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Reconfigurable Solar Converter for Residential PV-Battery Applications

Sarath.N[1], H.Ansarudeen[2]

PG Student, Dept. of EEE, Govt. Engineering College Bartonhill, Thiruvananthapuram, Kerala, India[1]

Assistant Professor, Dept. of EEE, Govt. Engineering College Bartonhill, Thiruvananthapuram, Kerala, India[2]

ABSTRACT: Reconfigurable Solar Converter (RSC) is a family of single-stage converter used for integration of energy storage element with PV system, particularly for utility-scale PV battery application. The main concept of RSC is to use a single-stage three-phase grid-tie solar PV converter to perform dc/ac and dc/dc operations. RSC reduces the number of conversion stages thereby improving efficiency and reducing cost, weight and volume. This paper proposes a new topology for RSC which allows to use battery voltage higher than PV voltage. The RSC concept is implemented in domestic/consumer-scale PV-battery application. A set of operating modes of RSC optimised for domestic use is proposed. Automatic switching between these operating modes is another objective of this paper. Harmonic content in the output of RSC is minimised by making use of three-level converter. Performance of the proposed converter is validated using MATLAB-SIMULINK.

KEYWORDS: Converter, Energy storage, Photovoltaic (PV), Solar.

I.INTRODUCTION

Increase in energy demand in a future scenario where issues like depletion of fossil fuels, inherent hazards of thermal and nuclear plants may be tackled effectively, calls for a shift from conventional sources to a more sustainable cleaner energy like the solar. A reliable energy source is supposed to dispatched at required power level without compromising stability. However solar photovoltaic (PV) electricity is not available during night and less available depending on the time of the day and the weather conditions. Solar PV electricity output is also highly sensitive to shading. Output falls considerably even when a small portion of PV cell, module, or array is shaded, while the remainder is in sunlight. That is solar PV electricity is highly fluctuating in nature. Therefore, integration of energy storage elements like batteries and fuel cells to solar PV system improves the stability of the system. There are different options for integrating energy storage into a 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. Reconfigurable solar converters (RSC) are a new family of single stage converters used for integration of energy storage elements to solar PV systems. The basic concept of the RSC is to use a single power conversion system to perform different operation modes such as DC/DC conversion and DC/AC conversion. The RSC concept arose from the fact that energy storage integration for solar PV systems makes sense if there is an enough gap or a minimal overlap between the PV energy storage and release time [1]-[3].

Consider a grid with off-peak time in day and peak load demand during night. The RSC concept makes sense for a consumer connected to this type of grid. This paper proposes a reconfigurable solar converter optimised for residential PV-battery applications. Operation modes of the RSC are defined for collecting maximum solar energy in battery during day. Grid power usage is minimised by making use of the stored energy during night, when grid power becomes costlier. Operation modes defined here avoids grid tie operation of the converter which minimises the complexity of controller and avoids the islanding problem.

Section II describes the proposed RSC circuit for residential PV-battery applications and different operation modes. Control of RSC is discussed in section III. Section IV verifies the proposed RSC with simulation results. Section V summarises and concludes the paper.

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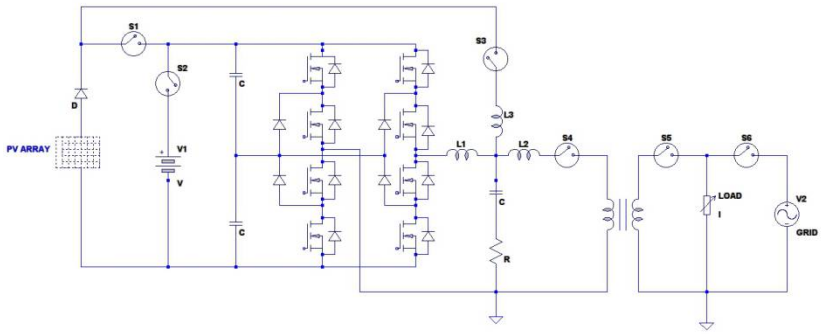

Fig. 1 Schematic of the proposed RSC circuit.

