RECONFIGURABLE SOLAR CONVERTER: A SINGLE-STAGE POWER CONVERSION PV-BATTERY SYSTEM

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ABSTRACT

This paper introduces a new converter called reconfigurable solar converter (RSC) 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 operations. This converter solution is appealing for PV-battery application, 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 proposed RSC.

Index Terms: Converter, Energy Storage, Photovoltaic (PV), Solar.

I INTRODUCTION

SOLAR photovoltaic (PV) electricity generation is not available and sometimes less available depending on the time of the day and the weather conditions. Solar PV electricity output is also 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 varies. From an energy source standpoint, 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 energy source and it can be dispatched at the request, which results in improving the performance and the value of solar PV systems [1]–[3].

There are different options for integrating energy storage into a utility-scale solar PV system. Specifically, energy storage can be integrated into the either ac or dc side of the solar PV power conversion systems which may consist of multiple conversion stages [4]–[33]. Every integration solution has its advantages and disadvantages. Different integration solutions can be compared with regard to the number of power stages, efficiency, storage system flexibility, control complexity, etc.

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. Fig. 1 shows different scenarios for the PV generated power time of use. In case (a), the PV energy is always delivered to the grid and there is basically no need of energy storage. However, for cases (b) and (c), the PV energy should be first stored in the battery and then the battery or both battery and PV supply the load. In cases (b) and (c), integration of the battery has the highest value and the RSC provides significant benefit over other integration options when there is the time gap between generation and consumption of power.

II SOLAR POWER

A solar cell is the most fundamental component of a photovoltaic (PV) system. The PV array is constructed by many series or parallel connected solar cells to obtain required current, voltage and high power [8]. Each Solar cell is similar to a diode with a p-n junction formed by semiconductor material. When the junction absorbs light, it can produce currents by the photovoltaic effect. The output power characteristic curves for the PV array at an insolation are shown in Fig. 3. It can be seen that a maximum power point exists on each output power characteristic curve. The Fig: 4 shows the (I-V) and (P-V) characteristics of the PV array at different solar intensities. The equivalent circuit of a solar cell is the current source in parallel with a diode of a forward bias. The output terminals of the circuit are connected to the load. The current equation of the solar cell is given by:

$$I = I_{ph} - I_D - I_{sh}$$

$$I = I_{ph} - I_0[\exp(\frac{qV_D}{nkT})] - \frac{V_D}{R_{SH}}$$

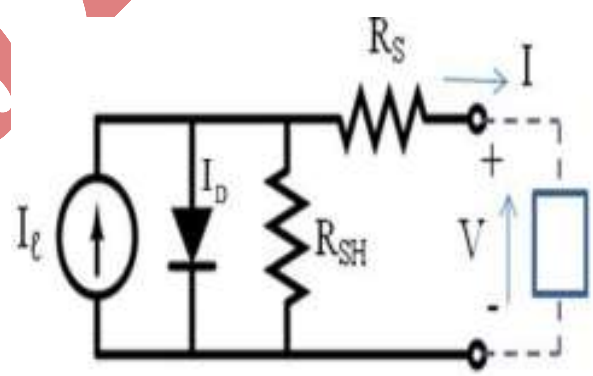


Fig 1: Equivalent Circuit of PV Module

The power output of a solar cell is given by P = V * I

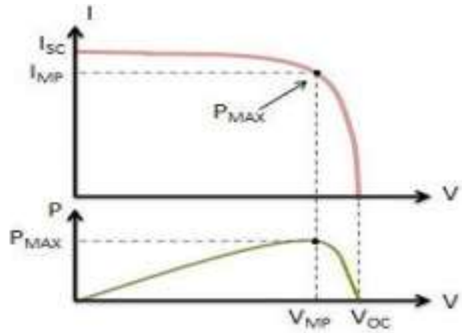


Fig 2: Output Characteristics of PV Array

III RECONFIGURABLE SOLAR CONVERTER

The schematic of the proposed RSC is presented in Fig. 3. The RSC has some modifications to the conventional 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 voltage source converter and its associated components, the RSC requires additional cables and mechanical switches, as shown in Fig. 3. Optional inductors are included if the ac filter inductance is not enough for the charging purpose.

