A Novel Single-Stage Single-Phase Reconfigurable Inverter Topology for a Solar Powered Hybrid AC/DC Home

Nikhil Sasidharan, *Student Member, IEEE*, and Jai Govind Singh, *Member, IEEE*

***Abstract*—This paper suggests a reconfigurable single-phase inverter topology for a hybrid ac/dc solar powered home. This inverter possesses a single-phase single-stage topology and the main advantage of this converter is that it can perform dc/dc, dc/ac, and grid tie operation, thus reducing loss, cost, and size of the converter. This hybrid ac/dc home has both ac and dc appliances. This type of home helps to reduce the power loss by avoiding unnecessary double stages of power conversion and improves the harmonic profile by isolating dc loads to dc supply side and rest to ac side. Simulation is done in MATLAB/Simulink and the obtained results are validated through hardware implementation using Arduino Uno controller. Such type of solar powered home equipped with this novel inverter topology could become a basic building block for future energy efficient smart grid and microgrid.**

***Index Terms*—Harmonic mitigation, hybrid ac/dc home, single-phase single-stage inverter, solar photovoltaic (PV).**

I. Introduction

THE current century has witnessed an unprecedented evolution and growth of renewable energy worldwide [1]. There has been a substantial increase in the capacity and production of all renewable technologies and also growth in supporting policies. Between 2009 and 2013, solar photovoltaics (PVs) experienced the swiftest growth rate in added power capacity among all the renewables. In particular, rooftop solar PV are gaining more popularity in distribution system due to reduction in cost of solar panel, appropriate government policies such as feed in tariffs promoting renewable energy utilization, modularity, less maintenance, etc. However, the intermittent nature of the renewable causes the significant stability and reliability issues in the distribution system. The restructuring of the electric supply industry has pro-mpted the situation, where customer is a critical business player. To mitigate the uncertainty in solar PV generation, storage options such as battery system and fuel cells, etc., are introduced.

To improve the productivity and comfortability, the modern household adds more and more nonlinear equipment, which are also main source of generating harmonics current in distribution feeder. This further adversely affects power quality, power losses and creating a significant challenge for electrical engineers. Modern household loads have different characteristics compared to loads present in earlier stage. However, harmonic mitigation and/or its minimizations are big challenges in distribution system. Many literatures works have been reported to address aforementioned problems as follows.

Harmonic mitigation in the distribution system using solar inverter by virtual harmonic damping impedance method is discussed in literature [2]. In [3], PV-battery storage system is used to control the voltage stability in distribution system. The control of solar powered grid connected inverter for electric vehicle charging is suggested in [4].

Patterson [5] has proposed the dc microgrid and shown its advantages and challenges of making a complete dc home microgrid. Further, this paper has analyzed by considering all buildings in 2050, 80% of buildings are already built. So, focus is more on improving the efficiency of existing buildings than making a new complete dc home. Vossos *et al.* [6] has analyzed the efficiency of residential building when it is converted into dc house over the conventional ac distribution house. They analyzed the data of 14 states in the USA, which used 380- and 24-V voltages for dc distribution in homes. There is a 33% savings when the ac equipment is replaced with dc equipment. But replacing all existing home appliances with its dc equivalent is not possible due to the high price and unavailability of the required standards/flexibilities of equipment. Sasidharan *et al.* [7] propose a novel solution to mitigate some of the harmonics related problems and efficiency issues by proposing a hybrid ac/dc home grid system. A solar home is discussed as a case study and a 12% improvement in efficiency and a 20% reduction in harmonics are achieved by shifting dc loads to the dc supply side.

Conventional grid connected inverter uses high dc link voltage, which will be the peak magnitude of the line–line grid voltage [8]. For this particular purpose, two stage conversions are required to boost up the dc voltage and to invert it. However, this will increase the cost, size, and loss of the system. To avoid this, single-phase single-stage topologies of inverter are suggested in [9]–[12]. In the single-phase inverter topology,

Manuscript received January 11, 2016; revised September 1, 2016 and October 30, 2016; accepted November 22, 2016. Date of publication December 22, 2016; date of current version March 8, 2017. This work was supported by the Asian Institute of Technology, Pathumthani, Thailand.

The authors are with the Department of Energy, Environment and Climate Change, School of Environment, Resources and Development, Asian Institute of Technology, Pathumthani 12120, Thailand (e-mail: nikhilscet@gmail.com; jgsingh@ait.ac.th).

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Digital Object Identifier 10.1109/TIE.2016.2643602

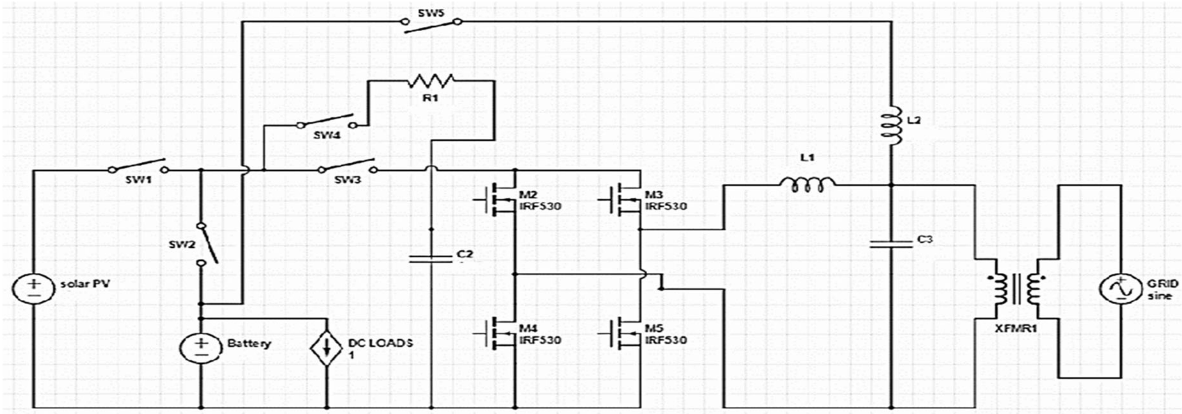

Fig. 1. Schematic of the proposed RSC circuit.

