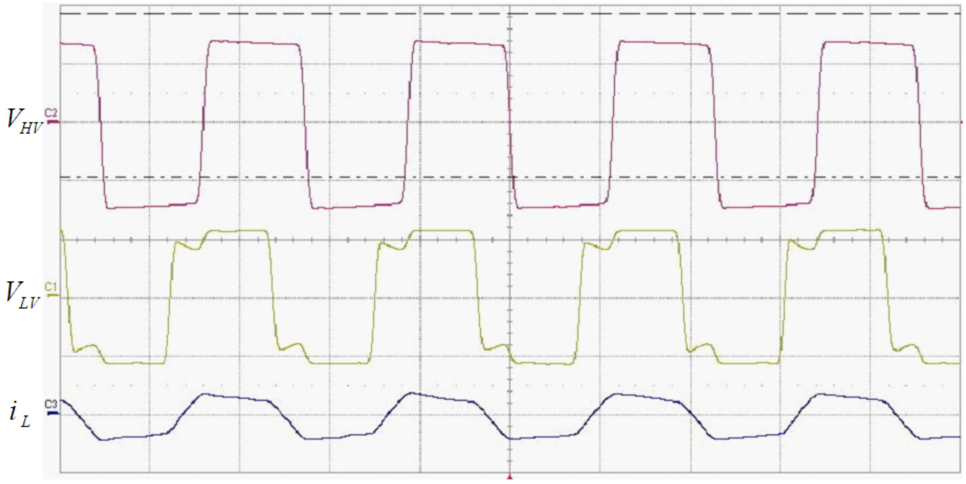
FIGURE 7. The DAB operated in the charging mode

When the PV cells produce insufficient energy, the DAB will be operated in discharging mode, and the transformer primary voltage, V_{HV}, has a lagging phase angle than the secondary voltage, V_{LV}. The battery energy passes through the DAB to support the load. Figure 8 shows the corresponding waveforms presented in the transformer and the inductor, and the discharging power is about 150W.

Figure 9 shows the high side bus voltage and related currents in accordance with the discharge mode shown in Figure 8. It shows the bus current supplied from the PV source is decreased, and the battery provides power about 100W to support the bus load, where I_{bus} denoted the output current coming from the PV energy.

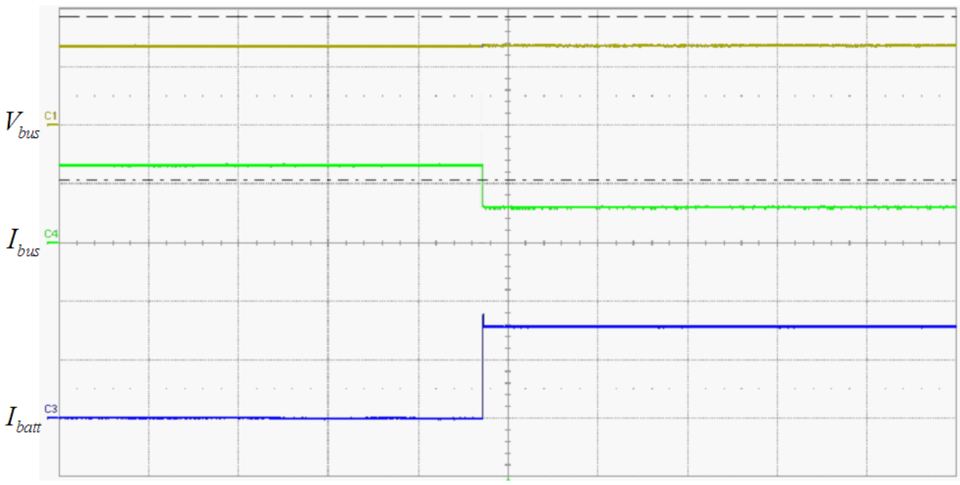
5. **Conclusions.** This paper presents a DAB converter to achieve the bidirectional energy transfer. The proposed system has the advantage of zero voltage switching function, and can allow fast and smooth bidirectional power flow. By adjusting the phase shift angle between the two sides, it can be controlled to achieve the charging or discharging functions. A prototype of 150W is set to verify the proposed idea. From the experimental results, it shows the theoretical analysis and the circuit architecture is feasible.

An important feature of the proposed idea is that the transition for the DAB operated between charging modes and discharging modes is regulated automatically and smoothly,



V_{HV} = 50V/div, V_{LV} = 10V/div, i_L = 5A/div, time = 10μs/div

Figure 8. The DAB operated in the discharging mode



V_{bus} = 50V/div, I_{bus} = 2A/div, I_{batt} = 5A/div, time = 1μs/div

Figure 9. The high side bus voltage and related currents corresponding to Figure 8

and no change in the control loop is required. Based on the idea, it is feasible to extend the currently system to combine with bilateral power factor correction rectifier to transfer the surplus PV energy to the utility in the case that the load demand is low, and the battery is full of charge.

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