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

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Abstract-- This paper introduces a Reconfigurable Solar Converter (RSC). This RSC finds wide application in grid connected solar system since it uses single stage conversion instead of multistage conversion, reduced losses, low cost, simple in construction, improved efficiency and reduced volume. The main concept of the RSC is to prefer single stage power converter on behalf of multistage converter for dc/ac and dc/dc operation for solar energy storage applications.

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. 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. This project presents a new kind of single-stage solar converter called reconfigurable solar converter (RSC). The key notion of the RSC is to use a single power conversion system to achieve different operation methods 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.

Fig. 1. Different scenarios for PV generation and load supply sequence.

The RSC notion evolved from the fact that energy storage combination 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. In 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. PROPOSED RSC

A. Introduction

Fig. 2. Proposed RSC circuit
The schematic of the proposed RSC is presented in Fig. 2. 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. 2. Optional inductors are included if the ac filter inductance is not enough for the charging purpose.

B. Operation Modes of the RSC

The five possible operation modes for the proposed system are as follows.

a) **Mode 1**: PV to grid (S₁ and S₆ switches close remain open)

In this mode the solar panels are directly connected to the grid with Maximum Power Point Tracking (MPPT) by a dc/ac operation of the RSC.

![Fig. 3(a)](image)

b) **Mode 2**: PV to battery (switch S₆ close & S₅, S₃ open)

In this mode the solar panels charge the batteries through dc/dc operation of the converter. In this mode it is possible to track maximum power with the help of MPPT algorithm.

![Fig. 3(b)](image)

c) **Mode 3**: PV/battery to grid (switch S₆ open & remaining switches are close)

In this mode both the solar panels and batteries are connected to the grid by closing the switch S₁.

![Fig. 3(c)](image)

d) **Mode 4**: battery to grid (switch S₄ & S₆ open remaining switches are closed)

In this mode delivers the energy from battery to grid.

![Fig. 3(d)](image)

C. System Advantages of Solar Power Plant with the RSC Concept

The RSC provides significant merits to solar power plants. The current state-of-the-art technology is to integrate the energy storage into the ac side of the solar system. It can be utilized as a mean for shifting peak hours to solar power plants. This technique allows the system owners to have a strong asset which helps them to plan and operate the power plant with respect to their needs. The RSC has reduced conversion stages, high efficiency, low cost & simple in design etc.

![Fig. 4](image)

D. System Control Schemes

In response to the request of the grid operator, different system control techniques can be realized with the RSC solar power plants and are as follows:

1) **System control 1** for \( P_{\text{gen}} > P_{\text{req}} \);
2) **System control 2** for \( P_{\text{gen}} < P_{\text{req}} \);
3) **System control 3** for \( P_{\text{gen}} = P_{\text{req}} \);
4) **System control 4** for charging from grid (Mode 5)
III. RSC CONTROL

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

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 Fuzzy logic 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. 6 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. 6.

B. Control of the proposed 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 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. Thus, the dc/dc converter performing 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. 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. 7.

C. Design Considerations and Modifications to the Conventional Three-Phase PV Converter

One of the most important requirements of the project is that a new power conversion solution for PV-battery systems must have minimal complexity and modifications to the conventional three-phase solar PV converter system. Therefore, it is necessary to investigate how a three-phase dc/ac converter operates as a dc/dc converter and what modifications should be made. It is common to use a LCL filter for a high-power three-phase PV converter and the RSC in the dc/dc operation is expected to use the inductors already available in the LCL filter. There are basically two types of inductors, coupled three-phase inductor and three single-phase inductors that can be utilized in the RSC circuit. Using all three phases of the coupled three-phase inductor in the dc/dc operation causes a significant drop in the inductance value due to inductor core saturation. Table I presents an example of inductance value of a coupled three-phase inductor for the dc/dc operation, which shows significant drop in the inductance value. The reduction in inductance value requires inserting additional inductors for the dc/dc operation which has been marked as “optional” in Fig. 2. To avoid extra inductors, only one phase can perform the dc/dc operation. However, when only one phase, for instance phase B, is utilized for the dc/dc operation with only either upper or lower three insulated-gate bipolar transistors (IGBTs) are turned OFF as complementary 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. 8.

To prevent the circulating current in the dc/dc operation, the following two solutions are proposed;
1) All unused upper and lower IGBTs must be turned OFF;
2) The coupled inductor is replaced by three single-phase Inductors.

While the first solution with a coupled inductor is straightforward, using three single-phase inductors makes it possible to use all three phase legs for the dc/dc operation.

There are two methods to utilize all three phase legs for the dc/dc operation:
1) Synchronous operation;
2) Interleaving operation.

In the first solution, all three phase legs can operate synchronously with their own current control.

