Fuzzy Based RSC for Power Conversion in PV-Battery System

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ABSTRACT

The output power of PV module varies with module temperature, solar irradiation and loads. And in order to quickly and accurately track the sun. Solar PV electricity output is also highly sensitive to shading. In this paper introduces a new converter i.e. reconfigurable solar converter (RSC) for photovoltaic (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. In this paper fuzzy logic control (FLC) technique is used. 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 fuzzy logic controller is used for controlling the reconfigurable solar converter (RSC) for photovoltaic (PV)-battery application, particularly utility-scale PV battery application. The main advantages of fuzzy logic control are to eliminate steady state error and harmonic content and improve the system response.

Keywords: *Converter, Energy Storage, Fuzzy Logic, Photovoltaic (PV), Solar*

I. INTRODUCTION

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. 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. 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. 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. 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.

This paper deals with obtaining the proper algorithm in order to extract maximum power from available wind. To carry out this, fuzzy logic control of generator side converter and thus control of generator speed was used [3]. The advantages in using fuzzy logic controller against standard PI controllers, are pointed out in better response to frequently changes in wind speed. 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 simulation results that demonstrate the attractive performance characteristics with FLC. Section V summarizes and concludes the approach.

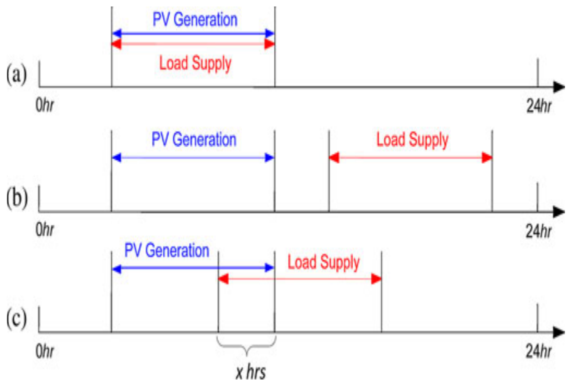


Fig. 1. Different scenarios for PV generation and load supply sequence

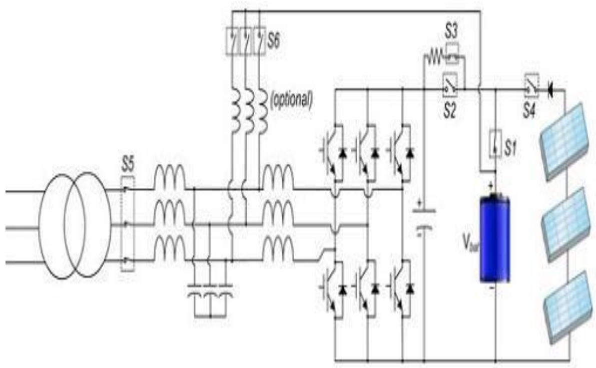


Fig.2. Schematic of the proposed RSC circuit

II. RSC CASE STUDY

A. Introduction

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. RSC Operation Modes

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 theS1and S6switches 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 theS5 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 theS1 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 Fig. 3.

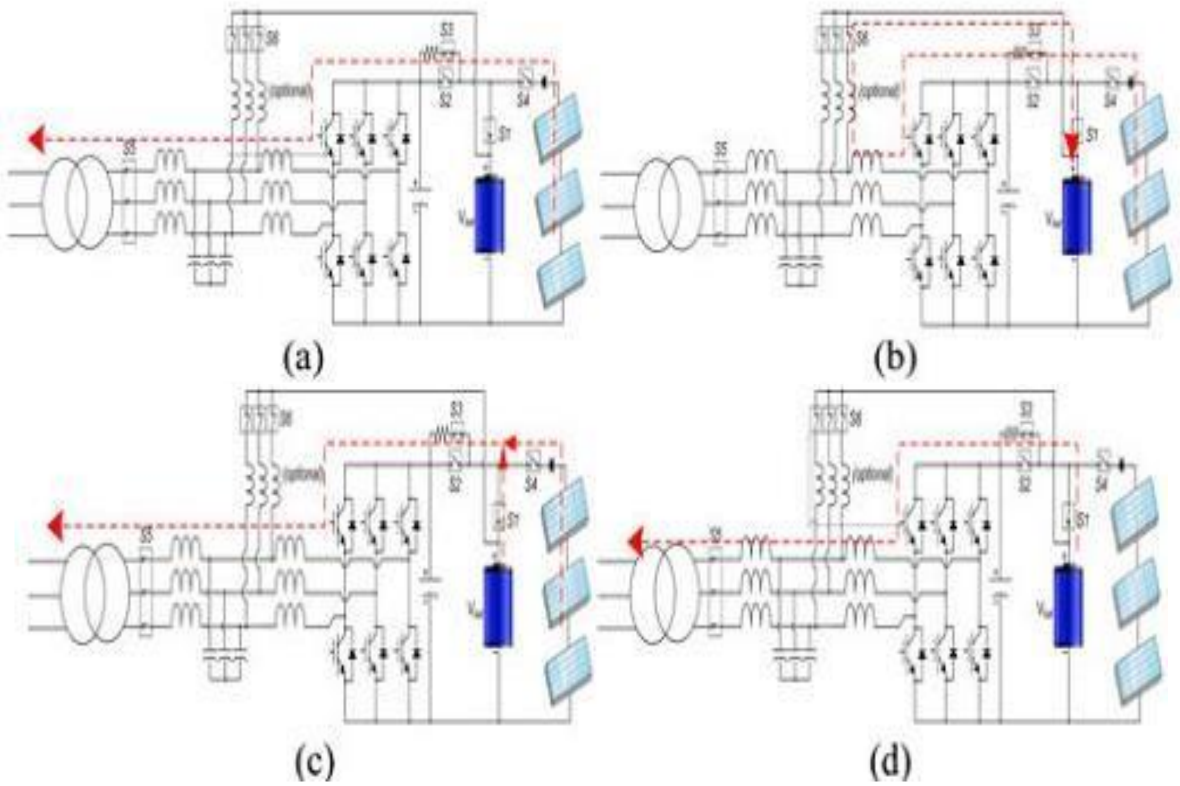


Fig.3. All operation modes of the RSC. (a) Mode 1—PV to grid. (b) Mode 2—PV to battery. (c) Mode 3—PV/battery to grid. (d) Mode 4—battery to grid

The RSC concept provides significant benefits to system planning 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 energy 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 capabilities, 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 solution with the RSC.

