

Photovoltaic Emulator for Grid-connected Quasi-Z-Source Inverter

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ABSTRACT

The performance of PV panel is very much dependent on the amount of sun light as well as the temperature of the surrounding environment which normally hard to be predicted. The use of PV emulator in the investigation of solar inverter especially at a lab scale platform helps to mitigate the inconsistency factors due to this uncontrollable variation. This work discussed on the design and development of a PV emulator for the grid-connected quasi-Z-source inverter which has different topology and control method compared to the conventional voltage source inverter. The I-V characteristics of the PV panel is modelled from the commercially available product and through circuit analysis the relation between capacitor voltage control and the PV terminal voltage is established, thus realizing the MPPT operation. Results from both simulation and experimental verification demonstrated that the PV emulator successfully able to produce power for the inverter according to the requirement.

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1. INTRODUCTION

Penetration of photovoltaic (PV) based distributed generation system in the energy grid becomes very significant nowadays. Data from the annual report produced by the International Energy Agency as in Figure 1 shows that the PV installation all over the world reaches 98 GW for the year 2017, which is 29% growth from the previous year with China leading the way by 32% of the total installed capacity [1].

Along with this rapid development, so as the research activities on the energy conversion aspect of the PV generation system to achieve high efficiency operation. In the design and development of power electronics circuitries for the PV energy conversion, having a stable condition over wide range of input power is important to verify the maximum functionality of the system. Although the sun light during the day is something which is abundantly available, testing a system under certain condition can be very challenging as the weather and temperature can vary unexpectedly. For that, the use of PV emulator especially for the laboratory scale experimental platform is preferable. Many works have been discussed in the literature among others such as in [2]–[4]. All these works in common, use a lookup data generated from the commercially available PV panel I-V characteristics as a reference. As the PV source can be modelled as a current source input to the system, the PV is then simulated by means of current control using power electronics circuit such as the DC-DC buck converter which is simple and effective. As a result, the power produced by the PV emulator can be specifically controlled to emulate the real environment condition. From the perspective of integration between the PV source and the grid-connected inverter, the DC-DC boost

converter is preferably used to increase the voltage across the inverter and to implement the the maximum power point tracking (MPPT) to gain maximum power from the PV source [5]–[6].

The Z-source inverter [ZSI] proposed in [7] which then evolves into many other types of impedance source inverters such as the quasi-Z-source inverter (qZSI) [8] which have been proven as an alternative to conventional voltage source inverter (VSI) for the grid-connected PV system with equivalent performance as discussed in the previous works such as in [9]–[12]. Compared to the conventional VSI based PV inverter system, the qZSI eliminates the necessity to have the DC-DC boost converter in between, thus an advantage in term of reducing the number of components as well as on the control complexity. From the point of real PV source implementation however, not very much have been discussed especially on realizing and evaluating the operation and effectiveness of the MPPT, which requires the use of PV emulator as discussed above. For that, this paper is filling the gap by specifically discussing on the implementation of the PV emulator for the case of the qZSI. It is expected that the results from this implementation can be applied to other type of impedance source as well.

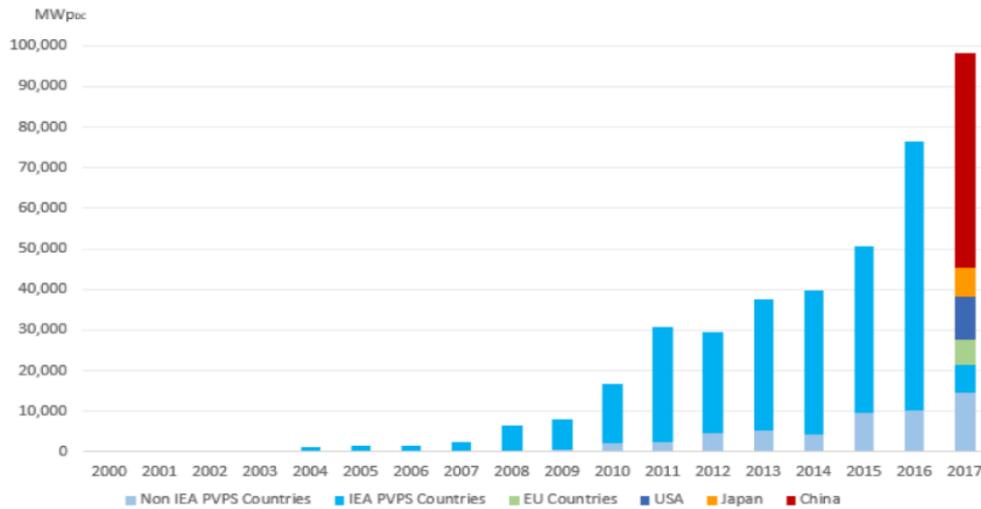


Figure 1. Evolution of annual PV installation (MW-DC) [1]

