Switched Inductor Quazi Switched boost Converter for the Nano-Grid Applications

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October 21, 2019

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Abstract — **Each commercial and residential buildings energy management system can be efficiently/ economically realized by integration of the solar photovoltaics (acting as the renewable power generator), battery energy storage system (ESS) along with the power electronic converters. The switched boost converters are the attractive solutions for the nano-grid applications where with a single stage operation, voltage boost, storage in battery and simultaneously inversion to the required AC voltage levels can be achieved. Here, a novel switched inductor Quasi switched boost converter is proposed. The proposed converter can operate in different modes such as multiple inputs and multiple outputs for the battery storage, PV and the load. The proposed converter reduces the shoot through requirement and improves the modulation index by increasing the gain of the DC-DC stage. The benefits of the proposed converter are: 1) high gain during PV to BESS mode, 2) high modulation index for the DC-AC stage, 3) continuous input current, 4) reduced shoot-through time which reduces the current ripple, 5) high efficiency and 6) increased reliability. The different operating modes to achieve these benefits are also presented in this paper. The detailed mathematical modelling of the proposed converter is carried out. MATLAB/SIMULINK simulation results which validates the benefits with proposed converter are given. Experimental results are obtained by developing a 120W prototype in the laboratory.**

Keywords—DC – AC converter, DC – DC converter, Pulse width modulation (PWM), Photovoltaic (PV), Shoot-through (ST) duty cycle, Micro-grid, Nano-grid.

I. INTRODUCTION

Distributed Generation (DG) is a replacement for centralized power generation plants. To decrease the degrading effects of fossil fuels, DGs are being integrated to conventional power system to meet the energy requirement in islanded as well as grid connected modes. DGs make exclusive use of solar PV and wind to exhibit least environmental effect. By making this practice more popular, carbon dioxide emission can be effectively decreased in residential and commercial building. Along with the use of DGs, reliability of RES can be improved by adding Battery Energy Storage (BES) to RES. With this integration, we can expect drastic changes in power system structure of both residential and commercial spaces. An example of this distributed energy management system (EMS) is nano – grid (NG). It consists of different energy sources, Energy Storage Systems (consists of battery and EV) and smart loads. Actually,

NG is a scaled down form of micro – grid (MG) rated from watts to few kilowatts [6]. NG can be either synchronized with the national grid or operate in isolated mode feeding ac or dc load [7]. Multiple NGs (forming MG) along with different power conversion stages along with interfacing gateway is shown in Fig. 1. This gateway facilitates power flow between MG and national grid. It is required to connect the NG to utility grid to effectively operate in an isolated mode, as it can handle the faults/failures in the conventional grid, in addition to that, it can also operate even in the absence of national grid [8]. Finally, NG is compact and closely packed power electronic integrated grid systems. It controls the power flow between renewable energy sources, home /commercial appliances and BES with variety of usage patterns by taking into consideration factors like cost, CO_2 release and energy availability [9].

Conventional methods provided low output voltage as voltage of PV panels is also low and was changing in nature because of change in solar insolation, dust accumulation and temperature of PV panels. DC – DC converters (controlled using MPPT algorithm) are conventionally employed to achieve high ac output voltage at the inverter output. An improvement over this is employment of single – stage power conversion-based systems. Additionally, it also overcome shortcomings like delay losses and shoot-through (ST). Z Source Inverter (ZSI) was developed to deal with shoot-through (ST) issue and achieve single stage power conversion. In order to decrease the size of capacitors and achieve continuous input current, Quasi Z-Source
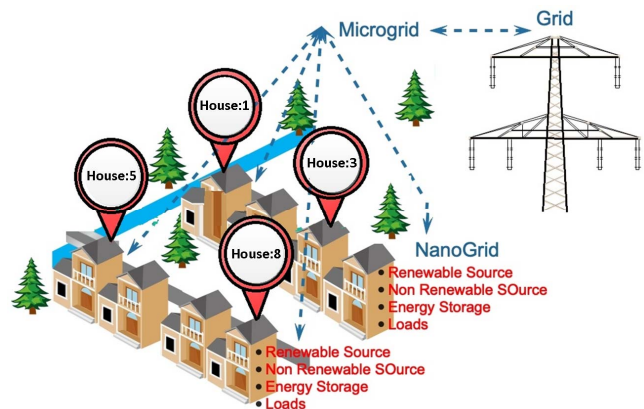