C. Benefits of Solar PV Power Plant with the RSC Concept

The technical and financial benefits that the RSC solution is able to provide are more apparent in larger solar PV power plants. Specifically, a large solar PV power plant using the RSCs can be controlled more effectively and its power can be dispatched more economically because of the flexibility of operation. Developing a detailed operation characteristic of a solar PV power plant with the RSC is beyond the scope of this paper. However, different system controls as shown in Fig. 4 can be proposed based on the requested power from the grid operator Preq and available generated power form the plant Pgen. These two values being results of an optimization problem (such as unit commitment methods) serve as variables to control the solar PV power plant accordingly. In other words, in response to the request of the grid operator, different system control schemes can be realized with the RSC-based solar PV power plant as follows

System control 1 for; $P_{gen} > P_{req}$
System control 2 for; $P_{gen} < P_{req}$
System control 3 for: $P_{gen} = P_{req}$

III.CONTROL OF RSC

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 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.

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 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. 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.

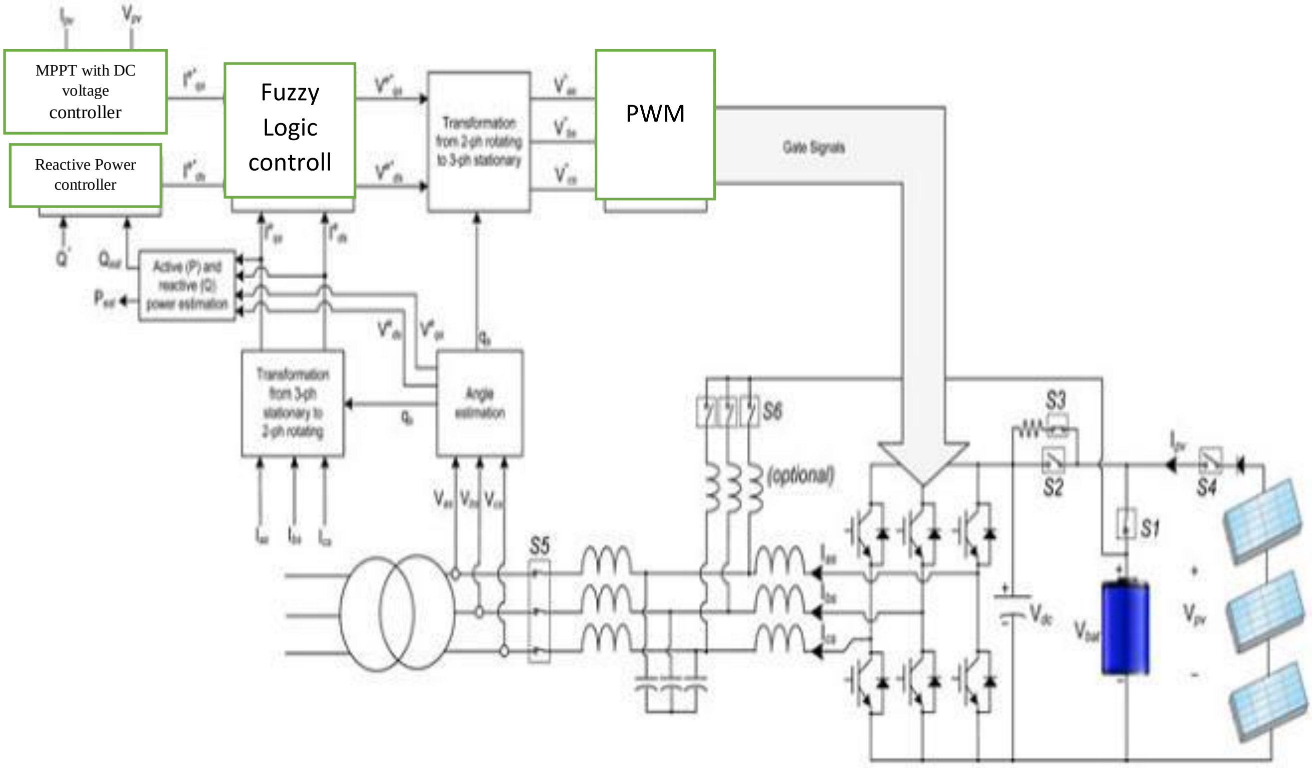


Fig.4. Overall control block diagram of the RSC in the dc/ac operation

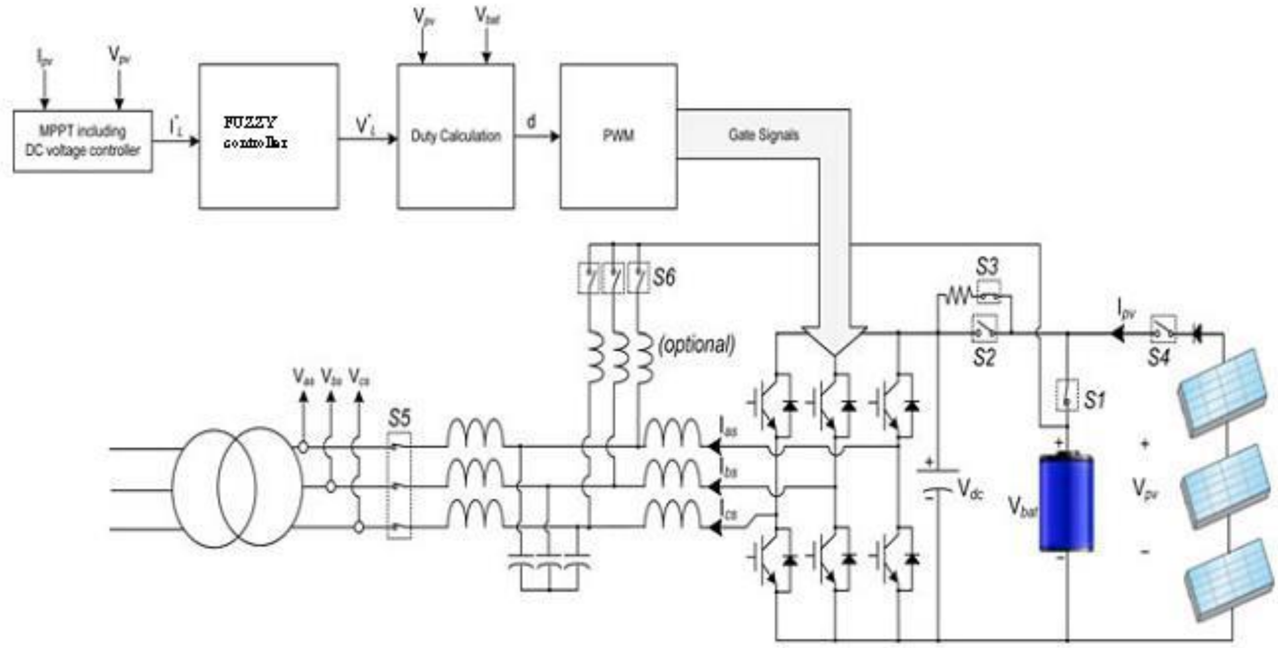


Fig.5. Overall control block diagram of the RSC in the dc/dc operation

C 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 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 response time such as how long it takes for a relay to completely close or open. Hence, the performance characteristics of all relays used in the RSC circuit must be investigated with their data sheets. All relays used in the RSC circuit have a maximum operating time equal to or smaller than 50ms. 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 SC hg DC in Fig. 6 is investigated during pre-charging of the inverter capacitors. 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.