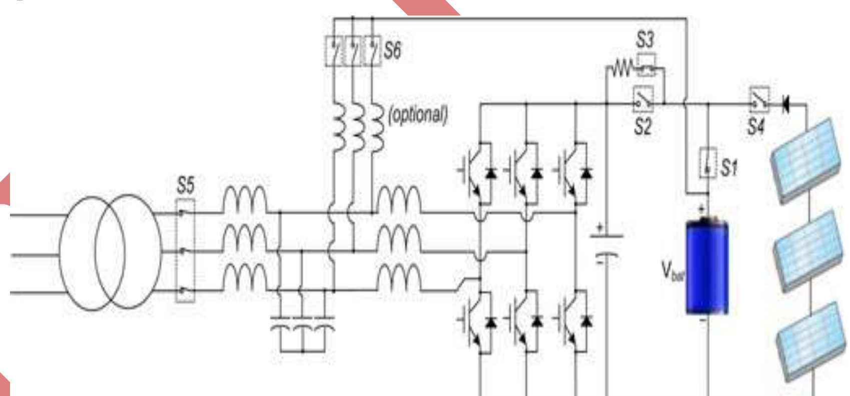


Fig. 3. Schematic of the proposed RSC circuit

IV RSC CONTROL

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 currents over a wide frequency range with high bandwidth and zero steady-state error. For the pulse width modulation (PWM) scheme, the conventional space vector PWM scheme is utilized. Fig. 4 presents the overall control block diagram of the RSC in the dc/ac operation. For the dc/ac operation with the battery, the RSC control should be coordinated with the battery management system (BMS), which is not shown in Fig. 4.

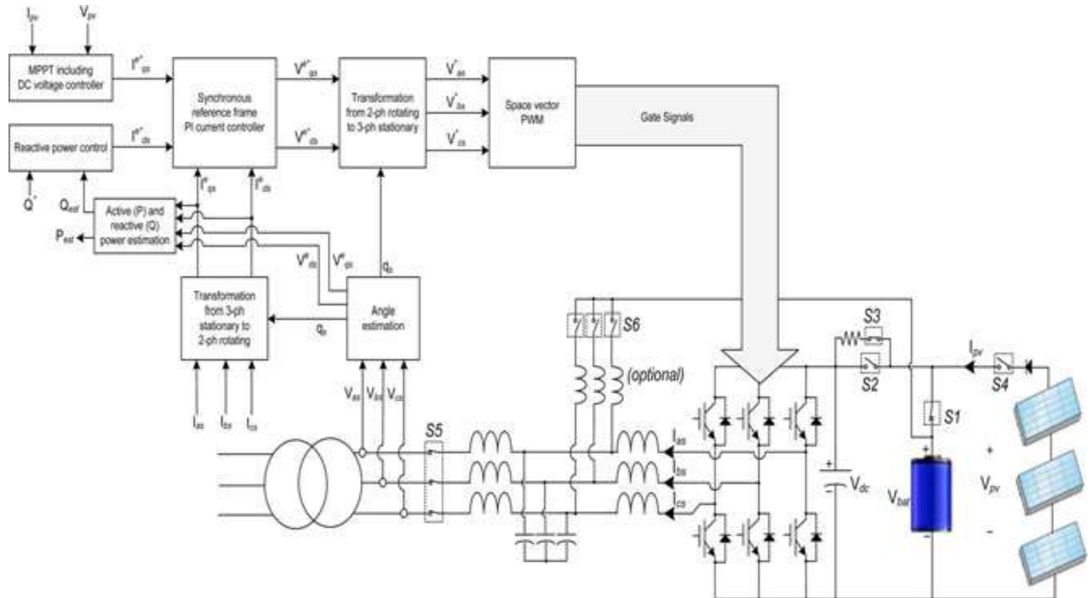


Fig. 4. Overall control block diagram of the RSC in the dc/ac operation

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 current 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 algorithm. 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 constant voltage mode, and provide the current necessary to hold the battery at this final voltage. 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 voltage 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. 5 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. 5.