Fig. 1. Structure of National Grid, Micro-grid & Nano-grid

Inverters (qZSI) are introduced. PWM modelling, methods and

controlling techniques of ZSI/qZSI for specific applications are explained in detail [14-19]. Converter efficiency decreases in ZSI/qZSI because of usage of bulky and costly 2 inductors and 2 capacitors. Size, weight, conversion efficiency and cost are important factors of micro inverter application which decreases the suitability of ZSI/qZSI for renewable energy applications. For low power applications, Switch Boost Inverter (SBI) was suggested in [20]. The working principle of ZSI/qZSI is similar to SBI. Fewer components like only one capacitor and one inductor are used with additional semiconductor switch and diode. The modulation technique is depicted in [21]. SBI is utilized for providing alternating and direct loads of NG as suggested in [22], adding one more bidirectional converter for the BES. However, discontinuous PV current is the major shortcoming. To enhance the continuous input current and boost factor, current fed SBI [23] is developed. BES stores the additional PV power available when it is connected across capacitor and the same is suggested in energy stored qZSI [24]. Discharging of energy stored is possible at the time of direct operation from BES.

In this paper, for NG applications, a battery embedded system of quasi - SBC (BES q-SBC) is suggested. Here we can feed BES, AC and DC loads simultaneously. As per the control given, it can take power from grid. In this article, efforts have been made to suggest a modulation method, which has high modulation index (M) to obtain same output voltage gain. The PWM technique presented here decreases the voltage stress across capacitors, diodes, MOSFETS and other components. Each element design is detailed here and is compared with traditional PWM techniques of SBI. Computer simulation and synthesis results verifying the suggested power circuit topology and related PWM technique are also explained. The remaining article is arranged as follows: Section II explains the suggested qSBC for NG application. Section III explains steady state gain analysis and complete PWM switching models. Comparison with available techniques and component design are presented in section IV. Complete simulation and synthesis reports are shown in section V and conclusions are made in section VI.

II. PROPOSED SWITCHED INDUCTOR QUAZI SWITCHEHD BOOST CONVERTER FOR NANO-GRID ARCHITECTURE

Fig. 2(a) depicts the traditional NG system. It contains several power converter based stages like high gain DC-DC converter, DC-AC converter (for interfacing with AC load and grid integration) and bidirectional DC-DC converter (for power management in BES). Fig 2(b) represents single stage SBI and associated performances of DC bus formation, load interface and synchronized conventional grid. It contains different converter for BES system. Fig. 2(c) shows the suggested NG architecture. It consists of single stage DC-bus (obtained directly due to high gain) including BES, AC bus for grid and load. The suggested circuit has fewer components when compared to traditional circuits. Fig 3 shows power converter called qSBC which has two switches (S_5 and S_6) one inductor, one diode and DC-bus capacitor interlinked between inverter bridge and PV source (V_{PV}). PWM control logic controls the voltage boost and BES. Complete PWM performance was explained in section III. Following advantages can be obtained with suggested NG: 1) Maintaining peak shaving and load levelling the power that can be supplied to grid and can be stored with the help of BES

(a) Conventional Nano Grid Structure

(b) Nano – Grid structure in [20]

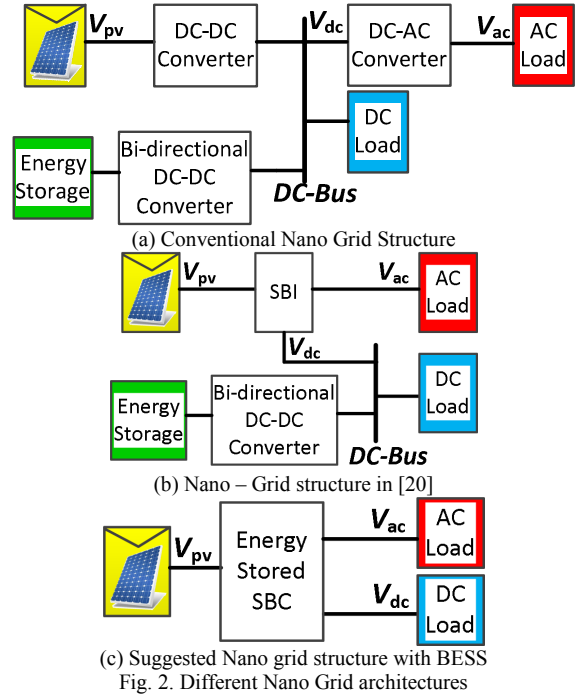(c) Suggested Nano grid structure with BESS
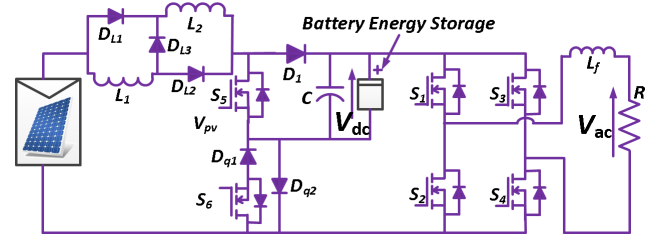Fig. 2. Different Nano Grid architectures