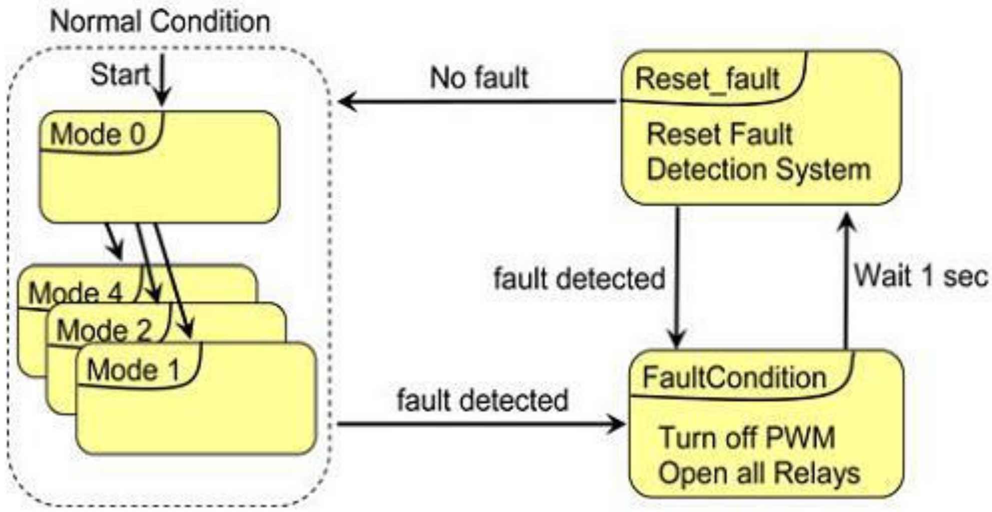
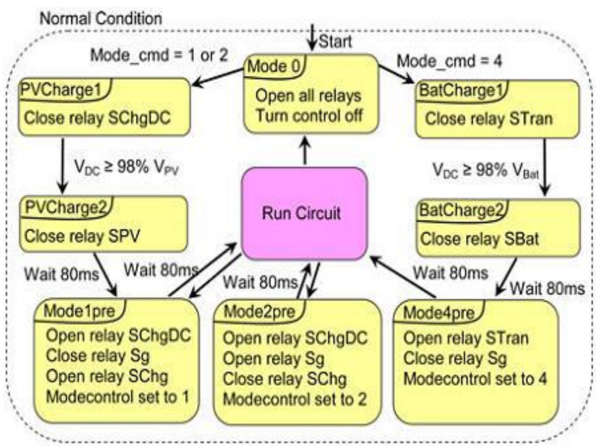


Fig. 6. Highest layer of the RSC mode change control.

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 there lay switching transient time for both closing and releasing. The highest layer of the RSC mode change control is shown in Fig. 6. 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 RSC 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 RSC to move to a new mode safely, after a fault is cleared. The control topology inside ―Normal Condition‖ is presented in Fig. 7. The RSC 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 ―PVCharge1‖ and relay ―SC hg DC‖

will be closed. This will charge the capacitor ―Cdc‖ through the resistor ―RC hg DC.‖ Once the dc voltage of the capacitor reaches 98% of the source voltage, the state will change to ―PVCharge2.‖ This will also close relay ―SPV,‖ while the relay ―SC hg DC‖ 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 ―SC hg DC‖ is opened, so that the pre-charging procedure is completed. Also, the three grid-switches ―Sag,‖ ―Sbg,‖ and ―Scg‖ are closed and therefore the load is connected to the RSC. Furthermore, the relay ―SC hg‖ is opened and the control is set to Mode 1, which is dc/ac control



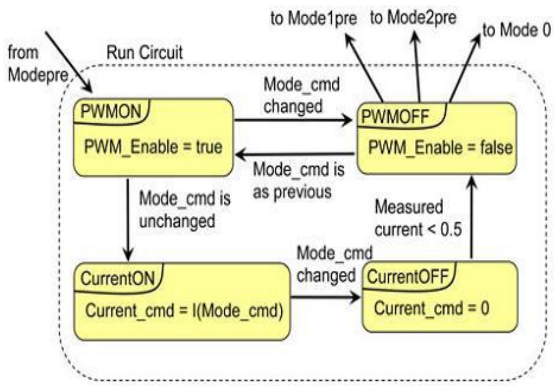


Fig. 7. States inside "Normal Condition" **Fig. 8. Control topology inside "Run Circuit"**

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. 7 are executed. After 80 ms, the state moves to ―Run Circuit‖ shown in Fig. 8. When the previous mode is Mode 2 and the new mode is Mode 1, the state directly moves from ―PWM OFF to ―Mode1pre‖ and back to ―Run Circuit‖ by avoiding the pre-charge process. 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 connects 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.

E. Fuzzy Logic Controller

Fuzzy logic control is a non-mathematical decision algorithm that is based on an operator’s experience. This type of control strategy is suited well for nonlinear Systems

