SIMULATION OF RECONFIGURABLE SOLAR CONVERTER
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Abstract: In this paper a converter called reconfigurable solar converter (RSC) for photovoltaic (PV)-battery applications is introduced, 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. 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. The analysis of the converter is done by PI controller and fuzzy controller to determine output voltage, PV current and voltage, battery current and voltages. Development of the model and Simulation is done using MATLAB/SIMULINK software.

Keywords:- Converter, energy storage, fuzzy logic, photovoltaic (PV), solar.

I. INTRODUCTION

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 [3]-[10]. 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.

Reconfigurable solar converter (RSC) is a single stage solar power converter. 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: Block diagram of reconfigurable solar converter

Figure 2: Different scenarios for PV generation and load supply sequence.

II. MODELLING OF RSC

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. The schematic of the proposed RSC is presented in Fig. 3.

![Figure 3: Schematic of the proposed RSC circuit](image)

All possible operation modes for the RSC are presented in Fig. 5. 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 S1 and S6 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 S6 switch and opening the S5 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 S1 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.

![Figure 5: operation modes of the RSC. (a) Mode 1-PV to grid. (b) Mode2-PV to battery. (c) Mode 3-PV/battery to grid. (d) Mode 4-battery to grid.](image)

**A. Control of the RSC in the dc/ac operation modes**

The dc/ac operation of the RSC is utilized for delivering power from PV to grid, battery to grid, PV and battery to grid. 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 [17]-[18]. 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.
B. Control of the RSC in the dc/dc operation mode

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. 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. 8 shows the overall control block diagram of the RSC in the dc/dc operation.

Figure 6: Overall control block diagram of the RSC in the dc/ac operation

Figure 7: control circuit for dc/ac mode using pi controller

Figure 8: Overall control block diagram of the RSC in the dc/dc operation
One of the most important requirements of the paper 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 [12]-[16].

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.8. 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.10 to prevent the circulating current in the dc/dc operation, the following two solutions are proposed.

- All unused upper and lower IGBTs must be turned OFF.
- 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.

- synchronous operation
- Interleaving operation

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

**Figure 11:** Inductor current sampling schemes in the interleaving operation. (a) Two-phase interleaving. (b) Three-phase interleaving.

For the interleaving operation using three phase legs, phases B and C are shifted by 120° and 240° respectively. The inductor current control in interleaving operation requires a different inductor current sampling scheme, as shown in Fig. 11. In general, for digital control of a dc/dc converter, the inductor current is sampled at either the beginning or centre point of PWM to capture the average current that is free from switching noises.

For two phase interleaving that two phases are 180° apart, there is no need to modify the sampling scheme since the average inductor currents for both phases can be obtained with the conventional sampling scheme [see Fig. 11 (a)]. 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° and 240°, respectively [see Fig. 11(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.

**III. SIMULATION RESULTS**

**A. Simulink results for 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 VDC of the inverter is set to 200 V. The current reference is set to 5Apeak for the frequency of 60 Hz. As shown in Fig. 12, a satisfactory steady state performance is obtained.

**Figure 12:** Steady-state performance of dc/ac control in Mode 1.

**Figure 13 a:** Steady-state performance of dc/ac control in Mode 4.

**Figure 13 b:** Steady-state performance of dc/ac control showing current flowing in a battery.
Fig. 13a 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 3Apeak for the frequency of 60 Hz. As shown in Fig. 13a, the satisfactory dc/ac steady-state performance is obtained. In Fig. 13b, 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.

**B. Simulink results for the dc/dc operation modes**

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. 14(b). The average current in phase B is now 5 A with a ripple of 5A 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 result of the test is presented in Fig. 14(c) showing that the current in the other phases remains zero while the battery is charged.

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. 14(a).

Fig.14 (d) 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 5A pk–pk and the battery current ripple is 1.4A pk–pk. The capacitor ripple current is about 4.2A pk–pk using three single-phase inductors enables the RSC to use all three phase legs in the dc/dc operation.
As discussed earlier, there are two methods to utilize all three phase legs for the dc/dc operation. In the first approach all three phase-legs operate synchronously with their own current controls. Fig. 15 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 Apk–pk. The battery current has the current ripple of 4Apk–pk and the capacitor current shows the current ripple of 12Apk–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. 16, the battery current has a ripple current of 0.5Apk–pk and the capacitor current has a ripple current of 1.5Apk–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.
C. Simulink results for mode change control

Mode change control is the most important aspect of the RSC operation. To implement the mode change control, MATLAB/Simulink state flow is used. Below are the simulink results of mode change control.

Figure 17a: Transient performance of mode changes in Mode 0 to 1

Figure 17b: Transient performance of mode changes in Mode 0 to 2

Figure 17c: Transient responses of mode changes in different modes

Mode change from 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. After Mode 0 as transition the dc capacitor is either discharged or charged through the pre-charging resistance. Therefore, the dc voltage is changed to either the battery voltage or the PV voltage, as demonstrated in Figures below.

Figure 17d: Transient responses when mode changes from mode 4 and mode 2

Figure 17e: Transient response when mode changes from Modes 2 to 4 and 4 to 0 and 0 to 2

Figure 17f: Transient response when mode changes from Mode 4 to 1

All mode changes show satisfactory performance in both transient and steady states.
IV. SIMULINK MODEL AND CONTROL CIRCUIT USING FUZZY CONTROLLER

A. Matlab module and control circuits of rsc using fuzzy controller

![Simulink module of rsc](image1)

**Figure 17:** simulink module of rsc

![Control circuit using fuzzy controller](image2)

**Figure 18:** control circuit using fuzzy controller

![Circuit module for fuzzy controller](image3)

**Figure 19:** circuit module for fuzzy controller

B. Results showing the difference between pi controller and fuzzy controller

The benefit of the fuzzy controller is that it does not have a special operating point. The rules evaluate the difference between the measured value and the set value, which is the error signal. The rules also evaluate the tendency of the error signal to determine whether to increase or decrease the control variable. The absolute value of the command variable has no influence. Another advantage of a fuzzy-PI controller over a conventional PI controller is that it can implement nonlinear control strategies and that it uses linguistic rules.

![Output power of PV using Fuzzy controller](image4)

**Figure 20:** Output power of PV using Fuzzy controller

![Output power of PV using PI controller](image5)

**Figure 21:** Output power of PV using PI controller

V. CONCLUSION AND FUTURE WORK

Conclusion
A converter called reconfigurable solar converter (RSC) is proposed for PV battery applications. RSC 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. The model is developed and evaluated for different operating modes and mode change conditions etc, and the simulation results validate the functionality of the proposed converter under different operating conditions. Simulation results shows that more accurate values can be obtained by using fuzzy controller over pi controller.

Future scope
This concept can also be applied to single-phase application. Development of RSC for wind energy power plant can be done as a future enhancement. Battery overcharging also can be avoided by implementing a control logic block.
REFERENCES


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