Fig. 3. Suggested Switched inductor qSBC

System. 2) qSBC can supply AC & DC concurrently and is a single stage power converter. In addition, it can store power in BES and can supply AC directly even when there is no PV power thereby reducing overall cost and size of the system. 3) In comparison to the conventional VSI, qSBC shows better electromagnetic interference (EMI) since there are no delays in PWM signals and dead short circuits qSBC systems are compact, reliable and less protection is needed.

III. DEVELOPED PWM SCHEME FOR THE SL-QSBC

A. PWM scheme for PV supplying BESS and AC load

Fig. 4 depicts the explanation of PWM control of proposed qSBC converter for NG and BES. Switching frequency (triangular carrier) with unit amplitude is compared with constant (ST reference-Green) in order to produce shoot through pulses (waveform) for S_5 and inverter leg. Identically, comparison is made between sawtooth (amplitude = two) and modulation signal. To produce switching pulse, OR (logic) is applied between these two pulses to achieve final switching pulse for S_5. To decrease switching losses of MOSFET switch, S_6 is kept in OFF condition for complete operating mode. Upper triangular carrier produces switching pulses for S_1 and S_2 during positive half cycle. On the other hand, lower triangle puts S_3 and S_4 ON. In a similar way in the negative half of fundamental cycle, lower triangle will produce switching pulses for switches
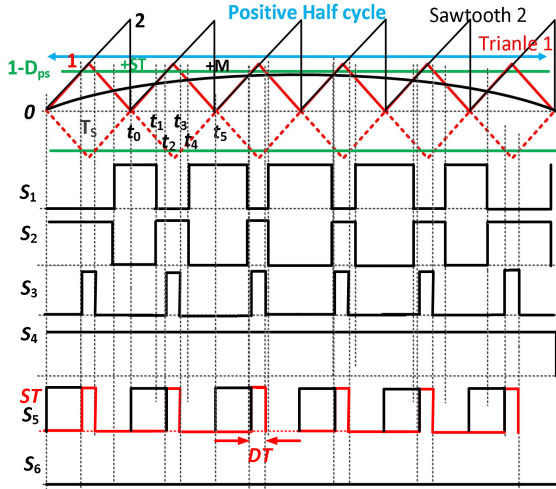
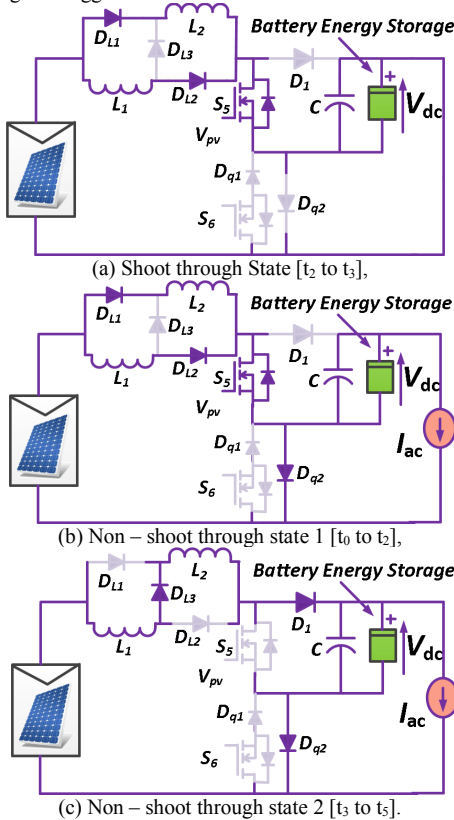Fig. 4. Suggested modulation for PV to BESS and load