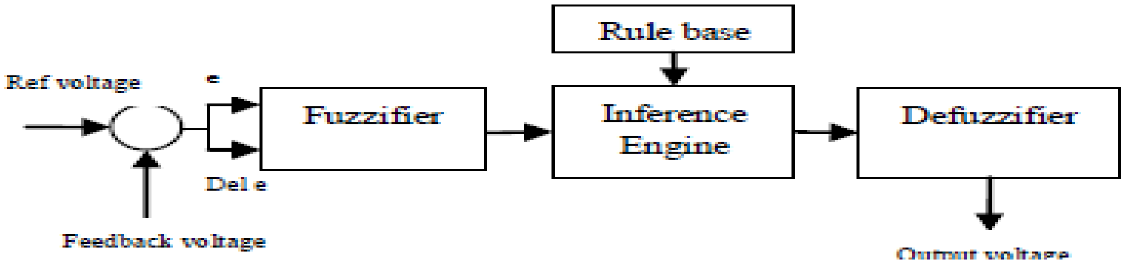
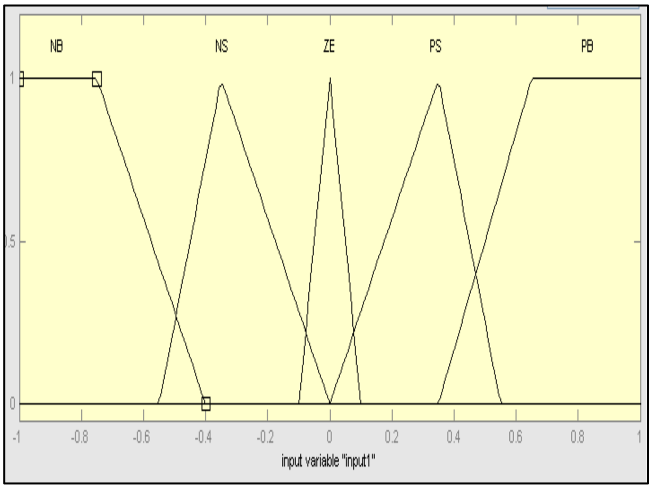


Fig. 9 The general structure of Fuzzy Logic Controller



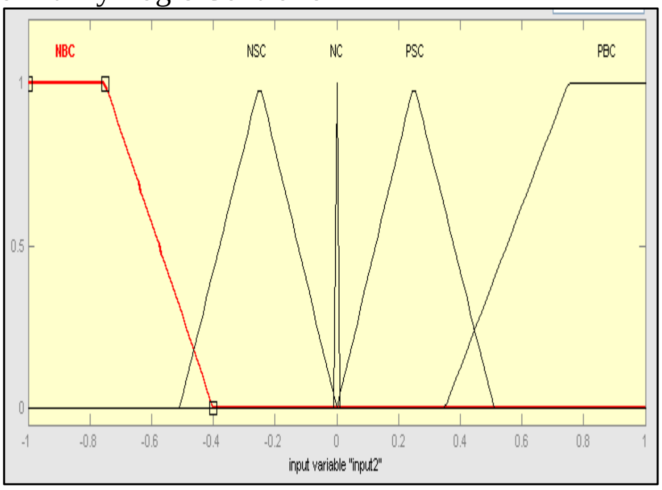


Fig 10. Membership function of change of error. Fig 11. Membership function of output

FLC contains three basic parts: Fuzzification, Base rule, and Defuzzification. FLC has two inputs which are: error and the change in error, and one output. The Fuzzy Controller structure is represented in fig. 9. The role of each block is the following: Fuzzifier converts a numerical variable into a linguistic label. In a closed loop control system, the error (e) between the reference voltage and the output voltage and the rate of change of error (del e) can be labeled as zero (ZE), positive small (PS), negative small (NS), etc. In the real world, measured quantities are real numbers (crisp). The FLC takes two inputs, i.e., the error and the rate of change of error. Based on these inputs, The FLC takes an intelligent decision on the amount of field voltage to be applied which is taken as the output and applied directly to the field winding of generator. Triangular membership functions were used for the controller (from figure 9 to 11). Rule base stores the data that defines the input and the output fuzzy sets, as well as the fuzzy rules that describe the control strategy. Mamdani method is used in this paper. Inference engine applies the fuzzy rules to the input fuzzy variables to obtain the output values. Defuzzifier achieves output signals based on the output fuzzy sets obtained as the result of fuzzy reasoning. Centroid defuzzifier is used here.

TABLE I: Rule Base For Fuzzy Controller

	NBC	NSC	NC	PSC	PBC
NB	BD	MD	SD	SD	NC
NS	MD	SD	SD	SI	SD
ZE	SD	NC	NC	NC	SI
PS	SD	NC	SI	SI	MI
PB	NC	SI	SI	MI	BI

TABLE II: Lithium-Ion K2 Battery parameters

Battery capacity	Kwhr/Ahr	5.9/51.2
Battery nominal voltage	V	115.2
Min battery voltage	V	90
Max discharge current	A	52
Max pulse discharge current	A	150(<2s)
Max charging voltage	V	132
Max charging current	A	10

IV.SIMULATION VERIFICATION OF THE RSC CIRCUIT

A. Simulation Setup

The circuit diagram of the RSC shown in Fig. 12 is used to verify the RSC concept in MATLAB/SIMULINK. Fig. 12 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. 2. As shown in Fig. 2, the RSC consists of six IGBTs and diodes that have the rating of 1.2 kV and 100A peak· There is a pre-charging circuit that limits an inrush current flowing into the capacitors of the three-phase inverter, when the dc power supply is initially connected to the three-phase inverter.

The filter capacitors are used to reduce voltage and current ripples for the batteries. There is the voltage balancing circuit that limits an inrush current flowing into the filter capacitors of the batteries, when the battery system including the battery filter capacitors is initially connected to the inverter. There are three relays used for battery charging in the dc/dc operation. The relay rating is determined by the battery charging current requirement. As mentioned earlier, a passive load is used in RSC verification. A passive load has a maximum power of 3 kW under the air-cooled condition. At the top of the picture is the RSC consisting of six IGBTs, six diodes, filter inductors, capacitors, relays, and wires. At the bottom of the picture is the energy storage device, the K2 Li-ion battery. The specification of the K2 battery is described in Table III. The K2 battery has its own BMS. The master controls four slaves who have nine battery cells assigned. The BMS measures the state of the battery cell voltages, temperatures, and the current flowing into or out of the battery. It also determines the battery operating status such as normal, warning, and error in which status BMS uses the relays to protect the battery system and prevent any damage. The battery system includes a pre-charging circuit to limit an inrush current flowing from the batteries into the capacitors that can be connected to the battery in parallel for a filtering purpose. The RSC control algorithms are implemented with

MATLAB/SIMULINK. 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. 13-15 will be presented.

B. Performance Investigation of the Dc/Ac Operation Modes

Fig. 13 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 5A peak for the frequency of 60 Hz. As shown in Fig. 19, a satisfactory steady state performance is obtained. Fig. 14 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 3A peak for the frequency of 60 Hz. As shown in Fig. 11, the satisfactory dc/ac steady-state performance is obtained. In Fig. 14, the current flowing into the battery is exhibited. The average battery charging current is 1.8 A. The battery charging current has about 0.85A pk−pk current ripple with the frequency of 60 Hz.