II.SYSTEM MODEL

Fig 1 shows schematic of the proposed RSC circuit. This RSC is a modification of conventional three-level inverter with of additional link and switches (switches S1 to S6) as shown in Fig 1. These modifications allows the RSC to perform battery charging function in addition to the inverter operation. Inductors L1 and L2 are ac filter inductance and C is filter capacitance. L3 is an optional inductor included for battery charging purpose if the ac filter inductance is not enough. The consumers loads are considered separately in this circuit. On comparing with the existing two level RSC the three-level topology used in this paper permits small values of filter inductance and capacitance without compromising the power quality[4].

A. Operation Modes of RSC

An assumption made in defining operation modes of RSC for residential PV-battery applications is peak load demand in utility occurs during off-PV hours, that is during night. Operation modes of RSC is determined based on four conditions named C1 to C4. These conditions are given in table.1

Table 1. Conditions checked for RSC mode selection.

C1	1	PV power is available.
	0	PV power is not available.
C2	1	Grid power is available.
	0	Grid power is not available.
C3	1	Battery SOC is above upper limit
	0	Battery SOC is below upper limit
C4	1	Battery SOC above lower limit.
	0	Battery SOC below lower limit.

All possible operation modes of the RSC based on the above conditions and optimised for residential scale PV-battery applications are depicted in the table 2.

In the first case given in table no power sources are available, then it is not possible to power the load the RSC has to enter into a shut down mode with all switches (S1 to S6) open. If solar irradiation is not available that is PV power is not available and battery state of charge (SOC) is above certain lower limit, then the load is connected to battery through dc/ac operation of the converter. Now switches S2, S4 and S5 are closed and rest of the switches remains open. If only grid power is available, then only switch S6 is closed and load is connected to grid. If only PV power is available, then switches S2 and S3 are closed and rest of the switches remains open. Here the battery is charged from

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PV through dc/dc operation of the converter with the possibility of maximum power point tracking (MPPT) control[5]. If PV power is available and battery SOC is above certain upper limit or PV power is available, battery SOC is in between upper and lower limits and grid power is not

Table 2. Operation modes of RSC with conditions, switch positions and control used in each mode.

Cases				Operation Modes	State of Switch						Control
C1	C2	C3	C4		S1	S2	S3	S4	S5	S6	
0	0	0	0	SHUT DOWN	0	0	0	0	0	0	No control
0	0	0	1	Battery → Load	0	1	0	1	1	0	Constant Load voltage
0	0	1	1	Battery → Load	0	1	0	1	1	0	Constant Load voltage
0	1	0	0	Grid → Load	0	0	0	0	0	1	No control
0	1	0	1	Grid → Load	0	0	0	0	0	1	No control
0	1	1	1	Battery → Load	0	1	0	1	1	0	Constant Load voltage
1	0	0	0	PV → Battery	0	1	1	0	0	0	MPPT control
1	0	0	1	PV + Battery → Load	1	1	0	1	1	0	Constant Load voltage
1	0	1	1	PV + Battery → Load	1	1	0	1	1	0	Constant Load voltage
1	1	0	0	PV → Battery, Grid → Load	0	1	1	0	0	1	MPPT control
1	1	0	1	PV → Battery, Grid → Load	0	1	1	0	0	1	MPPT control
1	1	1	1	PV + Battery → Load	1	1	0	1	1	0	Constant Load voltage

available, then switches S3 and S6 remains open and rest of the switches are closed and both PV and battery provide power to the load through dc/ac operation of the converter. If PV power and grid are available and battery SOC is below the upper limit, then switches S2, S3 and S6 are closed and rest of the switches remains open. Here battery is charged from PV and load is powered from grid simultaneously.
From the table 2 we can see five distinct operation modes and the working of RSC during each operation modes are depicted in Fig 2 (a)-(e).

III.RSC CONTROL

A. Mode change control

The basic concept of the RSC is to use a single power electronics circuit to perform different operation modes. Therefore, the seamless transition between different modes is 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. Based on the above table logic circuit is designed for control of all contactors S1 to S6 and the control logic is implemented as in fig 3.

B. Control of the RSC in the DC/AC Operation Modes (Mode 1 and 3)

The dc/ac operation of the RSC is utilized for delivering power from battery to load and PV and battery to load. RSC deliver constant voltage AC power to the load either from battery or from both battery and PV panel. Proportional

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integral (PI) controller is used for output voltage control of RSC. For pulse width modulation (PWM) phase disposition PWM technique is utilised[2]. Fig 4 presents the overall control block diagram of the RSC in the dc/ac operation.