(a) Shoot through State [t_2 to t_3],

(b) Non – shoot through state 1 [t_0 to t_2],

(c) Non – shoot through state 2 [t_3 to t_5].
Fig. 5. Operating modes of the proposed converter while delivering power from PV to the BESS and AC load

S_3 & S_4. Whereas the upper triangle turns S_1 OFF and S_2 ON. For achieving the shoot through state, logical OR operation is performed between S_3 and ST pulse during positive half cycle and the switches S_1, S_2, S_4 are kept same. This results in decrease in switching losses of H-Bridge (HB). Only S_2 is ORed (logic) with ST pulse and S_1, S_2 and S_4 are kept the same, for shoot through state generation in negative half of fundamental cycle resulting in reduced switching losses in HB. Conduction time (ON time) in the suggested PWM method is greater than traditional SBI and SBC. Simultaneously S_1-S_4 are modified for decreasing the switching losses of S_1-S_4 in comparison with traditional qZSI logic regular comparison with triangle is

mentioned as shoot through duty when compared with sawtooth (1-D)/2 will be mentioned represents the proposed PWM technique of qSBC. Switching frequency carrier (triangle 1 varying from 0 to 1) is compared with constant shoot through reference (green) to generate shoot through pulses for S_5 and inverter switches. In the same way, sawtooth signal (varying from 0 to 2) is compared with modulation signal to generate active switching pulses. Finally, logical OR operation is performed between these pulses and shoot through pulses to obtain switching pulses for S_5. S_6 is kept OFF throughout this mode. For positive half cycle operation, S_1 and S_2 pulses are generated by above zero triangular carrier whereas lower triangles generate for S_3 and S_4. Likewise, for negative half cycle, switching pulses for S_3 and S_4 are generated by below zero triangle carriers and S_1 is kept OFF and S_2 is turned ON. For obtaining STS, logical operation of S_3 is only performed with ST pulses. This results in reduced switching losses and thus ON time here is greater than other conventional circuits. At this instant, S_1-S_4 are changed in order to obtain reduced switching losses in contrast to conventional qZSI logic. Comparison of 1-D with triangle carrier is terms as shoot through duty whereas (1-D)/2 is compared with sawtooth signal is deliberated.

B. Detailed Operation of Proposed PWM control

In presented PWM control scheme of SBC three operating modes are available. All modes with simple figures are depicted in Fig 5. Duration t_2 to t_3 is shoot through state obtained by turning ON one of the legs of the inverter, HB can be short-circuited. At the same time S_5 is turned ON. This time duration is defined as DT_s, where T_s is switching time period.

$$L_1 \frac{di_{L1}}{dt} = L_2 \frac{di_{L2}}{dt} = V_{pv} + V_C ; C \frac{dv_C}{dt} = -I_{in} \Bigg\} \quad (1)$$

Duration t_0 to t_2 is non-shoot through state-1. When we turn ON S_5, inductor charges from PV voltage since the diode conducts (due to forward bias). AC load will receive power from BES or capacitor. During HB operation, zero states are applied after active states. This will continue for period of (1-D)/2. In this mode,

$$L_1 \frac{di_{L1}}{dt} = L_2 \frac{di_{L2}}{dt} = V_{pv} ; C \frac{dv_C}{dt} = -I_{ac} \Bigg\} \quad (2)$$

Non-shoot through state 2 is considered from [t_3 to t_5]. Active and zero state is achieved by turning the switch S5 (located in HB) OFF. As the current flows continuously in inductor. Its energy is delivered to capacitor output voltage. The time duration is kept as (1-D)/2 resulting in symmetricity of carriers. Appling KVL in this mode,

$$L_1 \frac{di_{L1}}{dt} + L_2 \frac{di_{L2}}{dt} = V_{pv} - V_C ; C \frac{dv_C}{dt} = I_{L1} - I_{ac} \Bigg\} \quad (3)$$

The following equation is obtained by the application of application of basic volt-second balance principle and charge balance.

$$V_C = \frac{3+D}{1-5D} V_{pv} ; I_{ac} = \frac{1-3D}{2(1-D)} I_{in} \Bigg\} \quad (4)$$