transformer less inverter gained significant research interest as suggested in [13]. Transformer less inverter has the advantage of low size and cost by avoiding the transformer but this will eliminate the galvanic isolation and inverter will become very sensitive to grid disturbances. The solar PV is limited by its inherent intermittency aspects and, hence, battery storage (assumed here) is required to supply the power when there are not enough solar radiations. But having a separate converter for battery's power management system will increase the cost and size of the converter as well. Hence, a three-phase topology of reconfigurable solar inverter is introduced in [14] and [16] for utility PV system with battery storage. This reconfigurable system is suitable to solar and wind farm applications. This topology is tested with a new algorithm and validated the results. Normally, every solar powered household have a battery system to provide a reliable supply system. These batteries are charged when connected to ac system or they need a separate converter to manage the charging operations when it connected to dc supply side. Though Parkhideh and Kim [16] provide very brief info but no details/outcomes are available about single-phase single-stage topology, which can supply both ac and dc loads in literature.

Therefore, the main contribution of this paper is to implement a single-phase single-stage solar converter called reconfigurable solar converter (RSC) in the solar powered hybrid ac/dc residential building with energy storage devices. The basic concept of the RSC is to use a single power conversion system to perform different operational modes such as solar PV to grid (Inverter operation, dc–ac), solar PV to battery/dc loads (dc–dc operation), battery to grid (dc–ac), battery/PV to grid (dc to ac) and Grid to battery (ac–dc) for solar PV systems with energy storage. This inverter is tested in a solar powered hybrid ac/dc home, which contains both ac and dc household loads. Individual appliances are selected according to the harmonic contributions they are injecting to the distribution grid from a typical modern house. Apart from the aforementioned, other additional contributions are as follows. The electrical components and sensors are different from [14], and normal inductor only used for dc/dc operation. The variation in solar radiation is also considered and solar PV-battery operation is verified. The circulation current is mitigated due to operation of the switches in the topology for dc/dc operation. Control logic and sampling of input quantities are also different in this paper.

TABLE I
MODES OF OPERATION

Modes of operation	ON switches	Off switches
PV-GRID	SW1 SW3 SW 4	SW2 SW 5
PV-BATTERY-GRID	SW1 SW2 SW3 SW4	SW5
PV- BATTERY	SW1 SW3 SW5	SW2 SW4
BATTERY-GRID	SW2 SW3	SW1 SW4 SW5

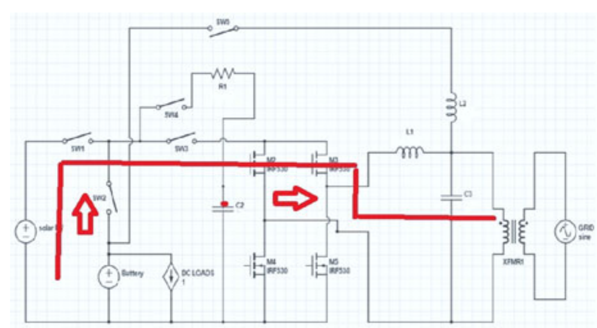

Fig. 2. PV to grid.

Section II introduces the proposed inverter circuit, modes of operation, and analysis. In Section III, control of the proposed converter is introduced and necessary design considerations to upgrade into proposed converter. Section IV verifies the proposed topology with experimental outputs, which will validates the proposed topology. Section V summarizes and concludes the outcomes.

II. TOPOLOGY OF RSC

The circuit diagram of reconfigurable solar inverter is given in the Fig. 1. Though it will reduce the no of power conversion stages but mechanical switches and cable requirement are more for this topology. The modes of operations of the proposed single-phase single-stage converter are given in Table I. In addition, different operations modes are given in Figs. 2–5.

A. Mode-1

The mode of operation as shown in Fig. 2 is directly connects PV to the grid. Maximum power point tracking (MPPT)

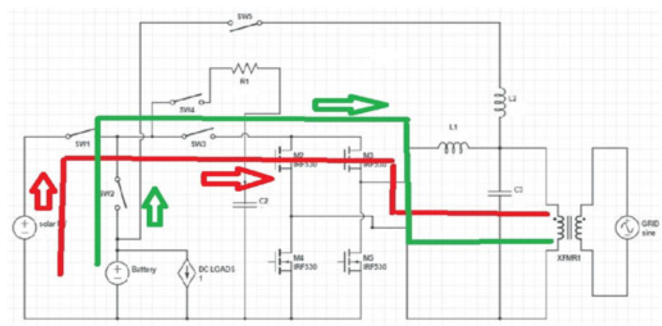

Fig. 3. PV-battery to grid.