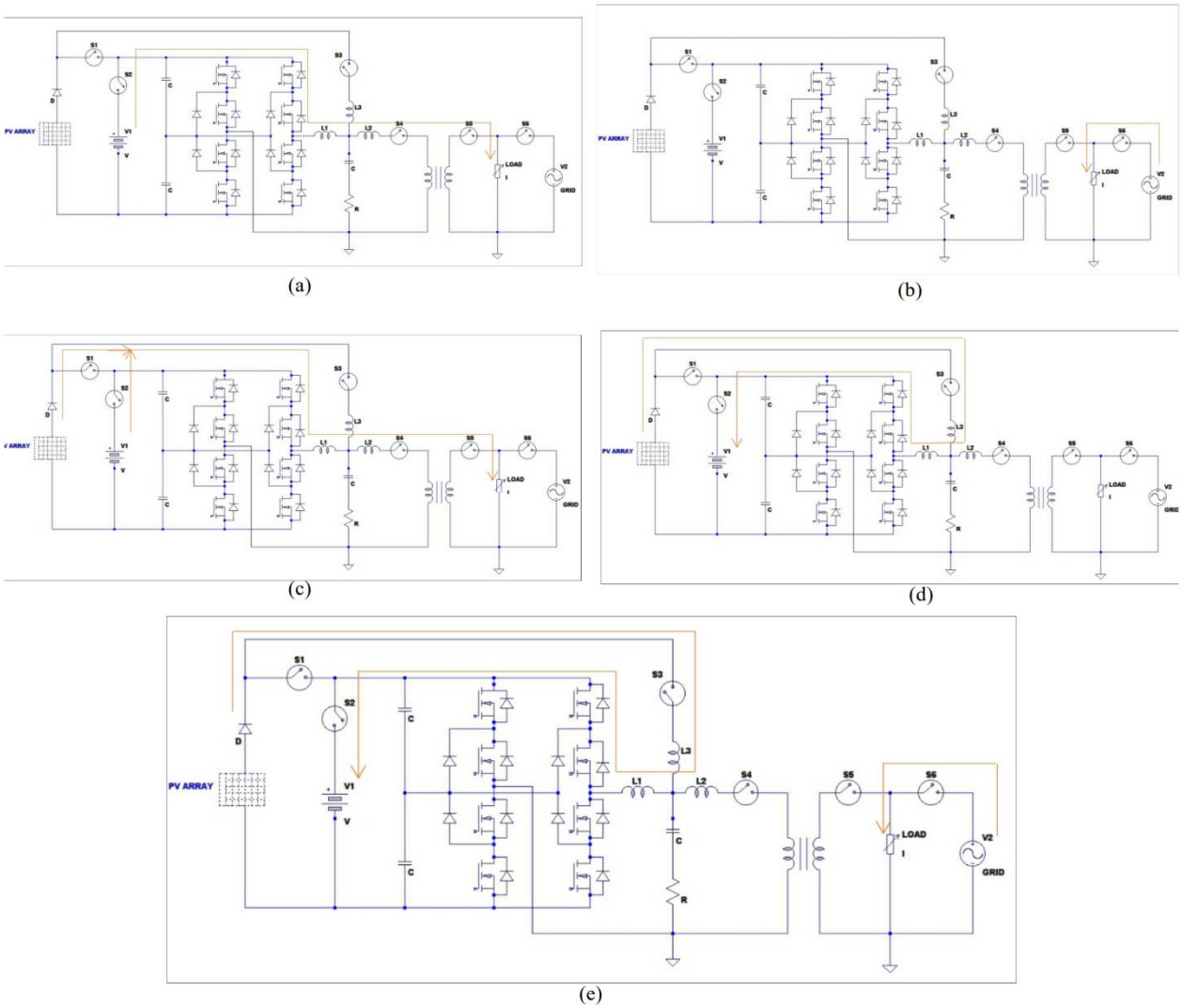

Fig. 2 All operation modes of the RSC. (a) Mode 1—Battery to grid. (b) Mode 2—Grid to load. (c) Mode 3—PV/battery to load. (d) Mode 4—PV to battery. (e) Mode 5—PV to battery, grid to load

C. Control of the RSC in the DC/DC Operation Modes (Mode 5 and 6)

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. Fig 5 shows the overall control block diagram of the RSC in the dc/dc operation. In dc/dc mode of operation MOSFET Q7 and Q8 are operated according to a duty ratio determined by MPPT algorithm and rest of the marmosets are turned off. With the help of filter inductor L1, inductor L3 (optional) and DC link capacitors the RSC work as a DC/DC boost converter that steps-up the PV voltage to charge the battery.