2. RESEARCH METHODOLOGY

2.1. Modelling of the PV Source Emulator

Power produced by the solar panel in general varies based on environmental factors such as the amount of sunlight and the temperature. The use of PV source emulator makes it easier to reproduce and maintains the same condition for investigating the performance of the PV inverter system. The PV emulator basically consists of two parts; a lookup table which consists of PV array I-V curve data and the DC-DC buck converter used to generate the current according to the lookup table data provided based on the voltage sensed at its output terminal. Figure 2 shows the structure of the DC-DC buck converter based PV emulator. A general PV array model can be defined from the following Figure 3 which shows the equivalent circuit of the PV cell. The relationship between the output current I and the terminal voltage V is given as [13],

$$I = I_{sc} - I_o \left(\exp\left(\frac{qV_d}{AkT}\right) - 1 \right) - \frac{V_d}{R_p} \tag{1}$$

where

$$\begin{cases} V_d = V + IR_s \\ I_o = I_{or} \left[\frac{T}{T_r} \right]^3 \exp\left[\frac{qE_{Go}}{Ak} \left(\frac{1}{T_r} - \frac{1}{T} \right) \right] \\ I_{sc} = [I_{scr} + K_I (T - 298)] \lambda \end{cases} \tag{2}$$

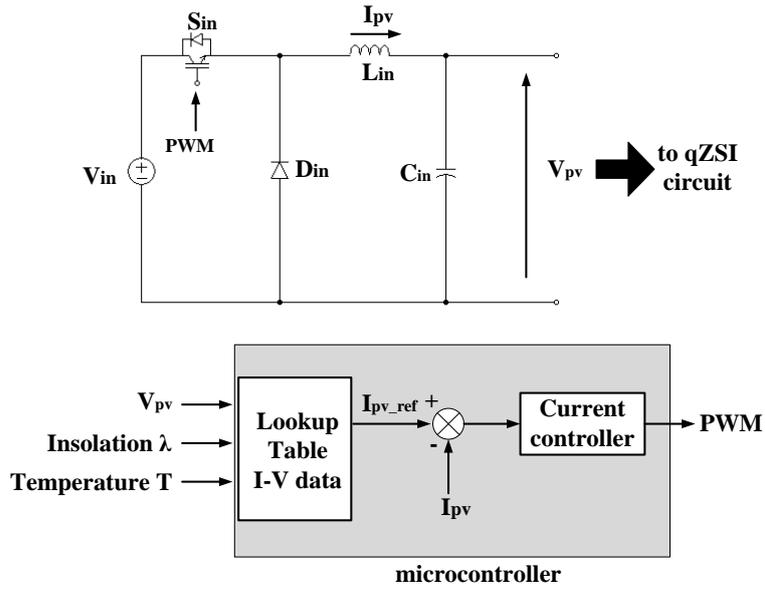


Figure 2. DC-DC buck converter based PV emulator

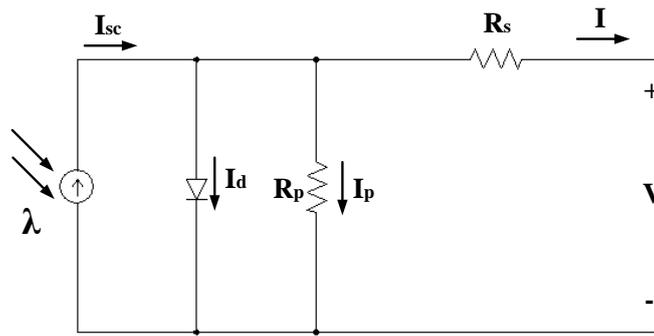


Figure 3. Equivalent circuit for a PV cell

Table 1 shows the definition of parameters involved in the above equations

A	Diode ideal factor	K	Boltzman constant 1.38×10^{-23} J/K
T	Temperature on absolute scale, K	q	electron charge 1.6×10^{-19} coulombs
λ	Sunlight insolation kW/m^2	I_{or}	Cell saturation current at T_r
E_{GO}	Band gap for silicon	T_r	Reference temperature at 301.18K
K_I	Current temperature coefficient at I_{scr} 0.0017 A/K		

Generally, the PV array consists of N_s cell in series to form a panel and N_p of panels in parallel according to the rated power required. The output voltage and current are given by the following equations.

$$\begin{aligned}
 V_{dc} &= N_s (V_d - IR_s) \\
 I_{dc} &= N_p I
 \end{aligned}
 \tag{3}$$

Figure 4 shows the graphs voltage-current I-V curve characteristic and the responded power curve calculated based on solar PV panel commercial product BP MSX 120 from BP Solar [14] which is used as the base for the configuration of the PV emulator output voltage, current and power.