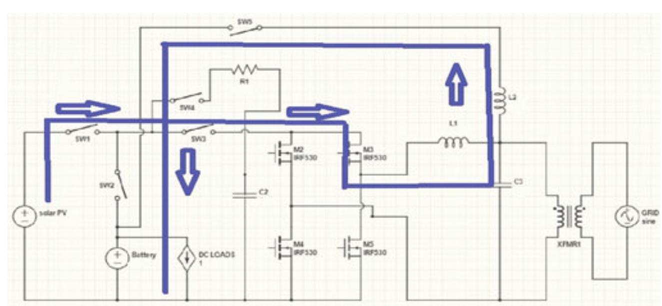

Fig. 4. PV to battery charging.

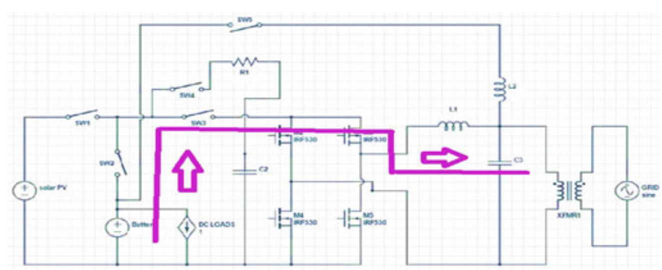

Fig. 5. Battery to grid.

controller is used to extract maximum power from the solar panel. Inverter controller is used to synchronize with grid and transfer active power to the grid.

B. Mode-2

In Fig. 3, the mode of operation is to supply power to the grid from both solar PV and battery. This mode operates when there is a shortage of power from the solar PV due to external conditions, e.g., weather, etc. One of the drawbacks of this connection is that the battery voltage and PV voltage should always be matching each other. Since battery voltage is stiff, MPPT controller cannot be used for this configuration.

C. Mode-3

Fig. 4 shows dc/dc operation of the proposed topology, where battery is charged by a chopper action of the converter. The extra inductor is optional to reduce ripple in the charging current further. When there is an excess energy available, the battery is charged for the night time usage.

D. Mode-4

From Fig. 5, the energy stored in battery can be released to the appliances or grid during the night hours or when there is no solar radiation due to clouds or rainy conditions. Battery can supply stable power to the inverter. Thus, it can be very helpful in power quality improvement and ancillary services provision.

III. Control of the Proposed Converter

For controlling this proposed single-phase inverter, PQ controller is used considering the advantage that it will control the active and reactive power according to the reference signal. Since the controlling elements for the ac system are very difficult due to their time-varying nature, the ac control variables are converted to a stationary reference frame from a rotating reference frame for effective control [15].

Let F_α and F_β be the rotating reference frame variables, which can be voltage or current, whereas F_d and F_q be the stationary variables. In rotatory reference frame, the active and reactive powers can be calculated by using

$$P = \frac{1}{2}\left[v_d \times i_d + v_q \times i_q\right] \tag{1}$$

$$Q = \frac{1}{2}\left[v_d \times i_q - v_q \times i_d\right] \tag{2}$$

where v and i are the instantaneous values of voltage and current, respectively.

When the inverter is synchronized to the grid, the value of v_q becomes 0, and (1) and (2) becomes

$$P = \frac{1}{2}\left[v_d \times i_d\right] \tag{3}$$

$$Q = \frac{1}{2}\left[v_d \times i_q\right]. \tag{4}$$

The active and reactive reference currents are given in (5) and (6) as

$$\widehat{i_d} = \frac{2 \times \hat{P}}{v_d} \tag{5}$$

$$\widehat{i_q} = \frac{2 \times \hat{Q}}{v_d} \tag{6}$$

where $\hat{P}$ and $\hat{Q}$ are the reference power signals of active and reactive power, respectively.

Calculated values of $\widehat{i_d}$ and $\widehat{i_q}$ are converted into stationary reference frame and given as signal to PQ controller to produce reference signals for the sinusoidal pulse width modulation controller. Synchronizing the solar inverter with grid requires the knowledge of the magnitude and phase of the grid supply voltage. Phase lock loop (PLL) will track the phase of the grid and help to synchronize with the grid. To obtain maximum power from the solar panel, according to maximum power transfer theorem, the panel resistance should be equal to the load resistance, which is connected to this panel. To achieve this, a hill climbing MPPT algorithm is used. This technique will equalize the resistances and extract maximum power from the solar panel.

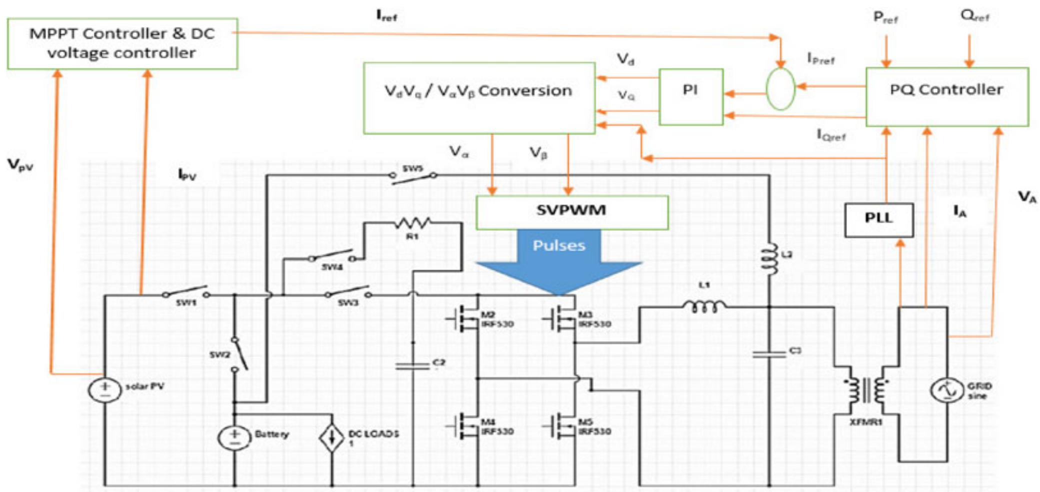

Fig. 6. DC/AC inverter operation.