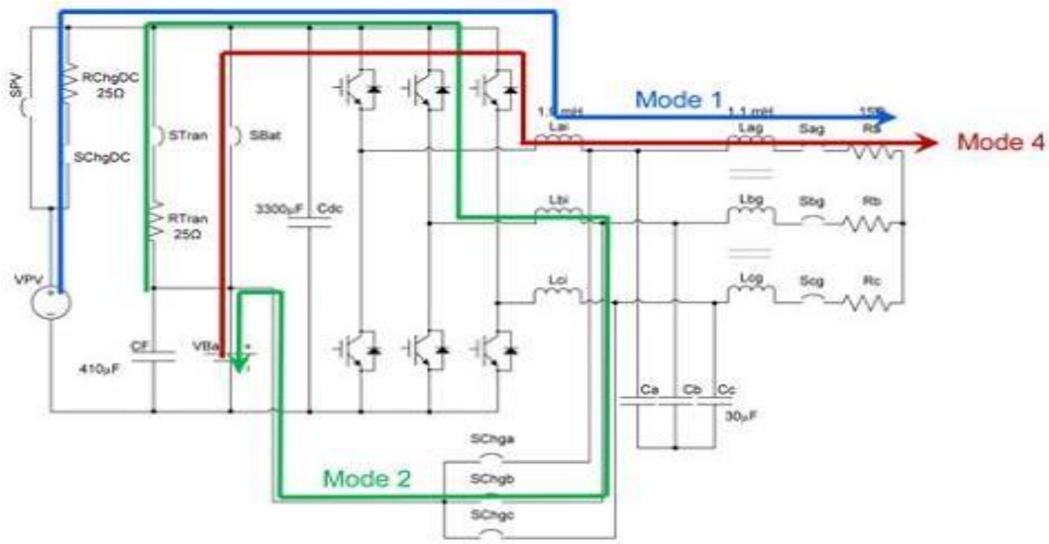


Fig.12. Different operation modes tested in the lab

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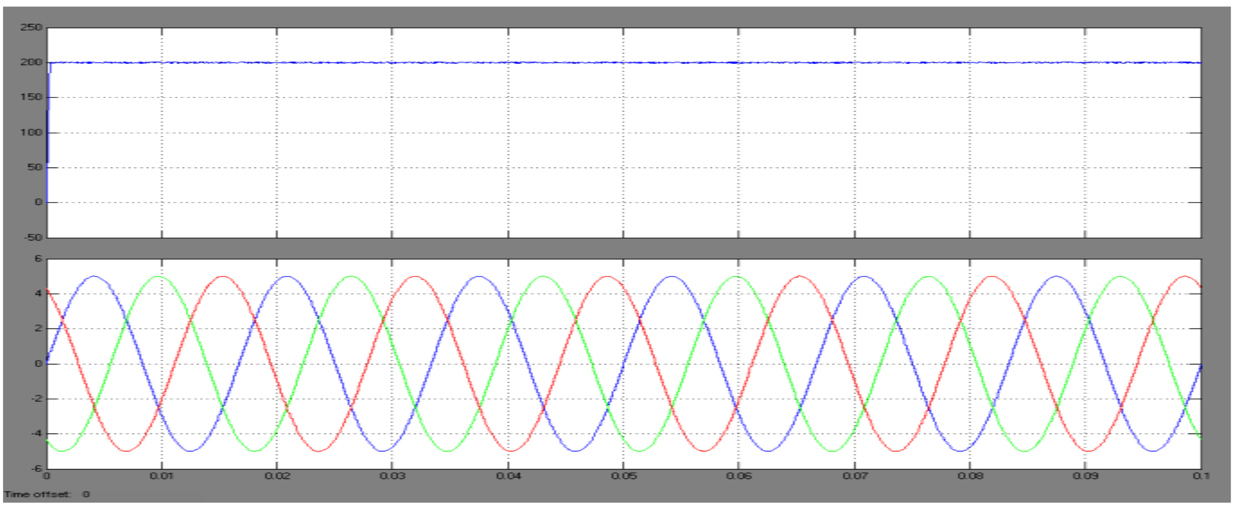


Fig. 13. Steady-state performance of dc/ac control in Mode 1.

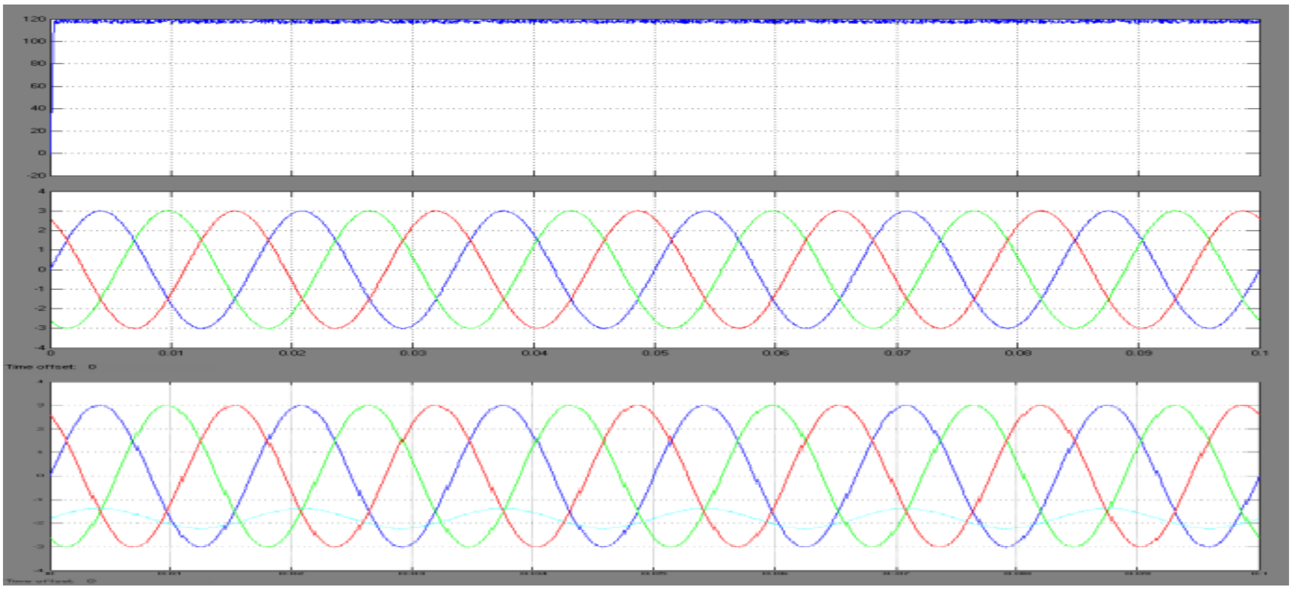
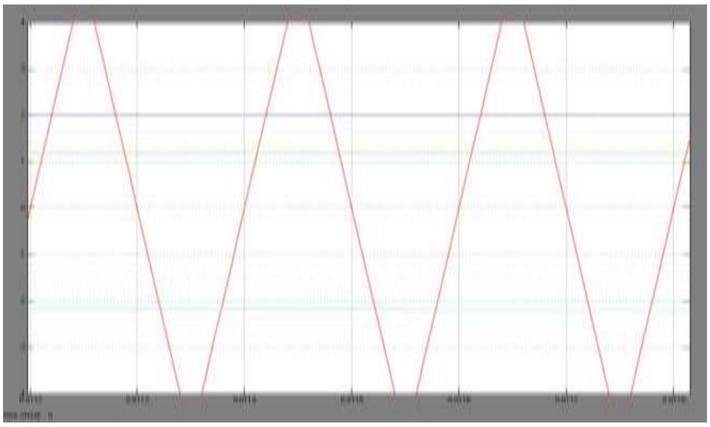