<table>
<thead>
<tr>
<th>DC Application</th>
<th>Inductance value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only A</td>
<td>1.42 mH</td>
</tr>
<tr>
<td>Only B</td>
<td>1.58 mH</td>
</tr>
<tr>
<td>A &amp; C</td>
<td>0.50 mH</td>
</tr>
<tr>
<td>A &amp; B &amp; C</td>
<td>0.13 mH</td>
</tr>
</tbody>
</table>
In this case, the battery can be charged with a higher current compared to the case with one-phase dc/dc operation. This leads to a faster charging time due to higher charging current capability. However, each phase operates with higher current ripples. Higher ripple current flowing into the battery and capacitor can have negative effects on the lifetime of the battery and capacitors.

To overcome the aforementioned problem associated with the synchronous operation, phases B and C can be shifted by applying a phase offset. For the interleaving operation using three phase legs, phases B and C are shifted by $120^\circ$ and $240^\circ$, respectively.

![Fig. 8. Circulating current path if one phase is used for the dc/dc operation of the RSC witha coupled three-phase inductor](image)

The inductor current control in interleaving operation requires a different inductor current sampling scheme, as shown in Fig. 9. However, for three-phase interleaving, a modified sampling scheme is required to measure the average currents for all three phases. Therefore, the sampling points for phases B and C must be shifted by $120^\circ$ and $240^\circ$, respectively [see Fig 9(b)], which may imply that computation required inductor current control for each phase should be done asynchronously. Using the interleaving operation reduces the ripples on the charging current flowing into the battery. Therefore, the filter capacitance value can be reduced significantly.

![Fig. 9. Inductor current sampling schemes in the interleaving operation](image)

**D) Mode Change Control**

The basic concept of the RSC is to use a single power electronics circuit to perform different operation modes such as PV to grid (dc to ac) and PV to battery (dc to dc) for PV systems with energy storage, as discussed earlier. Therefore, in addition to the converter control in each mode, the seamless transition between modes is also essential for the single stage converter operation. To change a mode, the single stage converter 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 single stage solar converter. Generally, it is necessary to understand the relay response time such as how much time it takes for a relay to completely close or open. Hence, the performance curves of all relays used in the RSC circuit must be investigated. 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 $S_{ChgDC}$ in Fig. 8 is investigated during pre charging 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 $\mu$s 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.

The highest layer of the single stage solar converter mode change control is shown in Fig. 11. This layer consists of fault detection, fault reset, and normal operation. The basic fault detection such as detecting over current and overvoltage and fault management like turning off PWM signals are implemented inside the converter control executed in the inner most control loop. In this way, fast fault detection and protection are possible.

In general, shutting down all PWM signals is able to clear the fault. In addition, all relays are forced to be opened. If the system is operating normal, the status of the system will be “Normal Condition.” Once the fault flag is set by detecting a fault, the status of the system will be changed to “Fault Condition.” In this status, all relays as well as PWM signals are turned off. When the system is in “Fault Condition,” the single stage converter control tries to clear a fault condition every 1 s. If a fault cannot be cleared, the system will remain in the “Fault Condition.” If a fault is cleared, “Normal Condition” will be reinstated. Inside “Normal Condition,” the system always starts with Mode 0, which is the shutdown mode. This allows the single stage converter to move to a new mode safely, after a fault is cleared.

The control topology inside “Normal Condition” is presented in Fig. 12. The single stage converter control mode can be changed to any mode from the present mode. If Modes 1 or 2 are commanded, the state will change from “Mode 0” to “$PV_{Charge1}$” and relay “$S_{ChgDC}$” will be closed. This will charge the capacitor “$C_{dc}$” through the resistor “$R_{ChgDC}$.” Once the dc voltage of the capacitor reaches 98% of the source voltage, the state will change to “$PV_{Charge2}$.”

This will also close relay “SPV,” while the re-lay “$S_{ChgDC}$” will remain closed, because no new action refers to this relay. To make sure that the relay “SPV” is fully closed, a delay of 80 ms, relay switching transient time, is used, as discussed earlier. For example, the procedure of Mode 1 is described. Let us assume that the current state is “Mode1pre,” the relay “$S_{ChgDC}$” is opened, so that the pre charging procedure is completed. Also, the three grid-switches “$S_{ag}$,” “$S_{bg}$,” and “$S_{cg}$” are closed and therefore the load is connected to the single stage converter. Furthermore, the relay “$S_{Chg}$” is opened and the control is set to Mode 1, which is dc/ac control. Because relay switching is included in the state “Mode1pre,” a delay of 80 ms is required to move to the state of “Run Circuit.” When the previous mode is 1, it is possible to directly move to “Mode2pre.”

This would bypass the pre charging process since the capacitors of the inverter are required to be
connected to the PV side in both modes. All the actions from “Mode2pre” shown in Fig. 12 are executed. After 80 ms, the state moves to “Run Circuit” shown in Fig. 13. When the previous mode is Mode 2 and the new mode is Mode 1, the state directly moves from “PWMOFF” to “Mode1pre” and back to “Run Circuit” by avoiding the pre charge process.