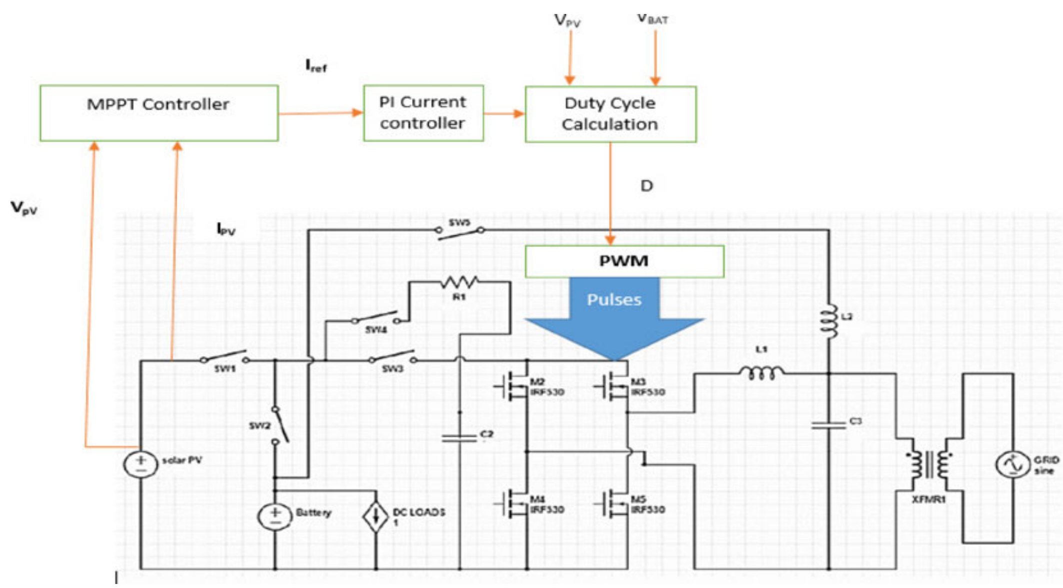

Fig. 7. DC/DC chopper operation.

The control diagram for different modes of operations of the RSC is given in Figs. 6 and 7. In Fig. 6, the inverter operation of the RSC is explained. From voltage and current measurement from the solar panel, voltage is set to extract maximum power from the panel using MPPT algorithm. This voltage is compared with the set dc-link voltage and error is given to a PI controller for DC link voltage regulation. This PI controller will produce reference current, which is compared with reference current produced using PQ controller, which is given in (5) and (6). This error is given to a PI controller, which will generate reference voltage for active power control. Reactive power is separately controlled using another PI controller. These reference voltages are converted to rotating reference frame voltages and given to space vector pulse width modulation (PWM) to drive the inverter.

Battery is charged from solar panel using dc/dc conversion mode of RSC, which is given in Fig. 7. One of the MOSFET switch is used to obtain required voltage level for the battery. Here, constant voltage charging is used. MPPT controller will produce the required current which is given to a PI controller to produce the reference voltage. This voltage is compared with the battery voltage and duty cycle is generated. From this duty cycle, PWM pulses are generated, which is given to the MOSFET switch. Thus, both ac and dc loads are given supply using a single reconfigurable inverter.

Simulation of the proposed converter is done in MATLAB/Simulink. The parameters used for the simulation are given in Table II. The radiation is kept at maximum at 1000 W/m^2. Inbuilt PLL and PWM pulse generator blocks in MATLAB/Simulink are used for controlling the inverter. The design is done for 500-W inverter topology. The active and reactive power output for a load of 320 W and 80 VAr is simulated and shown in Fig. 8.

In order to synchronize the solar inverter with grid, the magnitude and phase of the grid supply voltage must be known. PLL is system which will track a signal with other signal system. PLL

TABLE II
SIMULATION PARAMETERS

Components	Parameters
Battery	12 V, 9 Ah
Filter capacitor (C1)	47 μF
Filter inductor (L1)	2.3 mH
Switching frequency	4000 Hz
DC link capacitor (C2) 2 nos.	2200 μF, 16 V
Resistance (R1)	1 kΩ
Solar panel details	
No of cells per module	36
Open circuit voltage (V)	22.09
Short circuit current (A)	8.36
Voltage at maximum power (V)	17.7
Current at maximum power (A)	7.62
diode quality factor	1.25
number of series-connected module per module	1
number of modules per string	3
Series resistance (ohm)	0.165
Parallel resistance (ohm)	80

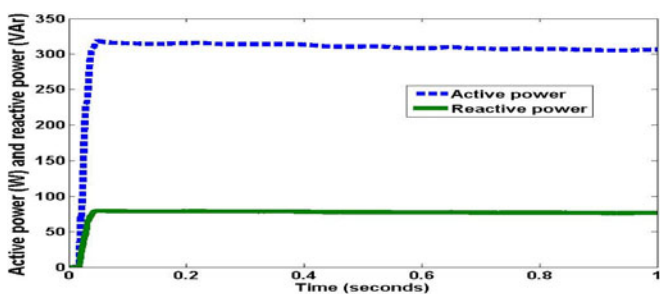

Fig. 8. Active and reactive power generation.