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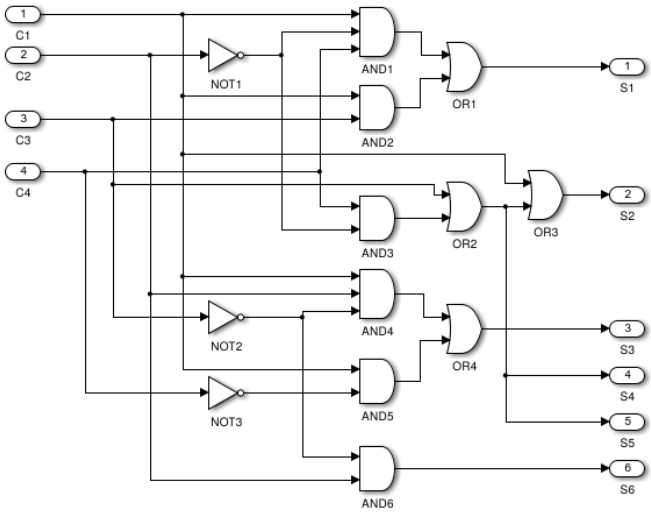

Fig. 3 Control logic for mode selection of proposed RSC.

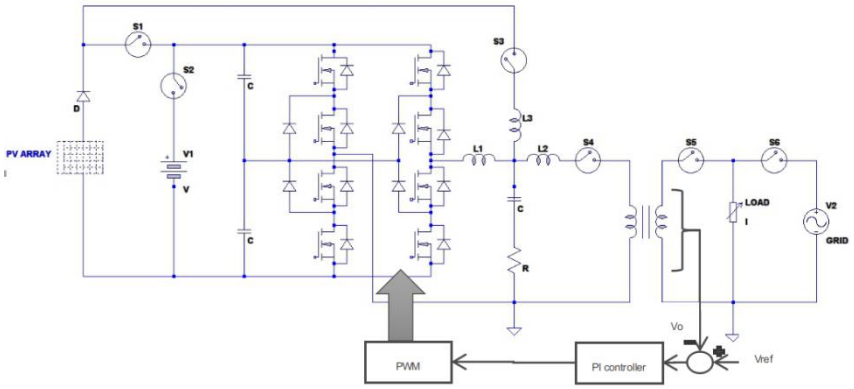

Fig. 4 Control of RSC during DC/AC operation modes.

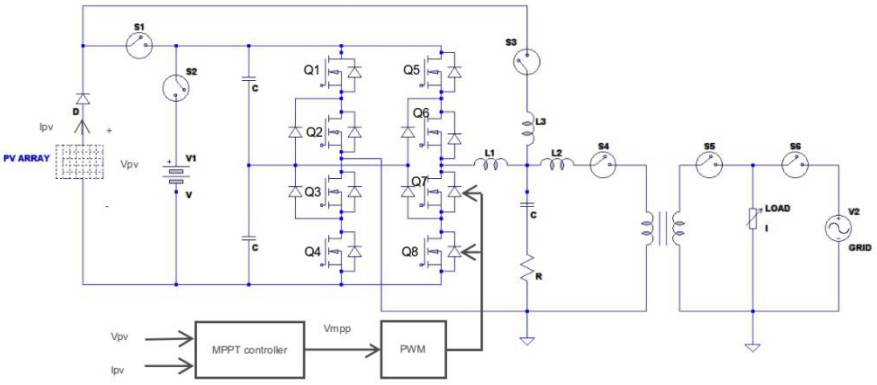

Fig. 5 Control of RSC during DC/DC operation modes.

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IV.SIMULATION RESULTS

The proposed RSC is modeled using MATLAB-SIMULINK and all operation modes are simulated. Simulation parameters are given in table 3 and 4.