Electrical Characteristics	MSX 120
Maximum power P_{max}	120 W
Voltage at P_{max} (V_{mp})	33.7 A
Current at P_{max} (I_{mp})	3.56 A
Minimum P_{max}	114 W
Short-circuit current (I_{sc})	3.87 A
Open-circuit voltage (V_{oc})	42.1 V
Temperature coefficient of I_{sc}	$(0.065 \pm 0.015)\% / ^\circ C$
Temperature coefficient of V_{oc}	$-(80 \pm 10)mV / ^\circ C$
Temperature coefficient of power	$-(0.5 \pm 0.05)\% / ^\circ C$
Nominal operating cell temperature	$47 \pm 2 ^\circ C$
Maximum system voltage	600 V (U.S. NEC rating) 1000 V (TUV Rheinland rating)
Maximum series fuse rating	20 A

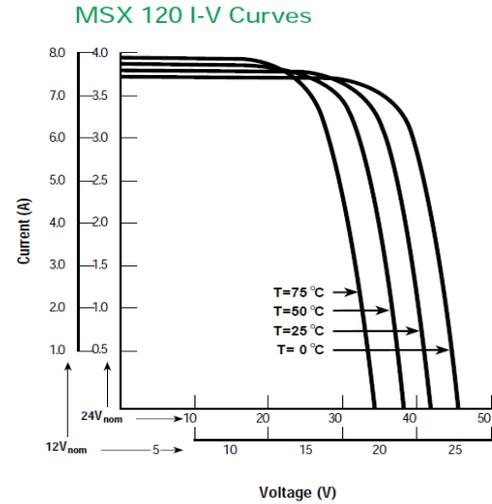


Figure 4. Solar PV panel specification from BP Solar [14] with the electrical characteristics (left) and the I-V curve characteristics (right)

From the circuit and structure of the PV emulator shown in Figure 2, according to the voltage across the output of the DC-DC buck converter, the corresponding reference current is obtained from the lookup table which is produced based from the MSX 120 product in Figure 4. The current controller adjusts the PWM duty ratio so that the average inductor current matches to the reference current. By controlling the average inductor current, the output power of the PV emulator can be controlled to the desired level.

2.2. Integration of PV Emulator with Grid-connected qZSI

As shown in Figure 2 the voltage and current output from the PV emulator is connected to the quasi-Z-source network which consist of asymmetrical LC network $L_1, L_2, C_1,$ and C_2 plus a diode D_1 . There are two states of operation in the conventional voltage source inverter (VSI); the active states when a non-zero voltage exists across the bridges and the zero states when either all upper and lower transistors are in ON or OFF condition ($S_1S_3S_5/S_4S_6S_2$ 000 or 111) to produce a zero voltage condition across the bridges.

In the qZSI, a shoot through condition (short-circuit of inverter switches) is purposely introduced during the zero states. Figure 5 shows the equivalent circuit of qZSI during both shoot-through and non-shoot-through operation.

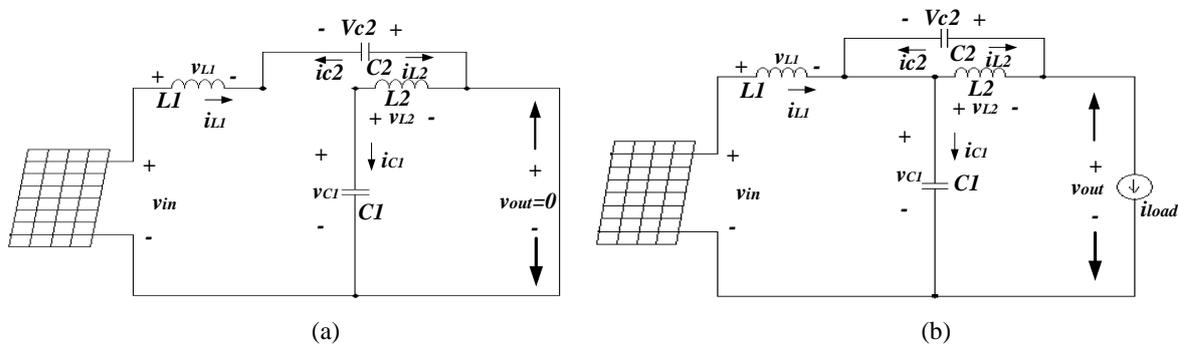


Figure 5. Equivalent circuit of qZSI during (a) shoot-through and (b) non-shoot-through

