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A Single-Stage Solar Converter Using PV-Battery System To Grid

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Abstract: *This paper introduce solar converter for photovoltaic (PV)-battery application, particularly utility-scale PV-battery application. The main concept of the new converter is to use a single-stage three- phase grid-tie solar PV converter to perform dc/ac and dc/dc oper- ations. This converter solution is appealing for PV-battery applica- tion, because it minimizes the number of conversion stages, thereby improving efficiency and reducing cost, weight, and volume. In this paper, a combination of analysis and experimental tests is used to demonstrate the attractive performance characteristics of the pro- posed .*

Index Terms: *Converter, energy storage, photovoltaic (PV), solar.*

I. Introduction

Solar PV electricity output is highly sensitive to shading. When even a small portion of a cell, module, or array is shaded, while the remainder is in sunlight, the output falls dramatically. Therefore, solar PV electricity output significantly varie From an energy source stand- point, a stable energy source and an energy source that can be dispatched at the request are desired. As a result, energy storage such as batteries and fuel cells for solar PV systems has drawn significant attention and the demand of energy storage for solar PV systems has been dramatically increased, since, with energy storage, a solar PV system becomes a stable.

This paper introduces a novel single-stage solar converter called reconfigurable solar converter (RSC). The basic concept of the RSC is to use a single power conversion system to perform different operation modes such as PV to grid (dc to ac), PV to battery (dc to dc), battery to grid (dc to ac), and battery/PV to grid (dc to ac) for solar PV systems with energy storage. The RSC concept arose from the fact that energy storage integration for utility-scale solar PV systems makes sense if there is an enough gap or a minimal overlap between the PV energy storage and release time.

Section II introduces the proposed RSC circuit, different modes of operation, and system benefits. In Section III, control of the RSC is introduced and necessary design considerations and modifications to the conventional three-phase PV converter are discussed. Section IV verifies the RSC with experimental re- sults that demonstrate the attractive performance characteristics. Section V summarizes and concludes the paper.

I. RSC

A. Introduction

The schematic of the proposed RSC is presented in Fig. 2. The RSC has some modifications to the conventional

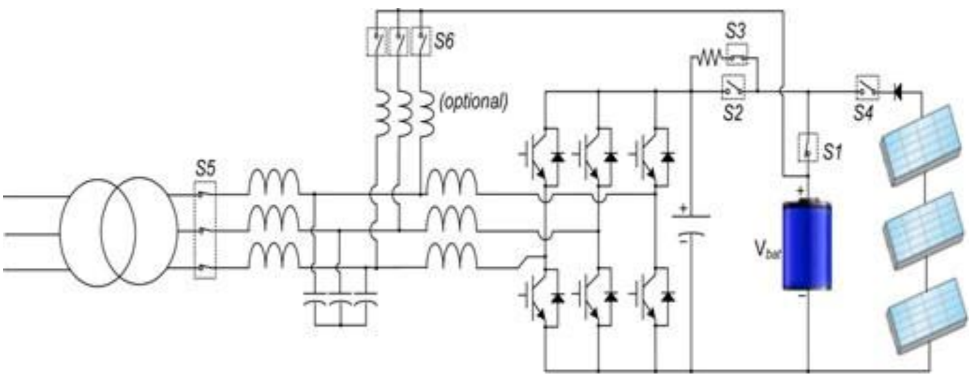

Fig. 2. Schematic of the proposed RSC circuit.

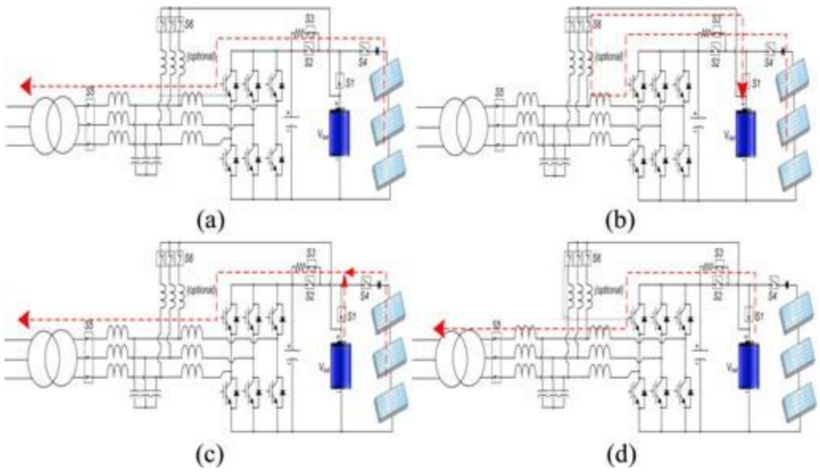

Fig. 3. All operation modes of the RSC. (a) Mode 1—PV to grid. (b) Mode 2—PV to battery. (c) Mode 3—PV/battery to grid. (d) Mode 4—battery to grid.