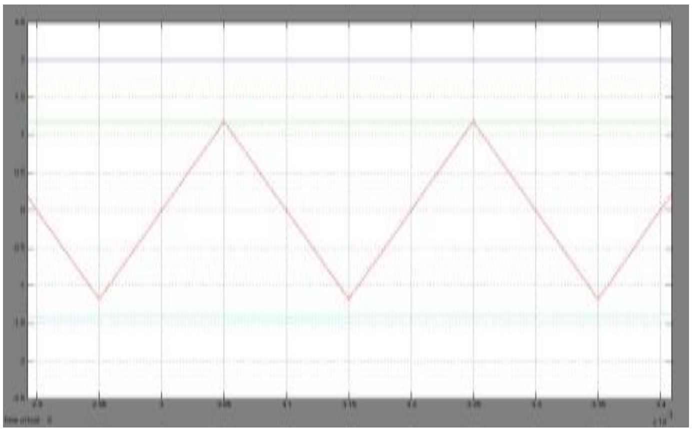
Fig.14. Steady-state performance of dc /ac control in Mode 4.

C. Performance Investigation of the DC/DC Operation Mode

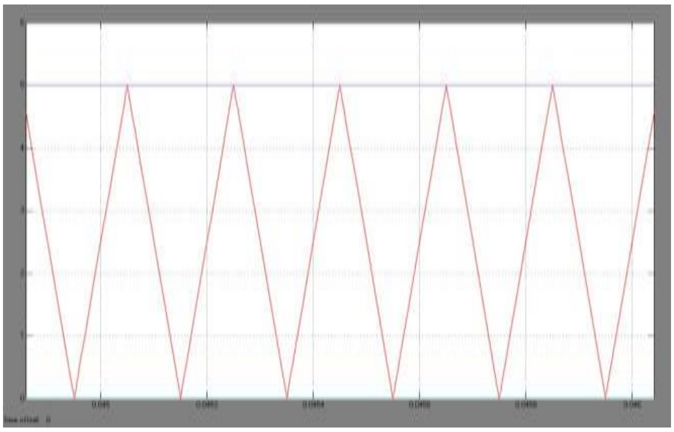
In Mode 2 (PV to battery), the three-phase inverter is used as a dc/dc converter. As explained, initially a coupled three-phase inductor is used for the filter inductor to the inverter side. When only phase B is utilized for the dc/dc operation with only either upper or lower three IGBTs are turned off 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. 21(a). To solve the aforementioned problem, as explained, two solutions are proposed.



(a)



(b)



(c)

Fig. 15. 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.

First, the switches unused are turned off and consequently the phase current presents much lower ripple as shown in Fig. 15(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 result of the test is presented in Fig. 15(c) showing that the current in the other phases remains zero while the battery is charged. Fig. 16 shows the current going into the battery for the test shown in Fig. 15(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 The capacitor ripple current is about 4.2 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. 17 shows the waveforms of the synchronous operation.

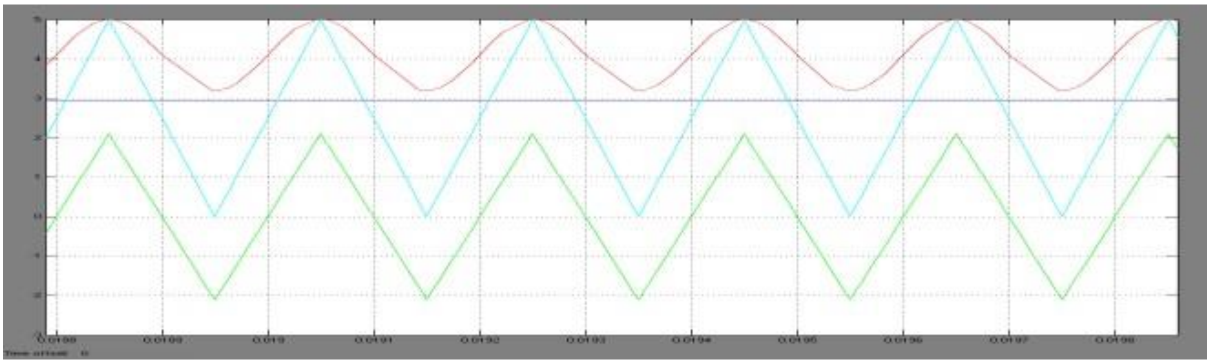


Fig. 16. Steady-state capacitor and battery current for single-phase operation using three single-phase inductors in the dc/dc operation.