The shoot through interval is defined as T_0 , the non-shoot-through interval as T_1 and the switching period as T_s where $T_s = T_0 + T_1$. The shoot-through duty ratio d is defined as $d = T_0 / T_s$. When the qZSI is in a

shoot through condition for a duration of T_0 from switching cycle of T_s , using the KCL, KVL, the following equations can be defined.

$$\begin{aligned} L_1 \frac{di_{L1}}{dt} &= v_{in} + v_{c2} & L_2 \frac{di_{L2}}{dt} &= v_{c1} \\ C_1 \frac{dv_{c1}}{dt} &= -i_{L2} & C_2 \frac{dv_{c2}}{dt} &= -i_{L1} \end{aligned} \quad (4)$$

Then when the qZSI is in an active states condition for duration of T_1 from switching cycle of T_s , the following equations (5) can be defined.

$$\begin{aligned} L_1 \frac{di_{L1}}{dt} &= v_{in} - v_{c1} & L_2 \frac{di_{L2}}{dt} &= -v_{c2} \\ C_1 \frac{dv_{c1}}{dt} &= i_{L1} - i_{load} & C_2 \frac{dv_{c2}}{dt} &= i_{L2} - i_{load} \end{aligned} \quad (5)$$

Considering the average voltage of the inductors and average current of the capacitors are zero over one cycle in steady state, from (4) and (5),

$$\begin{aligned} L_1 \frac{di_{L1}}{dt} &= (1-d) \cdot (v_{in} - v_{c1}) + d \cdot (v_{in} + v_{c1}) = 0 \\ L_2 \frac{di_{L2}}{dt} &= (1-d) \cdot (-v_{c2}) + d \cdot (v_{c2}) = 0 \\ C_1 \frac{dv_{c1}}{dt} &= (1-d) \cdot (i_{L1} + i_{load}) + d \cdot (-i_{L2}) = 0 \\ C_2 \frac{dv_{c2}}{dt} &= (1-d) \cdot (i_{L2} - i_{load}) + d \cdot (-i_{L1}) = 0 \end{aligned} \quad (6)$$

From the above equations the capacitor voltage and inductor current can be obtained as,

$$\begin{aligned} v_{c1} &= \frac{1-d}{1-2d} v_{in} \\ v_{c2} &= \frac{d}{1-2d} v_{in} \\ i_{L1} = i_{L2} &= \frac{(1-d)i_{load}}{1-2d} \end{aligned} \quad (7)$$

and the DC link peak voltage across the inverter \hat{v}_{out} can be derived as

$$\hat{v}_{out} = v_{C1} + v_{C2} \quad (8)$$

It is shown from (7) and (8) that the capacitor voltage and the DC link peak voltage across inverter can be boosted from v_{in} by varying the shoot-through duty ratio d accordingly. As for the case the input voltage comes from the output of PV arrays ($v_{in}v_{pv}$), if the capacitor voltage v_{C1} can be controlled to be constant, the input voltage v_{pv} increases when the shoot-through time is decreased, and decreases when the shoot-through time is increased as in equation (9).

$$v_{pv} = \frac{1-2d}{1-d} v_{c1} \quad (9)$$

Considering this fact for the case of MPPT implementation, the maximum power point voltage ($V_{mpp}V_{pv}$) can be tracked by adjusting the shoot-through duty ratio d .

Figure 6 shows the overall configuration of the system with the grid-connected qZSI. It consists of the PV emulator as the main power supply to the inverter system which replicates the behaviour of the actual PV array I-V characteristic, the quasi-Z-source inverter, the local load and the 3-phase 415V grid-connection via a transformer.