three-phase PV inverter system. These modifications allow the RSC to include the charging function in the conventional three- phase PV inverter system. Assuming that the conventional utility-scale PV inverter system consists of a three-phase volt- age source converter and its associated components, the RSC requires additional cables and mechanical switches, as shown in Fig. 2. Optional inductors are included if the ac filter inductance is not enough for the charging purpose.

B. Operation Modes of the RSC

All possible operation modes for the RSC are presented in Fig. 3. In Mode 1, the PV is directly connected to the grid through a dc/ac operation of the converter with possibility of maximum power point tracking (MPPT) control and the S_1 and S_6 switches remain open. In Mode 2, the battery is charged with the PV panels through the dc/dc operation of the converter by closing the S_6 switch and opening the S_5 switch. In this mode, the MPPT function is performed; therefore, maximum power is generated from PV. There is another mode that both the PV and battery provide the power to the grid by closing the S_1 switch. This operation is shown as Mode 3. In this mode, the dc-link voltage that is the same as the PV voltage is enforced by the battery voltage; therefore, MPPT control is not possible. Mode 4 represents an operation mode that the energy stored in the battery is delivered to the grid. There is another mode, Mode 5 that the battery is charged from the grid. This mode is not shown in.

C. System Benefits of Solar PV Power Plant With the RSC Concept

The RSC concept provides significant benefits to system plan- ning of utility-scale solar PV power plants. The current state- of-the-art technology is to integrate the energy storage into the ac side of the solar PV system. An example of commercial en- ergy storage solutions is the ABB distributed energy storage (DES) solution that is a complete package up to 4 MW, which is connected to the grids directly and, with its communication ca- pabilities, can be utilized as a mean for peak shifting in solar PV power plants [33]. The RSC concept allows not only the system owners to possess an expandable asset that helps them to plan and operate the power plant accordingly but also manufacturers to offer a cost-competitive decentralized PV energy storage so- lution with the RSC.

I. RSC CONTROL

A. Control of the RSC in the DC/AC Operation Modes (Modes 1, 3, 4, and 5)

The dc/ac operation of the RSC is utilized for delivering power from PV to grid, battery to grid, PV and battery to grid, and grid to battery. The RSC performs the MPPT algorithm to deliver maximum power from the PV to the grid. Like the conventional PV inverter control, the RSC control is implemented in the synchronous reference frame. The synchronous reference frame proportional-integral current control is employed. In a reference frame rotating synchronously with the fundamental excitation, the fundamental excitation signals are transformed into dc signals. As a result, the current regulator forming the innermost loop of the control system is able to regulate ac cur- rents over a wide frequency range with high bandwidth and zero steady-state error. For the pulsewidth modulation (PWM) scheme, the conventional space vector PWM scheme is utilized. Fig. 6 presents the overall control block diagram of the RSC in the dc/ac operation.

B. Control of the RSC in the DC/DC Operation Mode (Mode 2)

The dc/dc operation of the RSC is also utilized for delivering the maximum power from the PV to the battery. The RSC in the dc/dc operation is a boost converter that controls the cur- rent flowing into the battery. In this research, Li-ion battery has been selected for the PV-battery systems. Li-ion batteries require a constant current, constant voltage type of charging al- gorithm. In other words, a Li-ion battery should be charged at a set current level until it reaches its final voltage. At the final voltage, the charging process should switch over to the con- stant voltage mode, and provide the current necessary to hold the battery at this final voltage. Thus, the dc/dc converter per-forming charging process must be capable of providing stable control for maintaining either current or voltage at a constant value, depending on the state of the battery. Typically, a few percent capacity losses happen by not performing constant volt- age charging. However, it is not uncommon only to use constant current charging to simplify the charging control and process. The latter has been used to charge the battery. Therefore, from the control point of view, it is just sufficient to control only the inductor current. Like the dc/ac operation, the RSC performs the MPPT algorithm to deliver maximum power from the PV to the battery in the dc/dc operation. Fig. 7 shows the overall control block diagram of the RSC in the dc/dc operation. In this mode, the RSC control should be coordinated with the BMS, which is not shown in Fig.