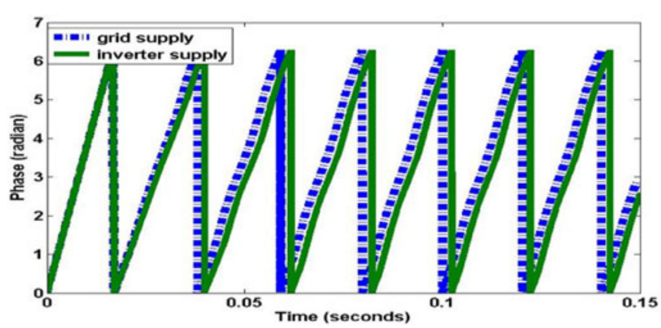

Fig. 9. Phases in radians.

is actually a servo mechanism which will reduce the difference between phase and frequency of incoming signal to a reference signal. Active power transfer to the grid is possible if there is a difference between the phase of the inverter and the grid supply system. PLL will capture the phase of the grid supply and required phase shift is generated using an inverter controller for power transfer. The phasor diagram of inverter and grid supply during the power transfer is shown in Fig. 9.

Battery charged through the proposed topology. Here, constant voltage charging method is followed. Li-ion battery which is an inbuilt block of MATLAB/Simulink is used as battery storage. The output voltage during the charging is given in Fig. 10. Thus, all operations of the converter are tested in simulation and results are analyzed. The control algorithm works perfectly in the simulation in MATLAB.

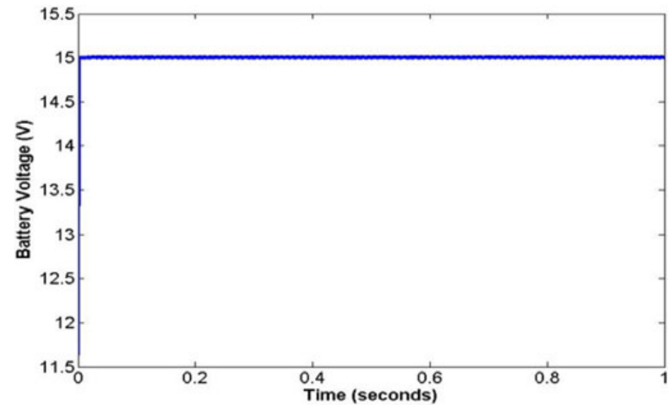

Fig. 10. Battery voltage.

TABLE III
HARMONIC CONTRIBUTIONS BY DIFFERENT APPLIANCES

Appliances	THDV (%)	THDI (%)
Air conditioner	3.72	18
Bread toaster	2.3	2.7
CFL bulbs	3.6	99.9
Computer	2.7	99.6
Induction cook top	1.8	3.8
Fan	1.8	1.5
Incandescent bulb	1.7	2.2
Iron box	2.3	2.8
Laptop charger	2.3	39.1
Microwave oven	3.3	22
Mixer	2.9	13
Refrigerator	3	5.2
UPS	2.9	18
Battery charger	2.5	54
Cooler	2.4	1.7
Florescent lamp	2	99.8
Rice cooker	2.2	2.4
Tele vision	3	99.9
LED bulb	2.2	33.8

The harmonic contributions of different appliances are calculated experimentally and given in Table III. From the table, current total harmonic distortions (THDI) are higher for mainly lighting loads like CFL, tubelight and charging loads like computer, battery chargers, etc., from this the loads, which injects more harmonics is replaced with it dc counterparts and connected to dc supply side. Thus, it mitigates harmonics injection by bypassing these loads to dc supply side.

IV. HARDWARE IMPLEMENTATION

To validate, the proposed topology, hardware implementation of RSC is done in the Energy Lab of Asian Institute of Technology, Pathumthani, Thailand. The hardware circuit diagram is given in Fig. 11. The Arduino Uno board is used as a controller in this experiment. This board is interfaced with

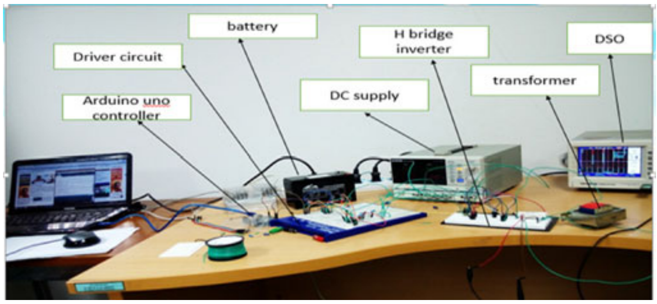

Fig. 11. Experimental setup.

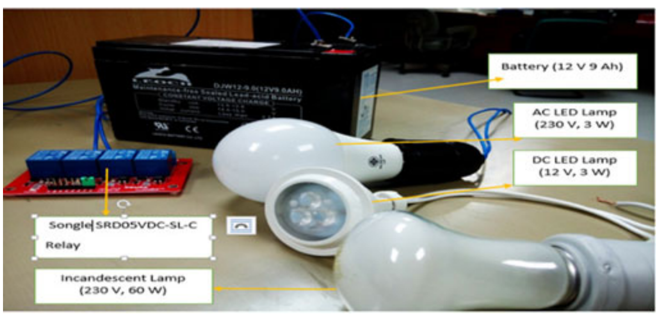

Fig. 12. Loads and relays.