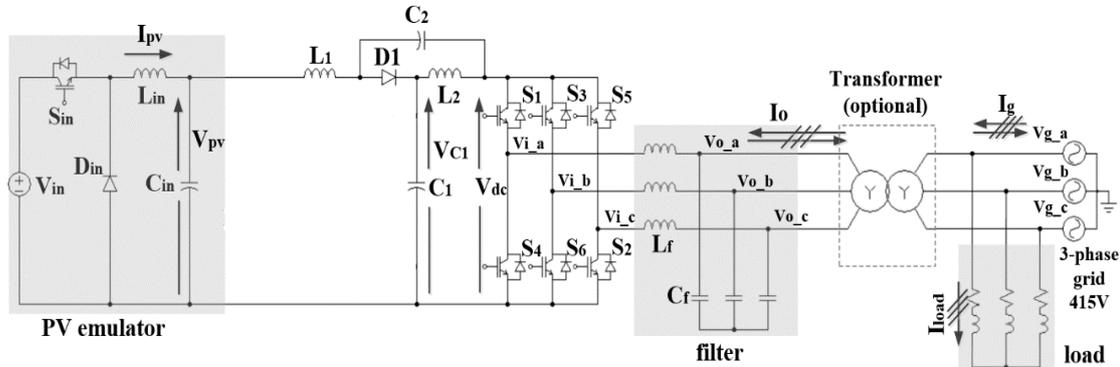


Figure 6. Overall block diagram of the grid-connected qZSI PV inverter system

2.3. The Maximum Power Point Tracking Algorithm

As the capacitor voltage V_{C1} is controlled constantly, the shoot-through duty ratio d is controlled by the MPPT algorithm to regulate the voltage across the PV terminal V_{pv} to achieve the maximum power point according to equation (9). Figure 7 shows the algorithm of the pertube and observe MPPT method (P&O) [15] used to control the d value. i is the time sequence $V(i)$ and $I(i)$ are the voltage and current at the PV terminal measured by the sensor and the produced power $P(i)$ is computed. Based on the computed $P(i)$ and the current voltage $V(i)$, decision is made whether to increase or decrease the shoot-through duty ratio d .

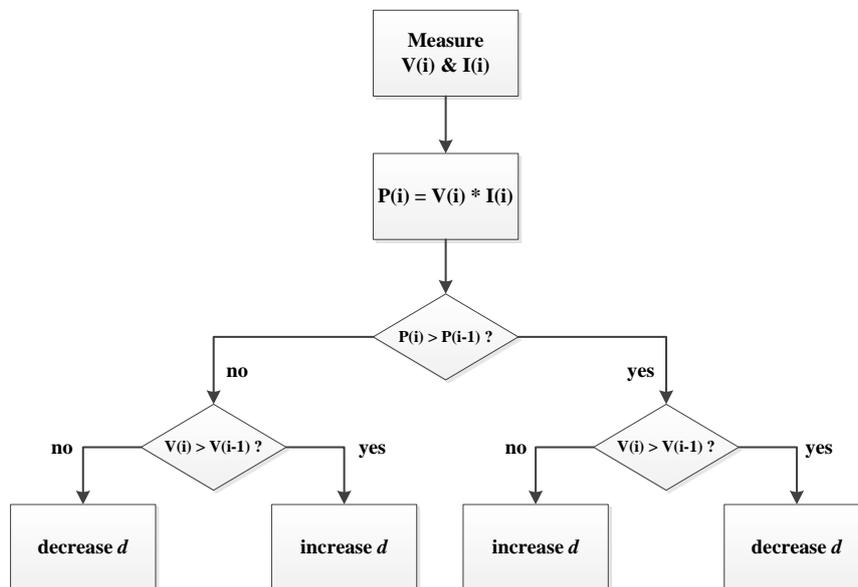


Figure 7. Flowchart of P&O algorithm used to control the shoot-through duty ratio d

3. RESULTS AND ANALYSIS

Based on the system designed and modelled in the previous sections, simulation using the Matlab® software is carried out with objective of verifying the operability of the designed PV emulator with the grid-connected qZSI PV inverter system. Two platforms of 5 kW and 0.5 kW systems are used for the simulation to show the that the proposed method is operable over wide range of power level under residential PV

installation category. Table 2 shows the parameters and specifications used for both platforms. For the 5 kW system, the PV source configuration is set at V_{mpp} 235.9 V with the capacitor voltage V_{C1} controlled at 680 V. This makes it possible for direct connection to the 3-phase 415 V_{l-rms} grid. The 0.5 kW system is the scaled down version of the 5 kW system, designed with the purpose for comparison with the results from the experiment works presented in the next sub-section. The PV source is configured at V_{mpp} 141.1 V, with capacitor controlled at 200 V and connection to the 3-phase 415 V_{l-rms} grid is made through a transformer.

Table 2. Parameters/Specification of Simulation Setup for Grid-connected PV based qZSI

Parameters/Specification	5 kW configuration (transformerless)	0.5 kW configuration (w/transformer)
Max power from PV	5 kW V_{mpp} 235.9V I_{mpp} 21.36A	0.5 kW V_{mpp} 141.1V I_{mpp} 3.6A
Max power to grid	5 kVA	0.5 kVA
DC bus voltage	V_{C1} controlled at 680 V, V_{dc} 1126 - 1148 V _{pk} shoot-through d : 0.39 – 0.41	V_{C1} controlled at 200 V, V_{dc} 258 - 279 V _{pk} shoot-through d : 0.2 - 0.3
Switching frequency f_{sw}		10 kHz
Grid connection	transformerless 3-phase 415 V _{l-rms}	with transformer 3-phase 104 V _{l-rms} : 3-phase 415 V _{l-rms}
Grid filter		L_f 10 mH, C_f 8 μ F
Standard/reference	1. AS4447 Grid Connection of Energy Systems via Inverters 2. IEEE 1547 Standard on Interconnect Distributed Resources with Elec. Power System	
qZSI network		L_1 L_2 4.7 mH, C_1 C_2 1000 μ F