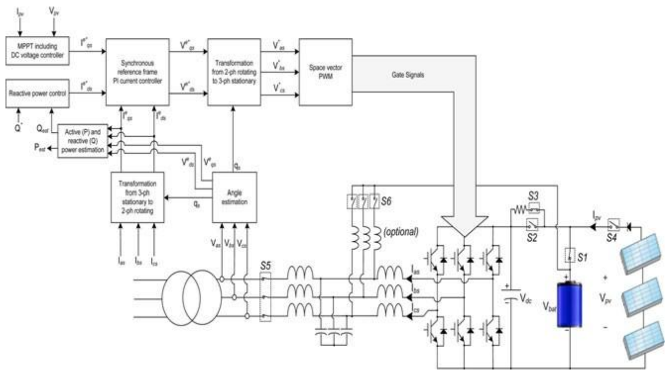

Fig. 6. Overall control block diagram of the RSC in the dc/ac operation

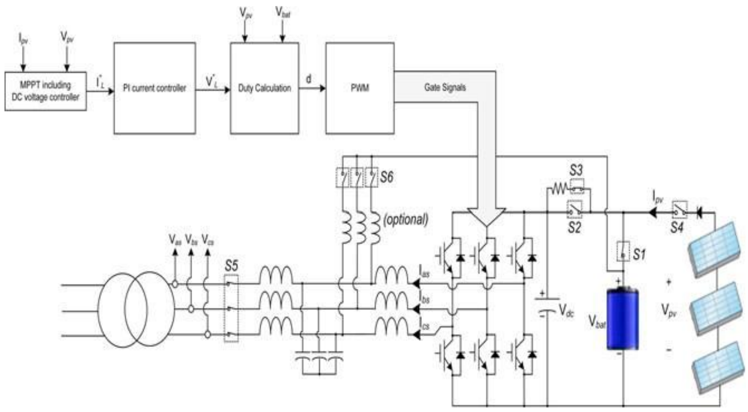

Fig. 7. Overall control block diagram of the RSC in the dc/dc operation.

A. Mode Change Control

The basic concept of the RSC is to use a single power elec- tronics circuit to perform different operation modes such as PV to grid (dc to ac) and PV to battery (dc to dc) for PV systems

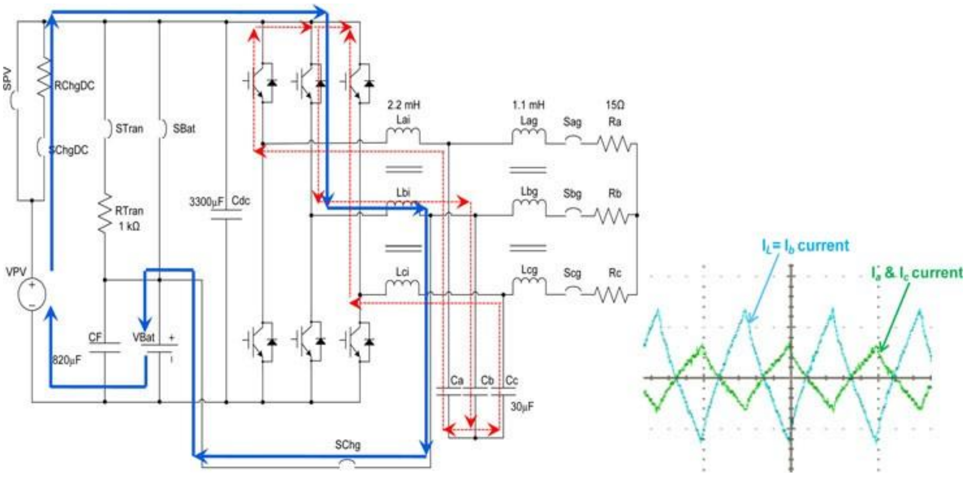

Fig. 8. Circulating current path if one phase is used for the dc/dc operation of the RSC with a coupled three-phase inductor