The DC-link voltage for the HB and the peak voltage across the capacitor are equal at the time of non - shoot through states, the DC link voltage is given by:
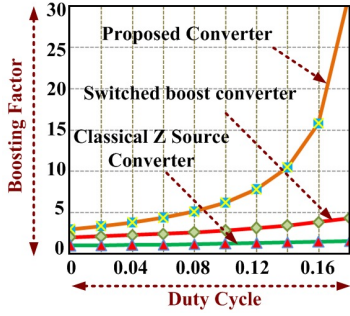
Fig. 6. Boosting factor Vs shoot through state (STS) duty

$$V_C = \frac{3+D}{1-5D} V_{pv}; I_{ac} = \frac{1-3D}{2(1-D)} I_{in} \bigg\} \qquad (5)$$

Voltage gain for the suggested qSBC:

$$B = \frac{V_C}{V_{pv}} = \frac{3+D}{1-5D} \qquad (6)$$

Comparison between voltage gain of suggested qSBC and the traditional converters (SBI, SBC) are shown in Fig 6. With the suggested PWM control, improved gain can be achieved with same ST duty cycle and additional NST states are included in modulation strategy. Peak voltage across stress improves drastically across the half – bridge switches. The presented technique be able to extend to DC – capacitor (link) type for qSBI circuits [22], which improves the voltage gain. Z source inverters (ZSI/qZSI) are used to obtain high quality response and maximum D value is given by D = 1-M. The suggested method derives boosting factor as follows:

$$G_{c.qzs} = \frac{M}{2M-1}; G_{c.qsbc} = \frac{2M}{3M-1}, G_{p.qsbc} = \frac{M(4-M)}{5M-4} \bigg\} \qquad (7)$$

With the suggested control technique, higher voltage gain can be obtained for same modulation index.

C. Battery Energy Storage supplying AC load

As the semiconductor switch S5 is switched OFF, the connection between the converter and inductor, input PV is unavailable. During this operation, the Switch S6 is turned ON. AC load can be powered directly by BES. The proposed modulation method is explained in Fig. 7. BES delay must be included in order to avoid dead short circuit in HB switches.
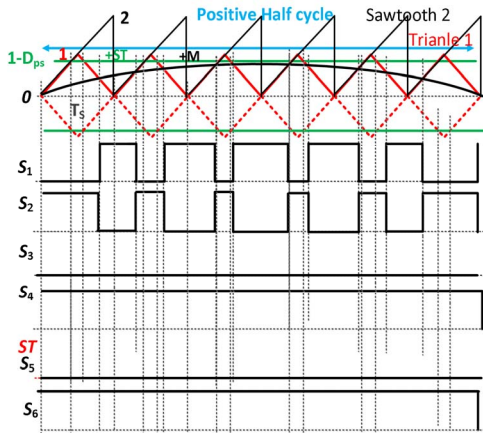

Fig. 7. Suggested PWM for power flow from BES to AC load

D. Component design

The expression for capacitor voltage ripple and inductor current under the NTS-2 for the PWM are given by:

$$\Delta I_L = \frac{(1-D)(V_{dc}-V_C)}{2L}; \Delta V_C = \frac{(1-D)(I_L-I_{ac})T}{2C} \bigg\} \qquad (8)$$

The inductor current ripple and capacitor peak to peak voltage are expressed as:

$$\Delta I_L = \frac{(1-D)(1+3D)*T*V_{dc}}{L*(1-5D)}; \Delta V_C = \frac{(1+D)*I_{in}*T}{4C} \bigg\} \qquad (9)$$

When compared to traditional SBC and SBI, the high switching frequency inductors and capacitor are relatively larger. Therefore, analysis for double switching frequency components for the proposed PWM technique is applicable for qSBC. The inductor and the capacitor currents of low frequency ripple are expressed as:

$$\hat{i}_L = \frac{(1-5D)*M*I_m}{16LC\omega^2-(1-5D)^2}; \hat{v}_C = \frac{4\omega LMI_m}{16LC\omega^2-(1-5D)^2} \bigg\} \qquad (10)$$

When compared to traditional SBI and SBC, the low switching frequency capacitors and inductors are very small. So the eventually obtained values are expressed as:

$$L > \frac{(1-D)(1+3D)*T*V_{pv}^2}{r_L\%(1-5D)P_o}; C > \frac{(1-D)(1-5D)*T*P_o}{4r_C\%(3+D)V_{pv}^2} \bigg\} \qquad (11)$$