3.1. Simulation Results at 5 kW

Figure 8 shows the I-V curve data used in the simulation for 5 kW configuration based on the actual PV panel product MSX-120 from BP Solar. From the calculation and the power curve shown below, it is expected the maximum power of approximately 5 kW can be obtained at approximately V_{mpp} 235.9 V and I_{mpp} 21.36A at 25°C.

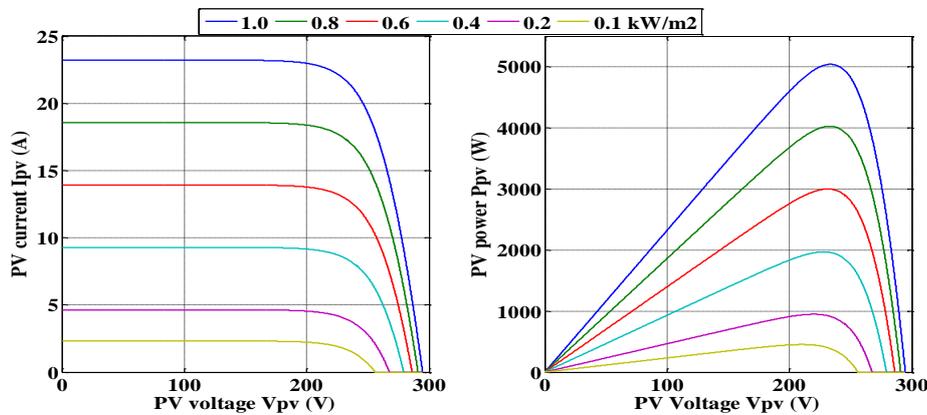


Figure 8. I-V curve data at 5 kW configuration based on BP Solar MSX-120 PV panel at 25°C

MPPT operation of the qZSI PV inverter is verified by gradually increasing and decreasing the insolation level between 0.2 to 1.0 kW/m² as shown in Figure 9. Variation in insolation value directly affects the power produced by the PV array, and the MPPT operates to find the V_{pv} value that will produce a maximum power. In Figure 9, V_{pv} changes in the range 220 V to 245 V through the adjustment in the shoot-through value d between 0.39 to 0.41. The PV emulator produces the output current I_{pv} based on I_{pv_ref} in the lookup table which corresponds to the controlled V_{pv} as shown in Figure 10 where the finally produced power P_{pv} is proportional to the given insolation value between 1 kW to 5 kW.

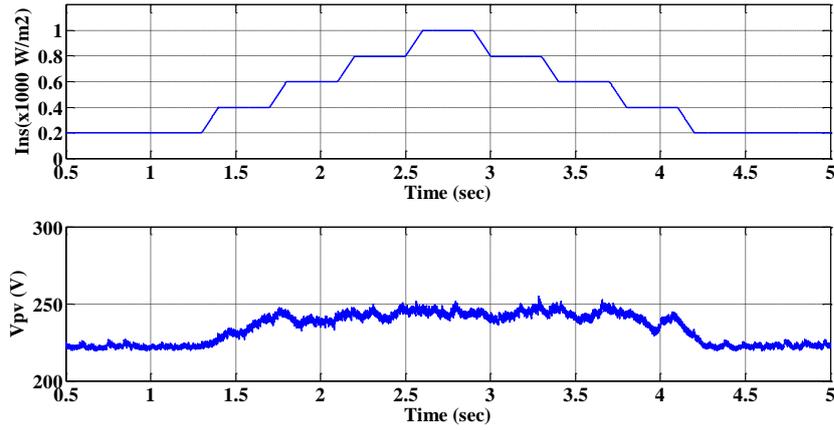


Figure 9. The given insolation level (top) and the changes in the voltage across emulator V_{pv} (bottom)