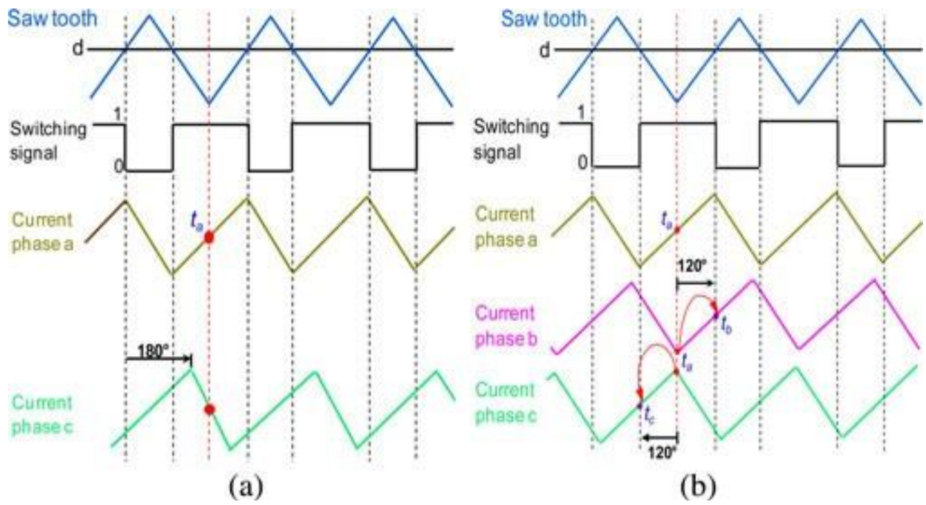

Fig. 9. Inductor current sampling schemes in the interleaving operation.
Two-phase interleaving. (b) Three-phase interleaving.

with energy storage, as discussed earlier. Therefore, in addition to the converter control in each mode, the seamless transition be- tween modes is also essential for the RSC operation. To change a mode, the RSC must be reconfigured by either disconnecting or connecting components such as the battery through contactors. It is very important to understand the dynamics of the RSC circuit. Specifically, it is essential to understand the relay re- sponse time such as how long it takes for a relay to completely close or open. Hence, the performance characteristics of all re- lays used in the RSC circuit must be investigated with their datasheets.

All relays used in the RSC circuit have a maximum operating time equal to or smaller than 50 ms. All switching, which occur during mode change, are done under zero or nearly zero current, except fault cases. To verify the operating time given in the datasheet of the relays, a test for one of the relays used is made. The operating time of the relay used for SChgDC in Fig. 8 is investigated during precharging of the inverter capacitors. The captured waveforms are shown in Fig. 10.

The relay signal inside the DSP is captured through a D/A converter. It takes 240 μs until the signal reaches a value, 12 V, that is high enough to trigger the relay switching. Once the operating voltage is applied to the relay, it takes 20 ms until the current starts flowing through the relay.In other words, it takes 20 ms for the relay to be fully closed. The measured relay operating time of 20 ms is only half of the value given in the datasheet. For all relays used in the circuit, 80 ms is used as the relay switching transient time for both closing and releasing.

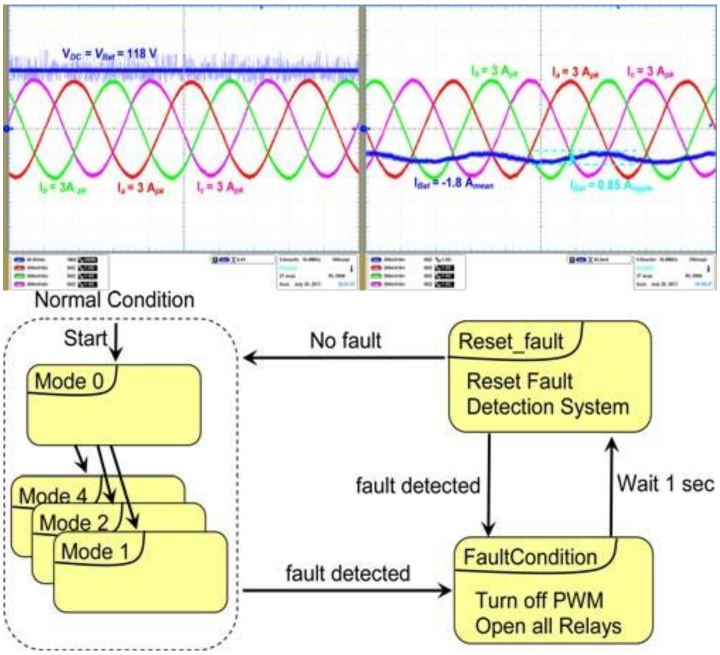

Fig. 10. Measured operating time of the relay.