IV. SIMULATION AND EXPERIMENTAL VERIFICATION

To explain the sustainability of nano-grid implementations, solar powered qSBC interlinked to ac RL load and dc load are drafted in MATLAB/Simulink. tools and components utilized for hardware presentation and simulation are represented in Table-I. PV Ratings are 320W, 36V at MPPT at $1kW/m^2$ and 25^0C. To get the input of qSBC of 72V, two panels are interlinked in series connection. Aapplied excitation voltage is

Table. II Element specifications for Recommended/proposed circuit

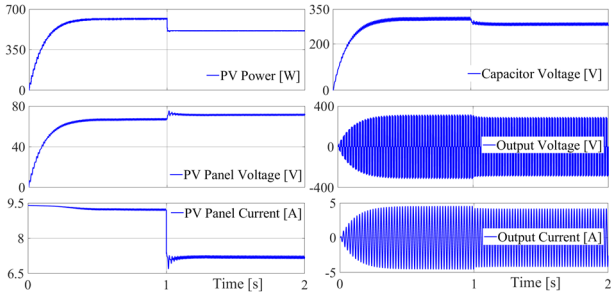| Components/Parameters	Specifications
L_1, L_2	1.6 mH, 15A
C	2000 uF, 400 V
$D_{L1}, D_{L2}, D_{q1}, D_{q2}, D_1$	STTH30R04, 400 V, 15 A
SIC-MOSFET S_1-S_6	FDP19N40, 1200 V, 40 A
Switching frequency	50 KHz
Load	120 W
Modulation Index (m)	0.9
Control Board	Virtex-5 FPGA

Fig. 8. Simulation results of the proposed solar powered qSBC converter powered. At t = 1s, irradiation level is varied from 1000 to 800 W/m².

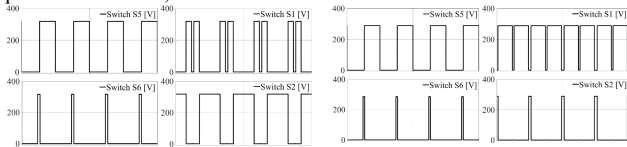
Fig. 9. Component voltage stress in simulation: V_L – voltage across the inductor ($V_{pv}+V_{dc}$=410V peak), S_5 voltage (350V peak), D voltage (350V peak), S_6 voltage (350V peak).

enhanced to 310V at 1kW/m² (with D = 0.07) and 295V at. 0.8kW/m² operation of MPPT. At the time of operation, dc voltage bus capacitor consumes power and across it dc resistive load is connected. In comparison with qSBC supplying ac RL load the shoot through duty varies.

Steady state response of qSBI at different solar insolations levels is shown in Fig. 8. Here, MPPT algorithm is used to generate shoot through duty for boosting operation of input voltage which is forced by PV panel response along with dc bus capacitor voltage. PV voltage and PV current are also depicted. At t = 1s, solar irradiation is varied from 1000 W/m² to 800 kW/m²(temperature is maintained at 25⁰C). ST duty ratio varies (from D = 0.07 to 0.05) to follow MPPT point at new value of solar insolation. MPPT is obtained without any transient overshoot are depicted in Fig. 9. Decline in solar irradiation is obtained as there is decline in output voltage and current. the decline which is obtained in output voltage and current due to partial shading. This leads to variation in resistive load power. Voltage stress of switches at different steady conditions are depicted in Fig. 9(a) and Fig. 9(b). Here, maximum stress remains equal for all the switches. Purpose of Switch S_6 is to achieve fault protection on the dc side meanwhile providing power to ac load during non – sunlight hours. Thus, by using S_6 with suggested PWM improves the suitability and consistency of system for nano-grid implementations.