MATLAB/Simulink environment in order to implement the control logic of RSC. It has inbuilt PWM pulse generators and analog and digital input reader, which will be very useful in controlling the voltage and phase of the proposed converter. The dc power supply is used as a replacement of solar panels in the laboratory experiment.

Different power levels are generated by changing the voltage and current setting of the dc power supply to replicate different operating conditions. The loads and relay used in this experiment are given in Fig. 12. The maximum harmonic producing loads in household is identified as charging and lighting loads in literature [7]. By replacing them with their dc counterpart and connected to a dc supply side of the hybrid ac/dc home, a significant improvement in the harmonic profiles can be achieved in residential feeder. So in this study, dc and ac LED lamps are used as ac and dc loads. For charging loads, a 12-V, 9-Ah battery is used, which is charged through RSC for dc supply side connection and charged from ac through an adaptor to show the difference between ac and dc charging in terms of harmonics.

The relay used in this experiment is SONGLE 4 relay module each with a rating of 250-V ac, 10 A or 30-V dc, 10 A. The operation time of this relay is 10 ms. The operating time of a relay when a pulse from UNO board is given for testing purposes of the relay is shown in Fig. 13. In mode 1, to synchronize with the grid LEM (a leading company manufactures current and voltage sensors) low-voltage transducer LV-25 is used to measure the voltage and it is given to the UNO analog input. Due to the interfacing with MATLAB, the analog input will read in MATLAB IDE and produce the synchronizing pulses using PWM pulse generator. This pulse is given to the PWM output pins of the UNO board.

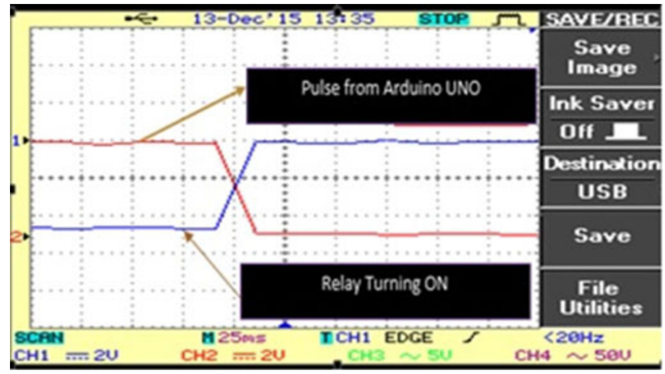

Fig. 13. Relay turn ON.

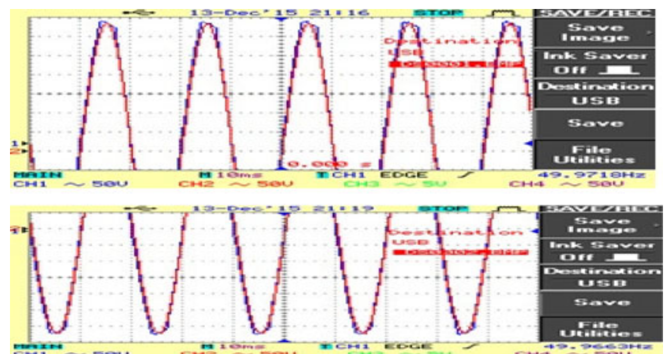

Fig. 14. Grid and inverter voltage.

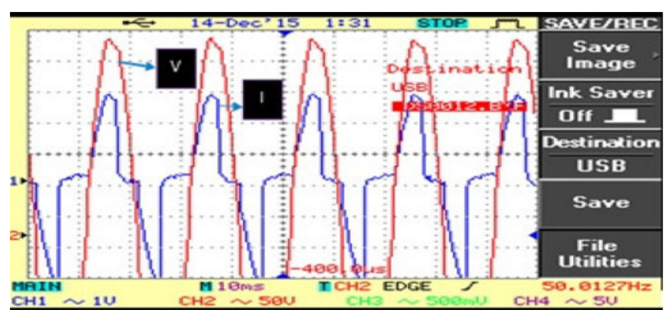

Fig. 15. Unity power transfer to grid.

The wave form of grid and interfacing voltage is given in Fig. 14. Since the peak voltage of DSO in the lab is 300 V maximum and so, two waveforms are given in Fig. 14 (upper and lower) to show the synchronization with the grid without any significant deviations.

The voltage of the inverter lies along the voltage of the grid. The active power transfer with the grid is shown in Fig. 15. Current transducer LA 25-P is used for the sensing of current and its setting is 1/1000, and 1-kΩ resistor is connected to read in the DSO.

In Fig. 15, waveform "V" is grid voltage and "I" represents as the inverter current injected to grid for active power transfer. From the figure, the current and voltage are in the phase which will inject the active power to the grid. The rms voltage is 220 V and current is 1.5-A peak.

The dc/dc operation of the RSC is done by keeping the battery voltage to 15 V as its nominal charging voltage. The input

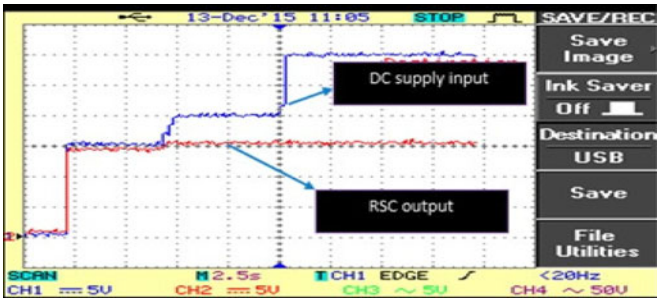

Fig. 16. DC/DC operation of the RSC.