Table 3. Specifications of PV panel modeled

Parameter	Rating
Power rating	250 W
Maximum power voltage	35 V
Maximum power current	7.14 A
Open circuit voltage	43.2 V
Short circuit current	7.5 A

Table 4. Specifications of LCL filter

Parameter	Rating
Inverter side inductance, L1	1.65 mH
Grid side inductance, L2	1 mH
Filter capacitance, C	32 uF

Fig 6 depicts the load voltage during dc/ac mode of operation. Here battery supplies the required load power through dc/ac operation of the converter. The load voltage THD is 0.05%. Fig 7 shows the battery SOC, battery current and battery voltage during this operation. The battery with 72 volts nominal voltage and 10 Ah rated capacity is used for simulation. The positive battery current indicates that power is flowing from battery to load.

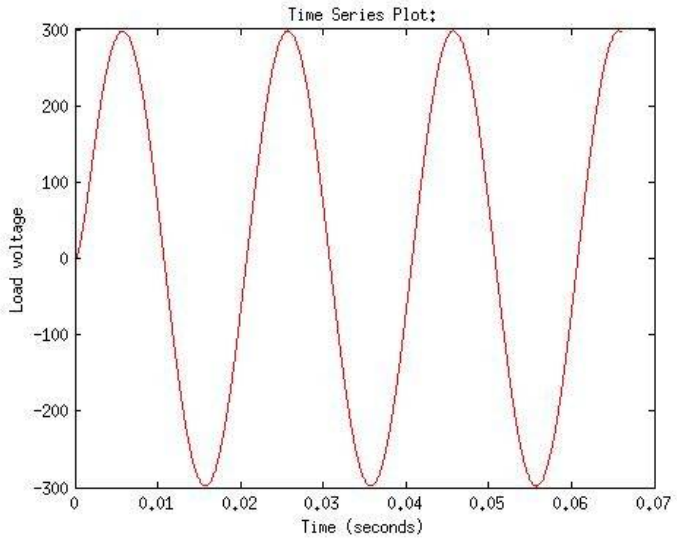

Fig. 6 Load voltage during dc/ac operation of the converter.

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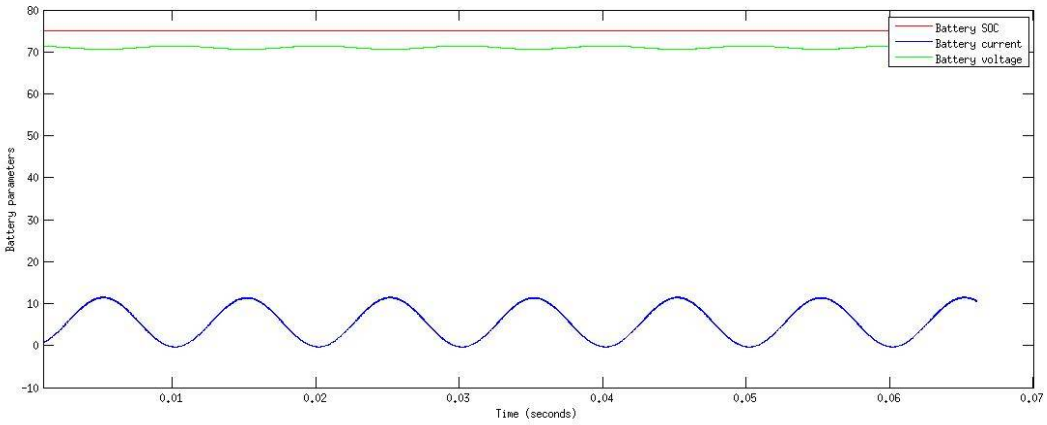

Fig. 7 Battery SOC, battery current and battery voltage during dc/ac operation of converter.

The load voltage during dc/dc operation of the converter is shown in Fig 8. Grid supplies the load power during dc/dc operation. Now the battery is charged form PV power. The battery SOC, battery current and battery voltage during dc/dc operation of converter is depicted in Fig 9. The negative value of battery current indicates that battery is charging. The battery voltage during charging is greater than 72 volts. The maximum power voltage of PV panel is 70 volts and from Fig 10 we can see that the PV voltage never goes beyond 71.5 volts in steady state. So the converter work as a Step up converter that extracts maximum power from PV panel.