For practical verification, hardware prototype rated for 120W is developed. For demonstration of dc output, dc resistor is connected across capacitor C whereas for demonstration of ac output voltage, load of 100 Ω, 22mH is connected at inverter output. Carrier signals of 50kHz frequency are generated at 100nS step size with the help of Vertex–5 FPGA. Voltage gain of 4.4 times is demonstrated by boosting input voltage of 75V to 330V as depicted in Fig. 10. Current of 0.5A (through dc resistive load) and 0.58A (through ac load) is obtained. Fig. 10(b) and 10(c) depicts zoomed waveforms of positive and negative halves of fundamental cycle respectively.
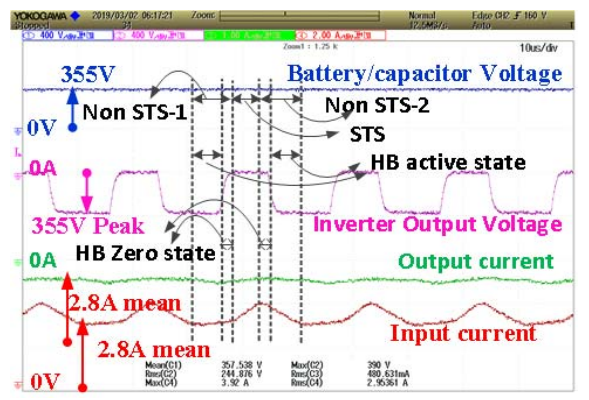
Fig. 10(c) depicts amplified version of positive half of fundamental cycle operation. Here operation of developed PWM algorithm is listed as: NSTS-1 (V_{pv} charges the inductor),
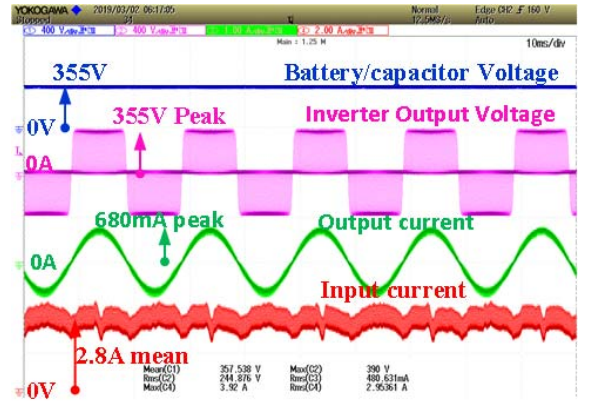
(a)
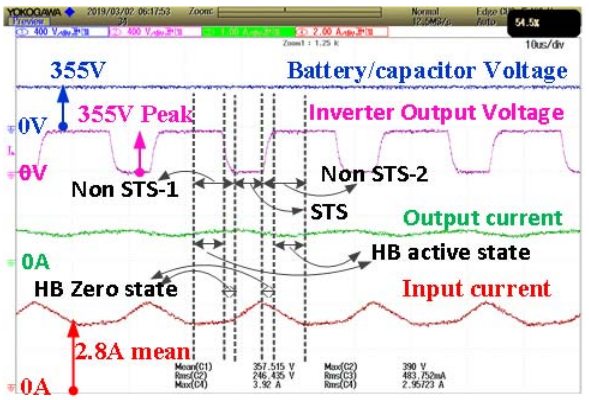
(b)

(c)

Fig. 10. Hardware results of the proposed PWM technique for qSBI, (a) Steady state waveform of the system, (b) Zoomed positive cycle and (c) Zoomed negative cycle.

NSTS-2 (potential of $V_{pv}-V_{dc}$ discharges the inductor), STS (potential of $V_{pv}+V_{dc}$ charges the inductor is charging), AS and zero output voltage states of the HB. Inductor and capacitor both operate concurrently for both positive and negative halves of the fundamental cycle. Maximum voltage across them is 330 V. Here, STS are inserted between the zero voltage states of the HB. M =0.75 and G_{max} = 7.54 are obtained at shoot through duty of 0.09 The expression M=1-D is used to achieve optimum choral profile. 89.3% of peak efficacy is achieved at 120 W.

V. CONCLUSION

In this article, a new Battery Energy Storage embedded qSBC converter for operation in grid connected or off-grid mode

was presented. Two novel PWM techniques are described for operation in all the operating modes consisting of power exchange between PV, single phase AC grid, BES and DC and AC load for the NG implementations. In comparison to traditional SBI, SBC and qZSI, the developed PWM techniques have higher M and achieves the desired output voltage with low ST duty cycle (D = 0.05 to 0.07). Minimizing of ST duty cycle is essential as it reduces the stress on passive as well as semiconductor components. Simulation results validates the advantages associated with this converter and PWM control for renewable energy application. In addition to this, condition of partial shading is also emulated by varying the solar irradiation from 1 to 0.8 kW/m^2 during operation. Even during this perturbation, the system performance is satisfactory. Hardware results pertaining to circuit performance are also presented.

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