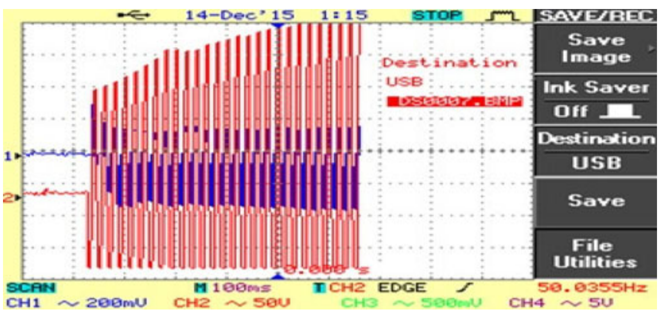

Fig. 17. Mode-0 to Mode-1.

voltage is changed and checked its effects on the proposed topology, which is given in Fig. 16. The input voltage of dc supply is varied to represent fluctuations in solar irradiation; the output voltage of RSC is maintained at constant voltage, which requires charging the battery. This topology hold good and the voltage are stiff as seen from Fig. 16. The input voltage is varied from 0 to 30 V and output voltage is constant at 15 V that is the charging voltage of battery. The dynamic operation is also very important for this particular converter topology. For analyzing dynamic behavior of the proposed RSC configuration, different topology of the converter is named by different labels.

A. Mode-0 to Mode1

For example, off state of the converter is labeled as Mode-0 stage. Similarly, Mode-1 is solar panel to grid, Mode-2 is solar panel/battery to grid, Mode-3 is battery to grid, and Mode-4 is solar panel to battery charging. A resistor of 1 kΩ is put in series to the dc-link capacitor to avoid high inrush current during the mode change.

The Mode-0 to Mode-1 operation of inverter is shown in Fig. 17. Inverter is started from off state and after some time it is connected to the grid. The voltage is 220 V and using PLL the inverter voltage is connected with respect to grid. Then unity power factor current is injecting to transfer power.

B. Mode-1 to Mode-2

In this mode, the battery is connected with solar panel to share the load. The output waveforms are shown in the Fig. 18. After the relay switched ON, there is momentarily delay to track the voltage which is shown in Fig. 18 as transition. The voltage is

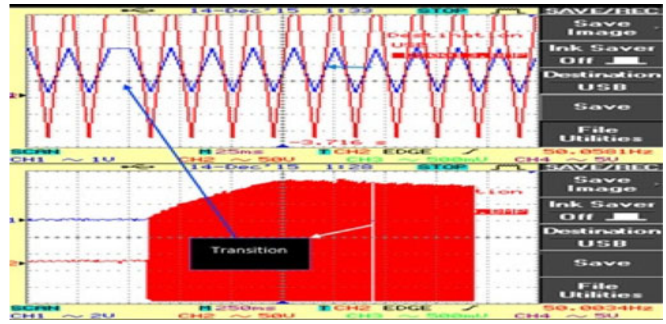

Fig. 18. Mode-1 to Mode-2.

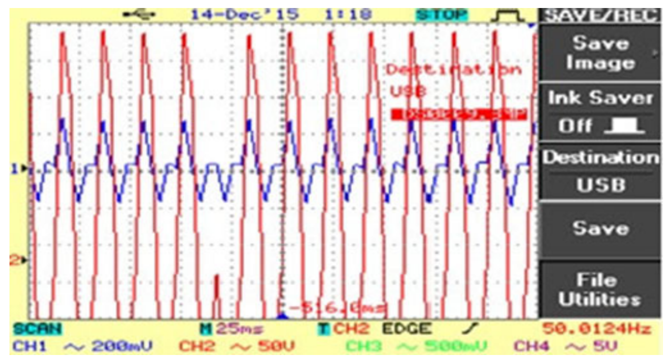

Fig. 19. Mode-2 to Mode-3.

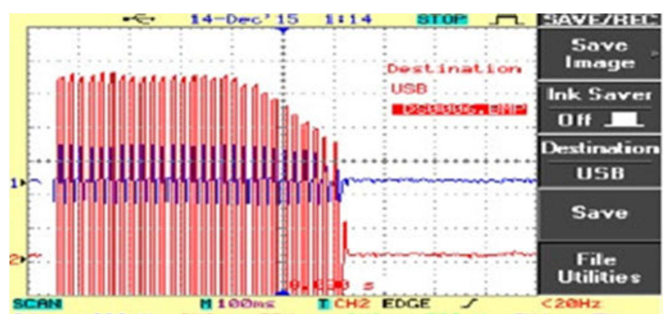

Fig. 20. Mode-3 to Mode-4.

220 V and current is 2-A peaks. The delay in one cycle is the time required for the controller and MPPT controller cannot be used in this mode.

C. Mode-2 to Mode-3

The transition from Mode-2 to Mode-3 is shown in Fig. 19. The solar panel is removed and battery is powering to the grid. The delay in changes is due to mode transition and controller is set to new stiff voltage by battery.

D. Mode-3 to Mode-4

In transition to Mode-4 operation from Mode-3, the inverter operation is shut down, which is shown in Fig. 20.