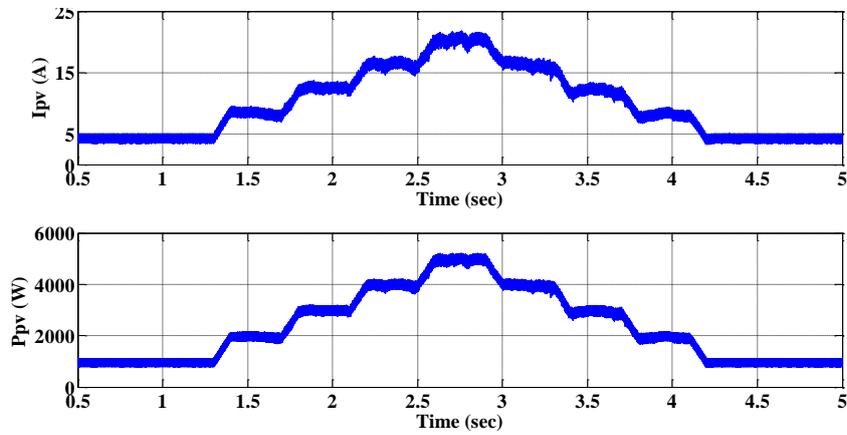


Figure 10. The output current of the emulator I_{pv} and the corresponds output power P_{pv} .

The successful operation of the MPPT depends on the ability to control the capacitor voltage V_{C1} which is shown in Figure 11 at around 680 V with the produced voltage across the inverter switches V_{dc} ranges between 1110 V_{pk} to 1140 V_{pk}. Figure 12 shows the output phase current of the inverter where the value between 2.5 A_{pk-pk} to 9.5 A_{pk-pk} at 339.4 V_{phase-pk} is proportional to the power produced by the PV emulator P_{pv} .

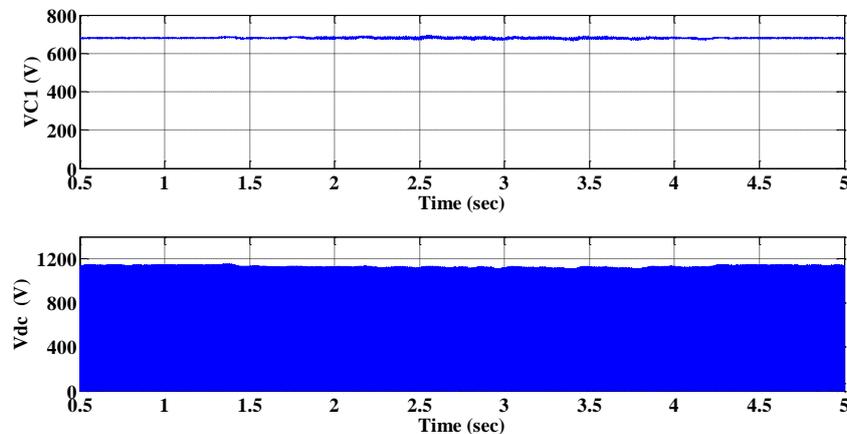


Figure 11. Voltage across V_{C1} (top) and the voltage produced across the inverter switches V_{dc} .

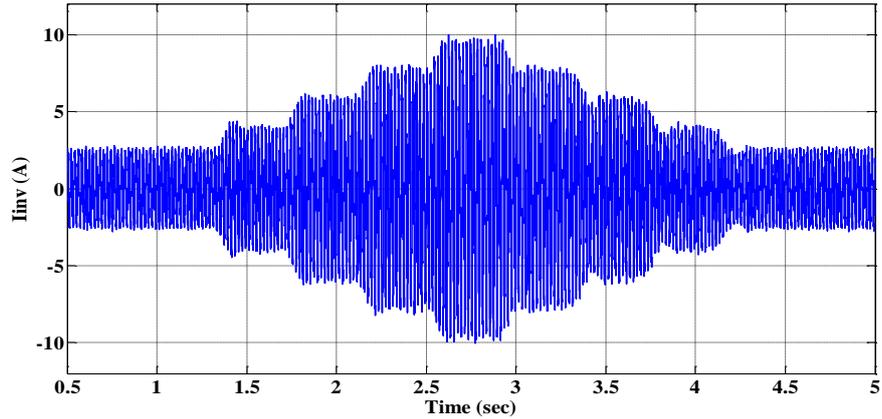


Figure 12. Inverter phase output current

3.2. Simulation Results at 0.5 kW

The I-V curve data used in the simulation at 0.5 kW power level based on commercial product MSX-120 from BP Solar is shown in Figure 13. The maximum power of approximately 0.5 kW is expected at V_{mpp} 141.1 and I_{mpp} 3.6 A at 25°C. MPPT operation of the qZSI PV inverter is verified through the same manner as for 5 kW power level and the results are shown in Figure 14. The insolation level is gradually increased and decreased between 0.3 to 1 kW/m² at 25°C. The MPPT algorithm operates to vary the V_{pv} between 120 V to 145 V to achieve maximum power P_{pv} at each insolation value ranges between 130 W to 530 W. The results show a good agreement with the I-V curve characteristic data in Figure 13.