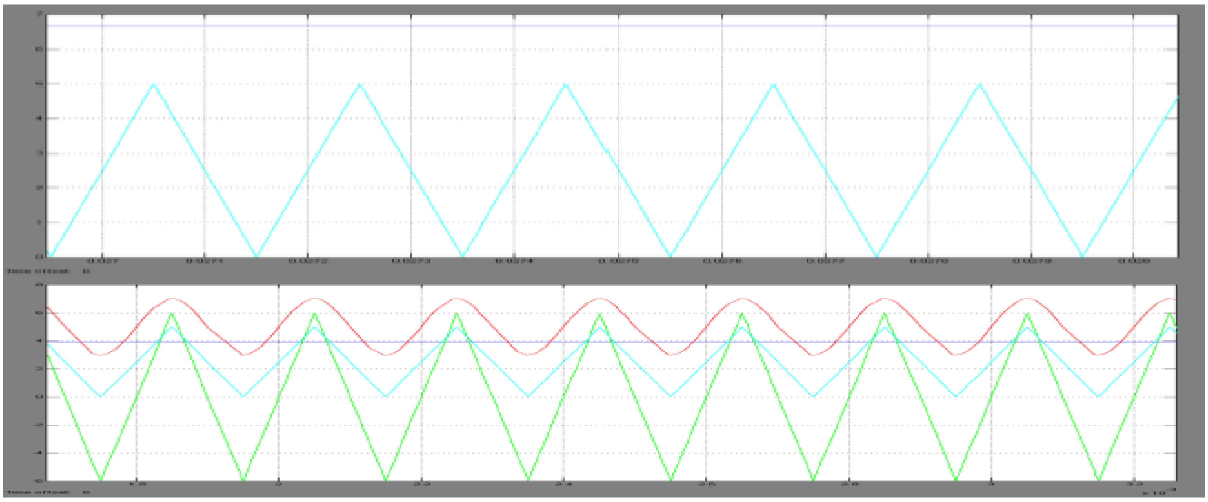


Fig. 17. Steady-state performance of the RSC with three- phase synchronous operation in the dc/dc mode (Mode2).

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· The battery current has the current ripple of 4 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.

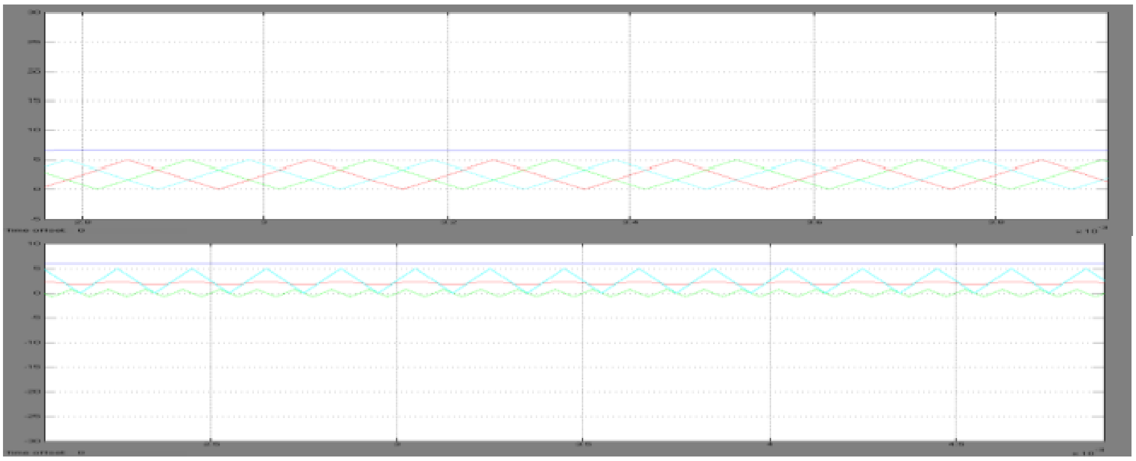


Fig. 18. Steady-state performance of the RSC with three- phase interleaved operation in the dc/dc mode (Mode2).

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. 18, the battery current has a ripple current of 0.5 A_{pk-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.

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 state flow is used. Fig. 19 shows the simulation 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 in matlab/simulink. 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. 26 and 27]. 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 Fig. 19 to 27.

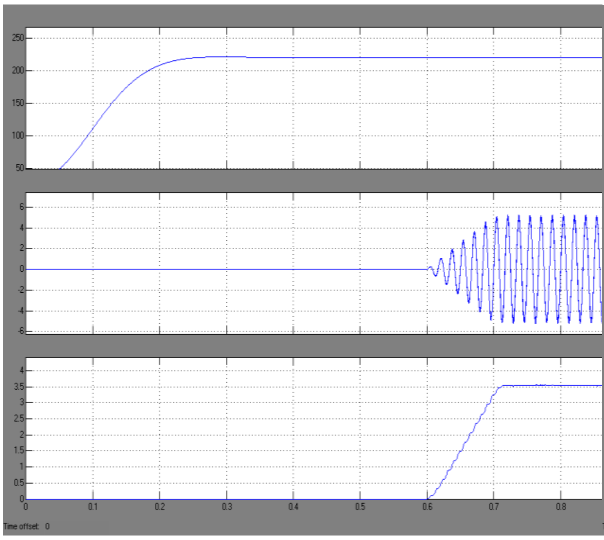


Fig. 19. Transient performance of mode change with Modes 0 to 1

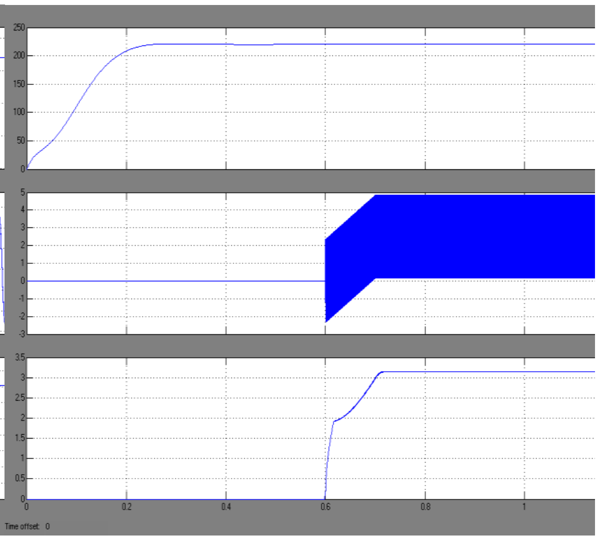


Fig. 20. Transient performance of mode change with Modes 0 to 2.

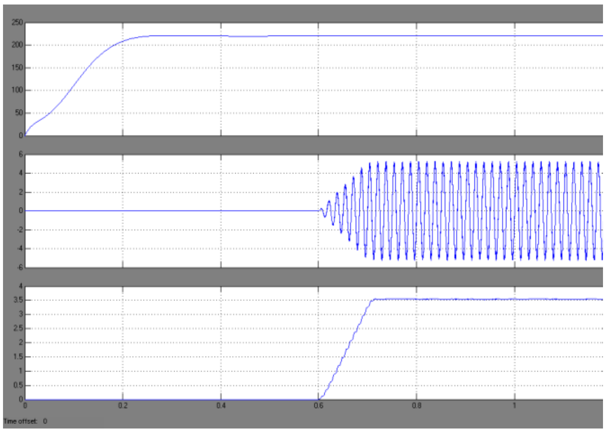


Fig. 21. Transient performance of mode change with Modes 0 to 4.