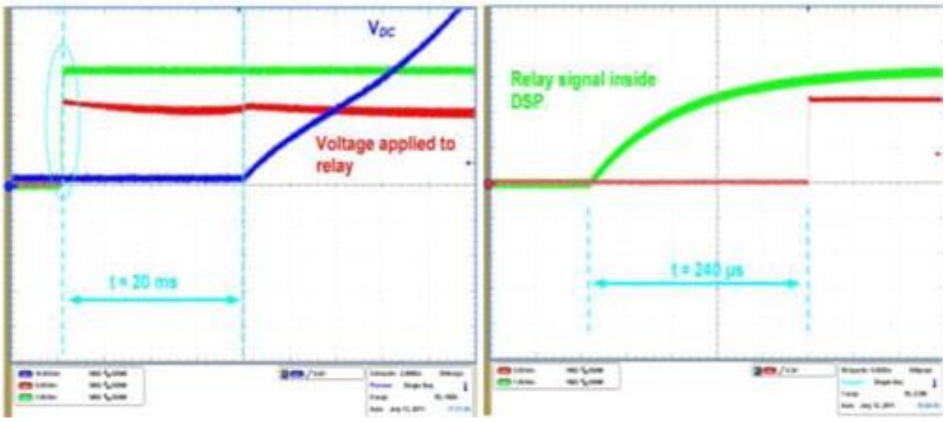

Fig. 11. Highest layer of the RSC mode change control.

A. Performance Investigation of the DC/AC Operation Modes

Fig. 12 shows the steady-state performance of dc/ac control in Mode 1. In this test, the voltage on the dc side V_{DC} of the inverter

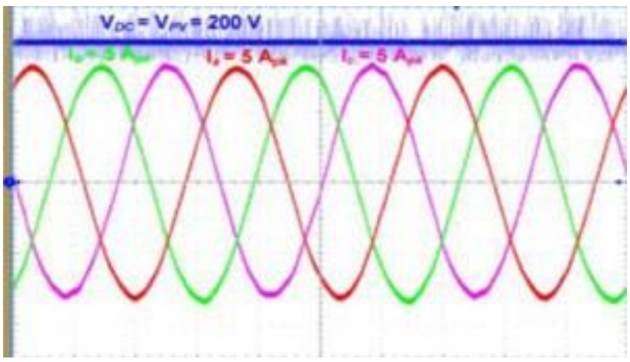

Fig. 12. Steady-state performance of dc/ac control in Mode 1.

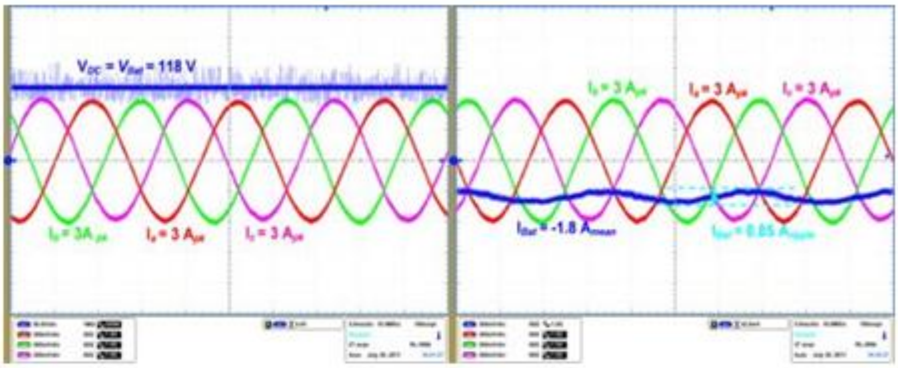

Fig. 13. Steady-state performance of dc /ac control in Mode 4.

is set to 200 V. The current reference is set to 5 A_{peak} for the frequency of 60 Hz. As shown in Fig. 12, a satisfactory steady- state performance is obtained. Fig. 13 shows the steady-state performance of dc/ac control in Mode 4. In the test, the voltage on the dc side V_{DC} of the inverter is 118 V which is the battery voltage. The current reference is set to 3 A_{peak} for the frequency of 60 Hz. As shown in Fig. 13, the satisfactory dc/ac steady-state performance is obtained. In Fig. 13, the current flowing into the battery is exhibited. The average battery charging current is 1.8 A. The battery charging current has about 0.85 A_{pk-pk} current ripple with the frequency of 60 Hz.