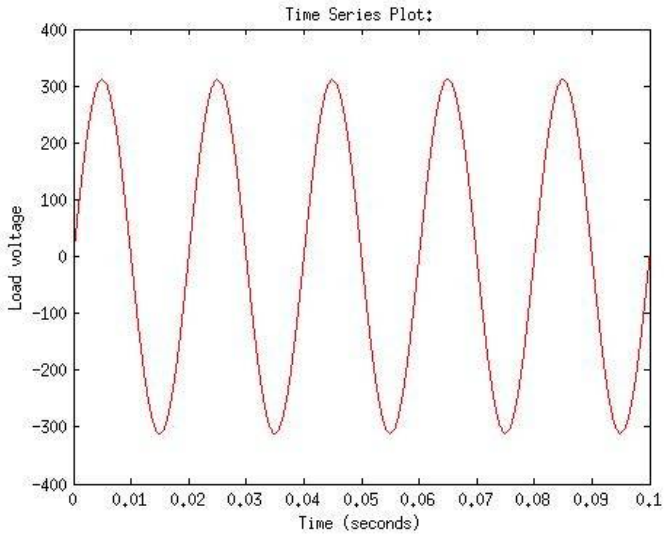

Fig. 8 Load voltage during dc/dc operation of converter.

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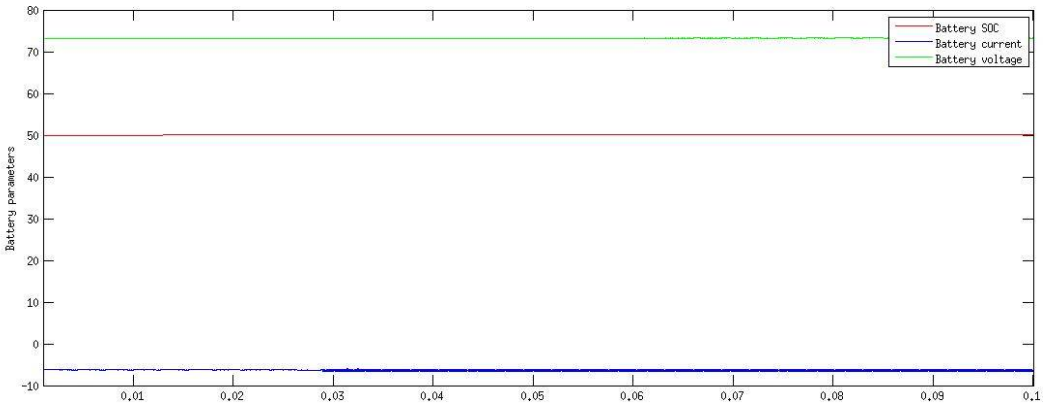

Fig. 9 Battery SOC, battery current and battery voltage during dc/dc operation of converter

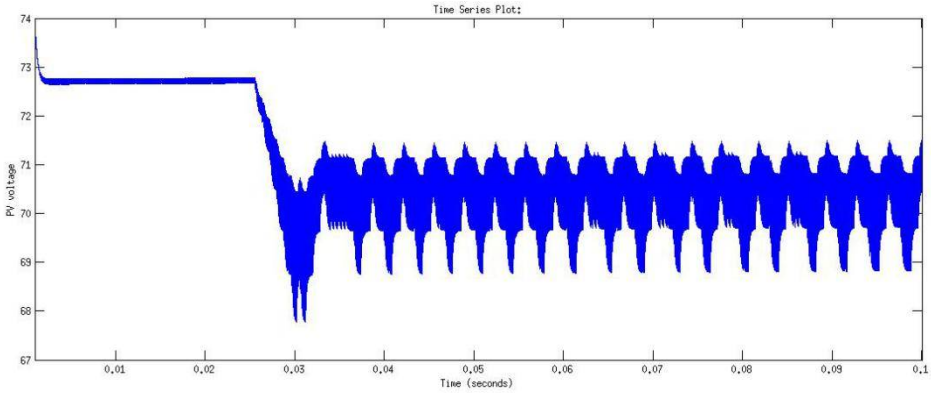

Fig. PV voltage during dc/dc operation of converter.

VI.CONCLUSION

This paper proposed a new RSC circuit for residential PV-battery applications. On comparing with the existing RSC circuit the proposed RSC circuit has the capability to charge battery with nominal voltage greater than PV voltage. For the same power higher battery voltage reduces the current and hence conduction lose in the power electronic switches. The proposed converter requires minimal complexity and modifications to the conventional solar PV converters for PV-battery systems. Control logic is developed for seamless transition between different operation modes. Three level topology for RSC is implemented for better power quality of the converter.

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