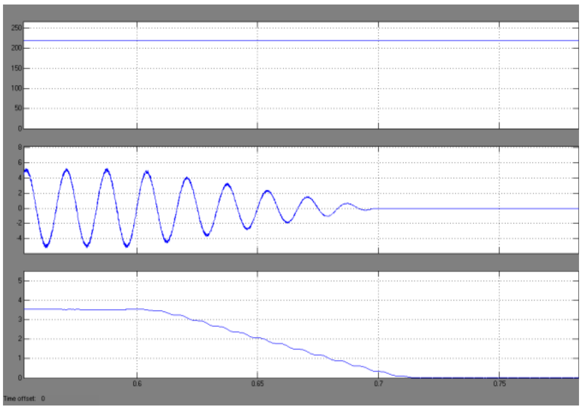


Fig. 22. Transient performance of mode change with Modes 1 to 0 and 0 to 2.

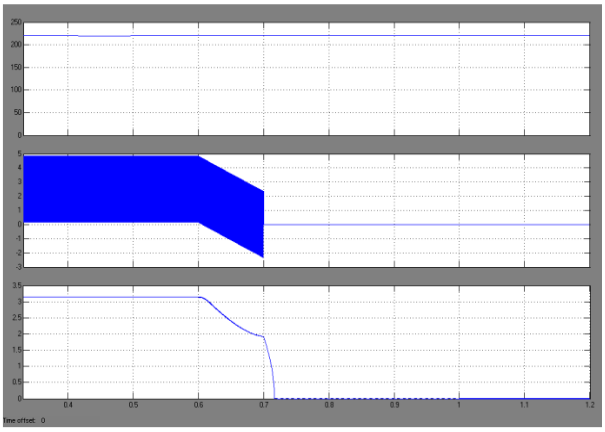


Fig. 23. Transient performance of mode change with Modes 2 to 0.

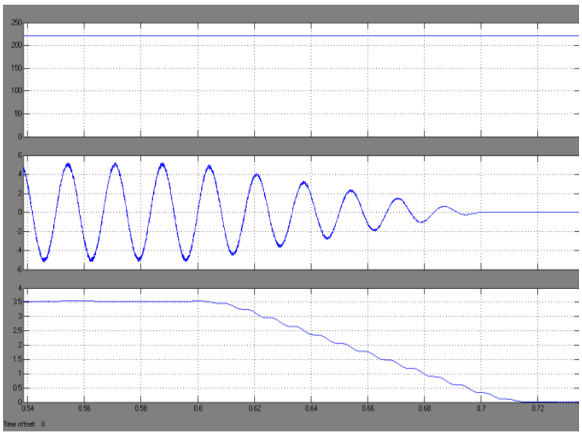


Fig.24 . Transient performance of mode change with Modes 4 to 0 and 0 to 2.

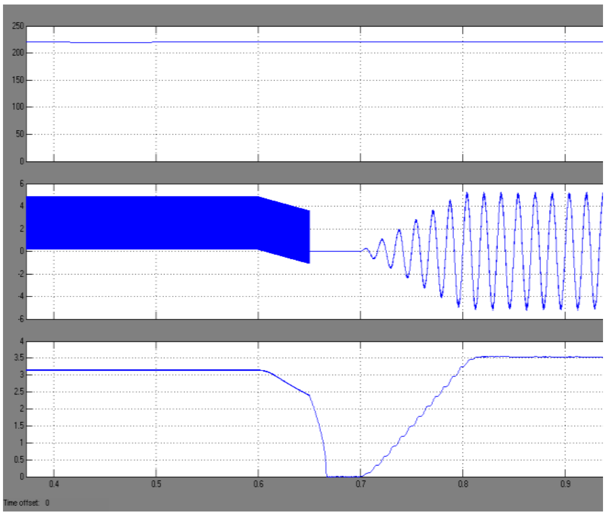


Fig. 25. Transient performance of mode change with Modes 2 to 1.

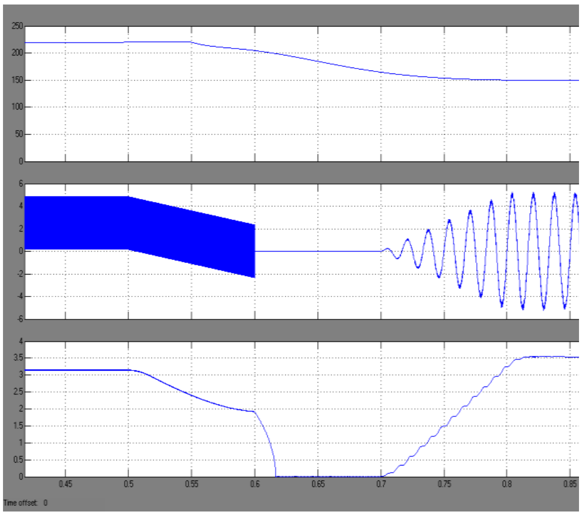


Fig. 26. Transient performance of mode change with Modes 2 to 4 and 4 to 0 and 0 to 2.

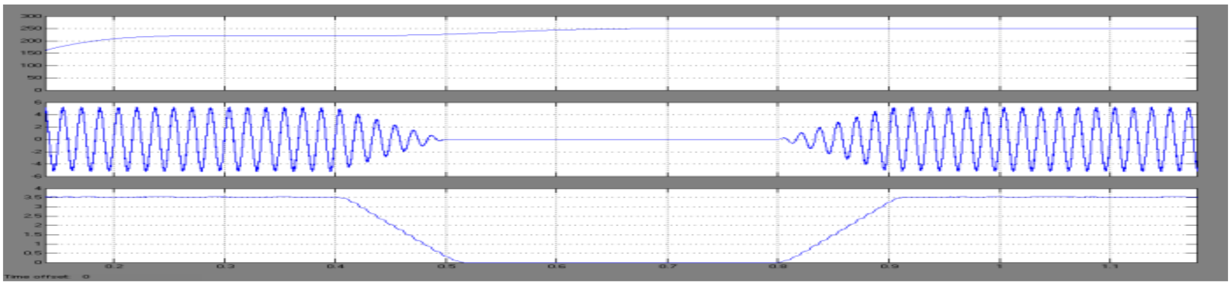


Fig. 27. Transient performance of mode change with Modes 4 to 1.

CONCLUSION

This paper has presented a new converter called RSC for PV-battery application, particularly utility-scale PV-battery application using fuzzy logic control for 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 provides significant benefits to system planning 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. 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. The technical and financial benefits that the RSC solution is able to provide are more apparent in larger solar PV power plants. These results confirm that the fuzzy based RSC is an optimal solution for PV-battery power conversion systems. 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.

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