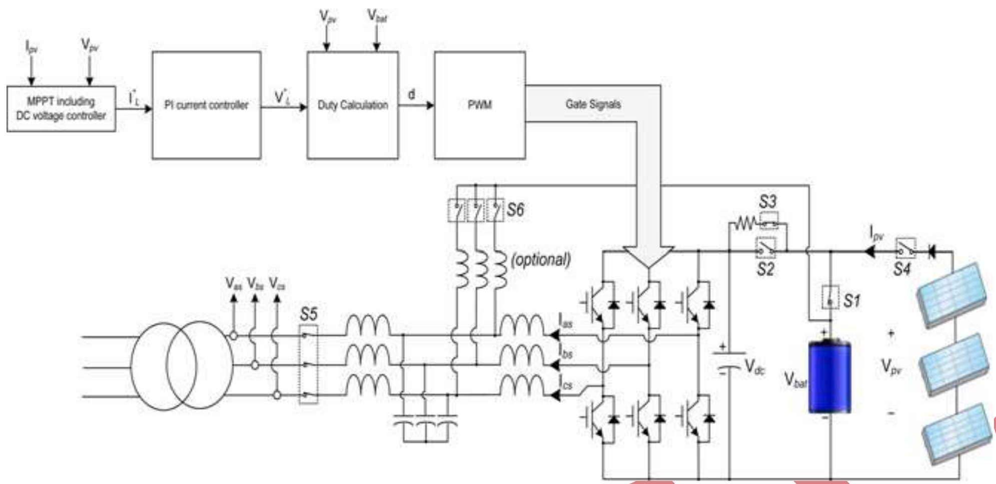


Fig. 5. Overall Control Block Diagram of the RSC in the Dc/Dc Operation

V EXPERIMENTAL DIAGRAM AND RESULTS

The circuit diagram of the RSC shown in Fig. 6 is used to verify the RSC concept experimentally. Fig. 6 shows the components used in the RSC circuit. The conventional grid-tie PV inverter is connected to the grid and delivers the power from the PV to the grid. Therefore, the conventional grid-tie PV inverter requires grid synchronization and power factor control functions. For RSC verification, the aforementioned functions are not implemented and tested. Since the RSC uses the same algorithms for those functions as the conventional grid-tie PV inverter, it is not necessary to verify them. Therefore, the RSC circuit is connected to a passive load. The conventional PV inverter also performs the MPPT to extract the available maximum power from the PV. For RSC verification, the MPPT is also not implemented and tested, since the RSC employs the same MPPT algorithms as the conventional PV inverter. Thus, verification of the RSC circuit is done with a controllable dc power supply, as shown in Fig. 6.