Fig. 13. Control topology inside “Run Circuit”

The startup of Mode 4 is different from Modes 1 and 2, because it connects the battery to the inverter instead of connecting the PV to it. But the pre charging procedure is quite the same. Only different relays are used—“STran” for charging the capacitor “Cdc” through the resistance “RTran” and relay “SBat” for directly connecting the battery to the inverter. Then, the state “Mode4pre” closes the grid switches and sets the mode control to number 4, which is again dc/ac control.

After “Mode4pre,” the state changes to “Run Circuit.” Going from Modes 1 or 2 to Mode 4 or vice versa is not as easy as the mode change between Modes 1 and 2. The dc voltage always has to be changed to either the battery voltage (coming from Mode 1 or 2) or the PV voltage (coming from Mode 4), which makes the mode change control to use Mode 0 for transition. This does not mean that the circuit needs to be fully de energized, since the pre charging resistances limit the current and can therefore take care of this process.

IV. RESULTS OF THE RSC CIRCUIT

A. Experimental Setup

The RSC control algorithms are implemented with MATLAB/Simulink real-time workshop into TI DSP TMS320F28335. The performance of the RSC in different operation modes has been tested extensively in the lab. In the following, the performance analysis of selected modes of operation shown in Fig. 15 will be presented.

B. Performance Investigation of the DC/AC Operation Modes

Fig. 16 shows the steady-state performance of dc/ac control in Mode 1. In this test, the voltage on the dc side Vdc of the inverter is set to 200 V. The current reference is set to 5 Apeak for the frequency of 60 Hz. As shown in Fig. 16, a satisfactory steady state performance is obtained. Fig. 17 shows the steady-state performance of dc/ac control in Mode 4. In the test, the voltage on the dc side Vdc of the inverter is 118 V which is the battery voltage. The current reference is set to 3 Apeak for the frequency of 60 Hz. As shown in Fig. 17, the satisfactory dc/ac steady-state performance is obtained. In Fig. 17, 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 Apeak–pk current ripple with the frequency of 60 Hz.
C. 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 complementary 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. 18(a), battery current is 0.55A.

To solve the aforementioned problem, as explained, two solutions are proposed. First, the switches unused are turned off and consequently the phase current presents much lower ripple as shown in Fig. 18(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, battery current is 0.6A.

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 result of the test is presented in Fig. 18(c) showing that the current in the other phases remains zero while the battery is charged. Fig. 19 shows the current going into the battery for the test shown in Fig. 18(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 A pk–pk. The capacitor ripple current is about 4.2 A pk–pk. Using three single-phase inductors enables the RSC to use all three phase legs in the dc/dc operation. In the first approach, all three phase-legs operate synchronously with their own current controls. Fig. 20 shows the waveforms of the synchronous operation. The sum of all three phase currents is 5A, which means that each phase carries one-third of it. Therefore, it is possible to charge the battery with even a higher current, which leads to a faster charging time. However, each phase current shows the current ripple of 5 A pk–pk. The battery current has the current ripple of 2 A pk–pk and the capacitor current shows the current ripple of 12 A pk–pk which is almost three times as high as the ripple current of the battery charging using a single phase leg. Higher ripple current flowing into the battery and capacitor can have negative effects on the lifetime of the battery and capacitors. As discussed earlier, using the interleaving operation can reduce the ripples on the charging current flowing into the battery.
As shown in Fig. 21, the battery current has a ripple current of 0.2 A_{pk} - pk and the capacitor current has a ripple current of 1.5 A_{pk} - pk when the sum of all three phase currents is 5 A and the average battery current is 5 A. These current ripples are one third of the ripple currents for dc/dc control using a single phase leg and one-eighth of the ripple currents for dc/dc control using all three phase legs in synchronous operation, which means significant ripple reduction is achieved by interleaving operation.

D. Performance Investigation of Mode Change

Mode change control is the most important aspect of the RSC operation. To implement the mode change control, MATLAB/Simulink stateflow is used. Fig. 22 shows the experiment results of mode change control. As mentioned earlier, only Mode 0 (Shutdown), Mode 1 (PV to Grid), Mode 2 (PV to Battery), and Mode 4 (Battery to Grid) are tested with the experimental setup. All mode changes show satisfactory performance in both transient and steady states. As discussed in Section III, mode change either from or to Mode 4 is not as simple as the mode change between Modes 1 and 2, since the dc voltage must be changed to either the battery voltage or the PV voltage. In the mode transition either to or from Mode 4, Mode 0 is used for transition [see Figs.22(h) and 22(i)]. After Mode 0 as transition, the dc capacitor is either discharged or charged through the precharging resistance. Therefore, the dc voltage is changed to either the battery voltage or the PV voltage, as demonstrated in Fig. 22.

V. 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. 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.

REFERENCES


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