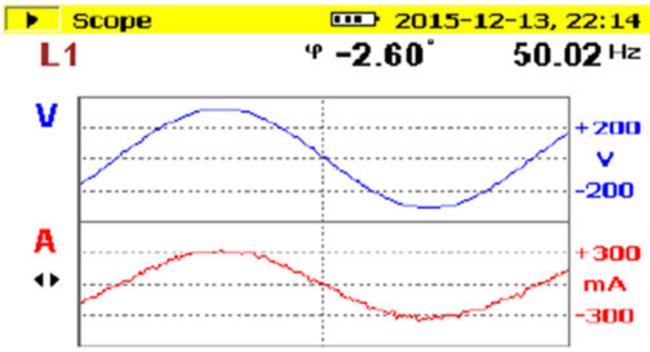

Fig. 21. Voltage and current waveform.

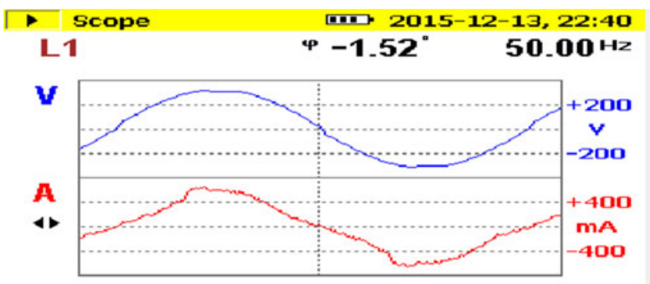

Fig. 22. Voltage and current wave form when battery charged in ac supply.

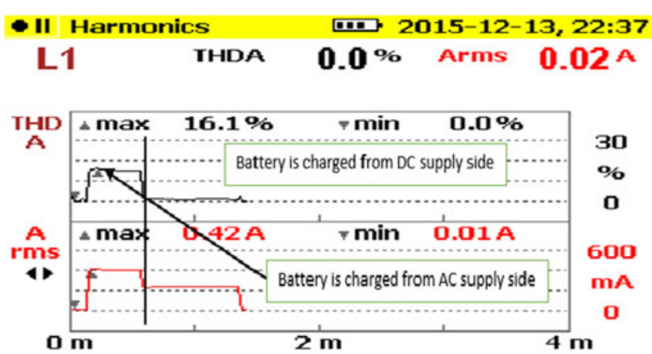

Fig. 23. Harmonic reduction—RSC converter.

Thus, the dynamic state of the proposed topology is verified with different operating Modes from 0 to 4. Since this proposed converter is for hybrid ac/dc home, this converter is tested with both ac and dc loads. When connected to a 60-W incandescent lamp, the output waveforms of voltage and current are given in Fig. 21.

When 3-W LED bulb and battery is connected along with this 60-W incandescent bulb, the harmonics are introduces and there is a distortion in wave shape, which can be observed in Fig. 22.

When connecting this battery and dc equivalent load of ac LED bulb to dc supply side, the total harmonic is reduced significantly (by 16%) as shown in Fig. 23.

The 60-W incandescent lamp is connected in ac supply side throughout this operation. From Fig. 23, it is observed that the THD in current is very high when a battery is charged from ac supply side. When it is removed or moved from ac supply side, the harmonic is reduced to 0 THD.

The load current reduces from 0.42 to 0.3 A to supply the bulb load. This single load of a single house can reduce 16% of current harmonics (THD) due to the proposed topology. Therefore, if a community adopting this RSC as their solar converter configuration, a significant reduction in harmonics can be achieved in the residential feeder. The dc side of the inverter shows 90% of efficiency, which is higher than when dc appliances when connected in ac side, which is 72–80%. It is due to avoiding the double conversion. Harmonics reduction also helps to reduce the distortion power.

V. Conclusion

This paper suggested a more suitable converter topology for a solar powered hybrid ac/dc home. The main idea of this topology is to utilize single conversion of ac power to dc and vice versa, which improves the efficiency, reduces volume, and enhances the reliability. The hardware implementation validates that the suggested converter topologies would be helpful to reduce significant amount of harmonics in the residential feeders of the future smart grid. Though, here only solar PV is considered as source of power, this topology could be equally applicable to wind, fuel cells, etc.

Acknowledgment

The authors would like to thank the Asian Institute of Technology, Pathumthani, Thailand, for providing the technical data for fulfilling this study.

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Nikhil Sasidharan (S'13) received the Bachelor's, Master's, and Doctoral degrees in electrical engineering from Kerala University, Thiruvananthapuram, India, VIT University, Vellore, India, and the Asian Institute of Technology, Pathumthani, Thailand, respectively.

He is currently a Senior Research Associate in the Department of Energy, Environment and Climate Change in the School of Environment, Resources and Development, Asian Institute of Technology. Before his Doctoral study, he was an Assistant Professor at the University of Calicut. His research interests include single-phase inverters, net zero energy buildings, low-voltage dc grid and community grid, and harmonic mitigation.

Jai Govind Singh (M'10) received the Bachelor's, Master's, and Doctoral degrees in electrical engineering from MNNIT Allahabad, Allahabad, India, IIT Roorkee, Roorkee, India, and IIT Kanpur, Kanpur, India, respectively.

He is currently an Associate Professor in the Department of Energy, Environment and Climate Change in the School of Environment, Resources and Development, Asian Institute of Technology, Pathumthani, Thailand. He was a Postdoctoral Research Associate at KTH, Stockholm, Sweden, followed by the University of Queensland, Brisbane, Australia, as a Postdoctoral Research Fellow. His research and teaching interests include power system dynamics, operation and control, smart grid and microgrid, renewable energy integration, and power distribution system planning.