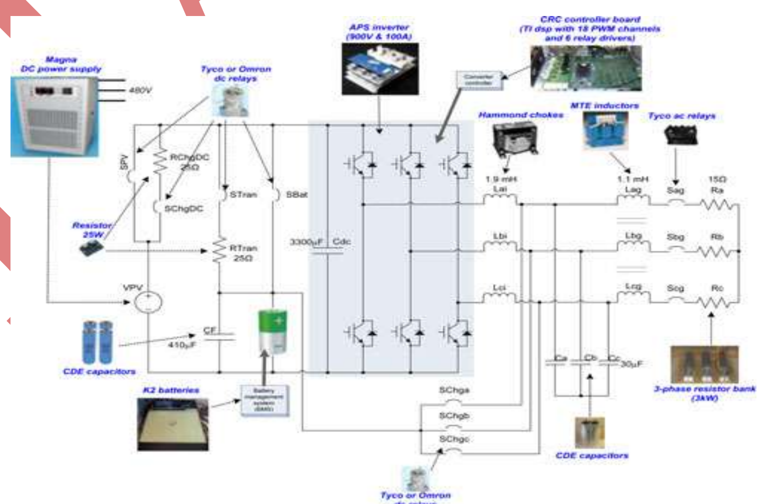


Fig. 6. Components used in the proposed RSC and a photograph of the test

Setup

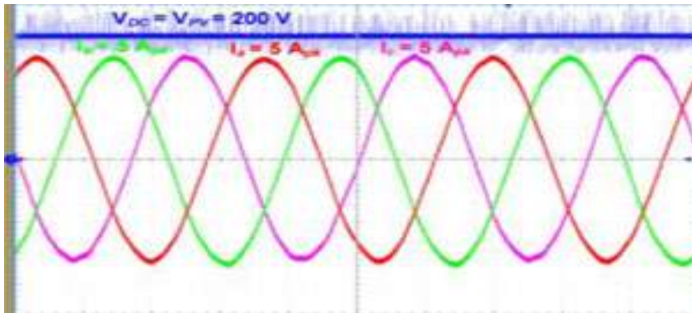


Fig. 7. Steady-state performance of dc/ac control in Mode 1

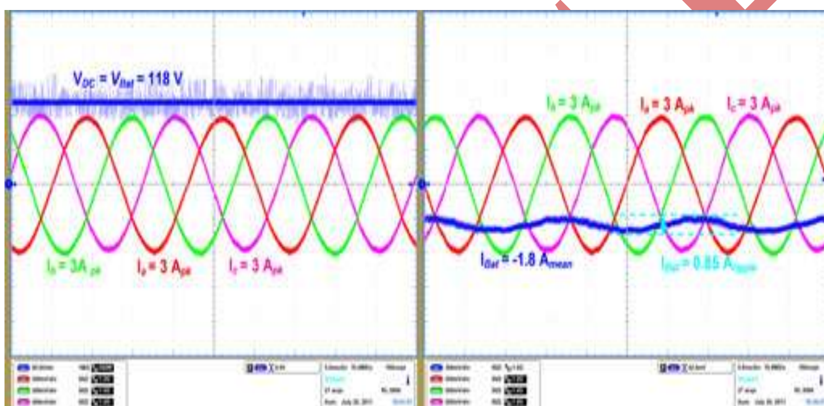
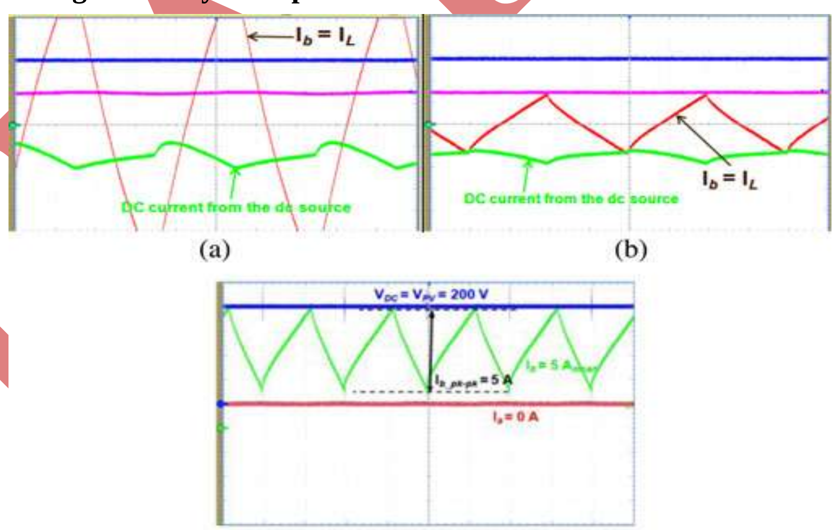


Fig. 8. Steady-state performance of dc /ac control in Mode 4



(a) (b)

(c)

Fig. 9. Steady-state performance of the RSC with single-phase operation in the dc/dc mode (Mode2). (a) When switches unused are not turned OFF. (b) When switches unused are turned OFF. (c) When three single-phase inductors are used

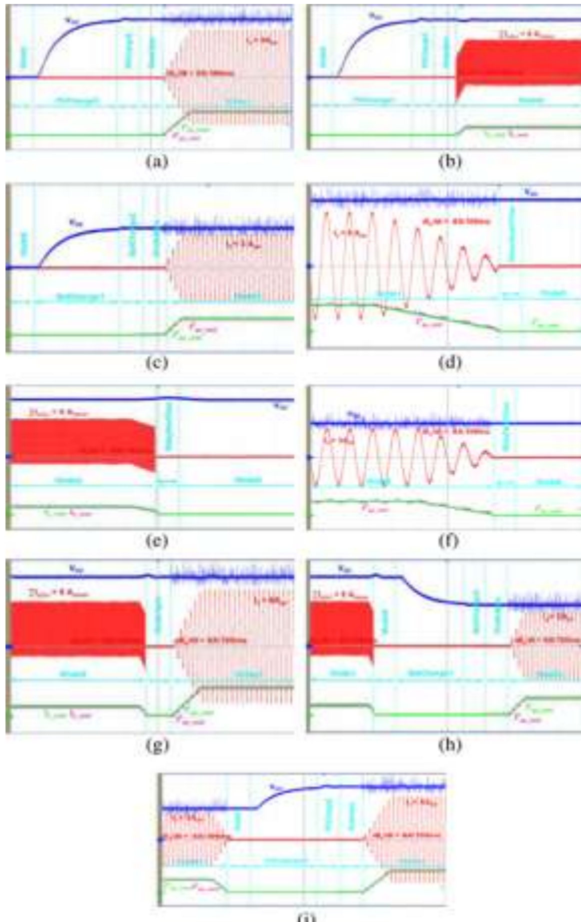


Fig. 10. Transient performance of mode change. (a) Modes 0 to 1. (b) Modes 0 to 2. (c) Modes 0 to 4. (d) Modes 1 to 0 and 0 to 2. (e) Modes 2 to 0. (f) Modes 4 to 0 and 0 to 2. (g) Modes 2 to 1. (h)Modes 2 to 4 and 4 to 0 and 0 to 2. (i) Modes 4 to 1

VI CONCLUSION

This paper introduced a new converter called RSC for PV-battery application, particularly utility-scale PV-battery 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), battery 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 conventional three-phase solar PV converters for PV-battery systems. Therefore, the solution is very attractive for PV-battery application, because it minimizes the number of conversion stages, thereby improving efficiency and reducing cost, weight, and volume. Test results have been presented to verify the concept of the RSC and to demonstrate the attractive performance characteristics of the RSC. These results confirm that the RSC is an optimal solution for PV-battery power conversion systems.

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