A. Performance Investigation of the DC/DC Operation Mode

In Mode 2 (PV to battery), the three-phase inverter is used as a dc/dc converter. As explained, initially a coupled three- phase inductor is used for the filter inductor to the inverter side. When only phase B is utilized for the dc/dc operation with only either upper or lower three IGBTs are turned off as complemen- tary switching, the circulating current occurs in phases A and C through filter capacitors, the coupled inductor, and switches, resulting in significantly high current ripple in phase B current, as shown in Fig. 14 To solve the aforementioned problem,

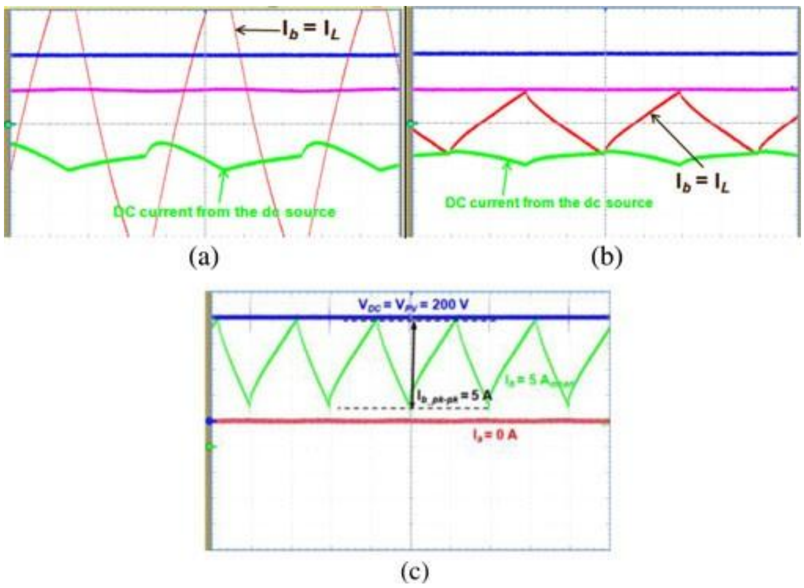

Fig. 14. Steady-state performance of the RSC with single-phase operation in the dc/dc mode (Mode2). (a) When switches unused are not turned OFF.

(a) When switches unused are turned OFF. (c) When three single-phase inductors are used.

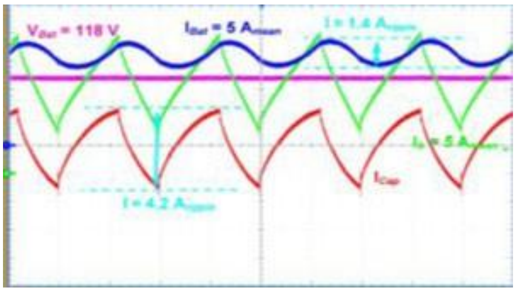

Fig. 15. Steady-state capacitor and battery current for single-phase operation using three single-phase inductors in the dc/dc operation.

as explained, two solutions are proposed. First, the switches un- used are turned off and consequently the phase current presents much lower ripple as shown in Fig. 14(b). The average current in phase B is now 5 A with a ripple of 5 A_{pk-pk} while the current in phases A and C remains zero. This means no circulating current. The second solution is to use three single-phase inductors in the RSC circuit. As expected with single-phase operation in this mode, the circulating current is vanished automatically. The re- sult of the test is presented in Fig. 14(c) showing that the current in the other phases remains zero while the battery is charged.

Fig. 15 shows the current going into the battery for the test shown in Fig. 14(c). The average phase B current is 5 A and the average battery current is also 5 A. The phase B ripple is 5 A_{pk-pk} and the battery current ripple is 1.4 A_{pk-pk}. The capacitor ripple current is about 4.2 A_{pk-pk}.

II. Conclusion

This paper introduced a new converter called RSC for PV-battery application, particularly utility-scale PV-battey application. The basic concept of the RSC is to use a single power conversion system to perform different operation modes such as PV to grid (dc to ac), PV to battery (dc to dc), bat- tery to grid (dc to ac), and battery/PV to grid (dc to ac) for solar PV systems with energy storage. The proposed solution requires minimal complexity and modifications to the conven- tional three-phase solar PV converters for PV-battery systems. Therefore, the solution is very attractive for PV-battery appli- cation, because it minimizes the number of conversion stages, thereby improving efficiency and reducing cost, weight, and volume.

Although this paper focuses on three-phase application, the main concept can be applied to single-phase application. The proposed solution is also capable of providing potential benefits to other intermittent energy sources including wind energy.

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