In order to realize the successful operation of the MPPT, the capacitor voltage is controlled at 200 V, shown in Figure 15 (top) and the shoot-through duty ratio d is adjusted between 0.2 to 0.3. This produces a peak voltage across the inverter V_{dc} ranges between 257 V to 275 V in Figure 15 (bottom) which is a good agreement with the theoretical values in Table 2.

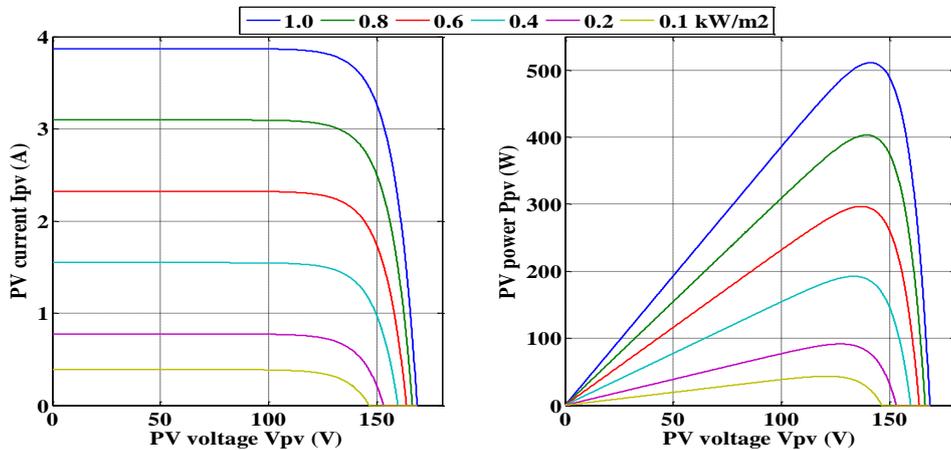


Figure 13. I-V curve data at 0.5 kW configuration based on BP Solar MSX-120 PV panel at 25°C

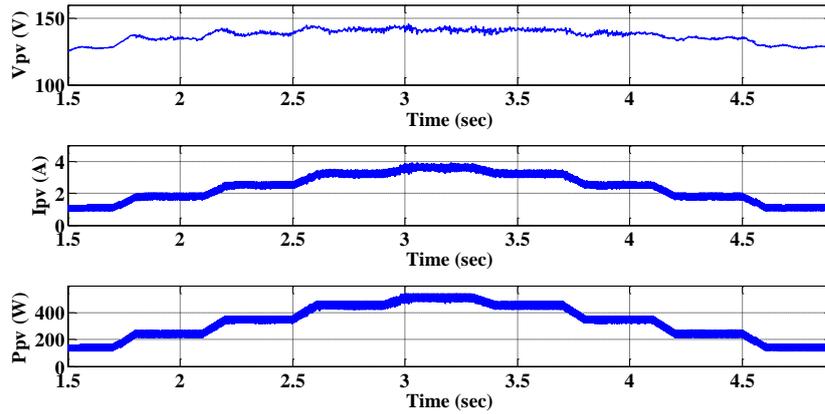


Figure 14. The control of PV source terminal voltage V_{pv} (top) and the corresponds output current I_{pv} (mid) and the produced power P_{pv} (bottom)

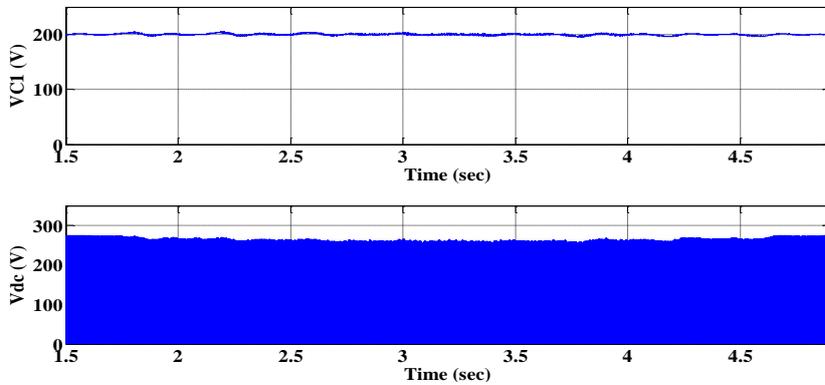


Figure 15. The control of capacitor voltage V_{c1} at 200V (top) and the produced peak voltage V_{dc} across the inverter (bottom)

3.3. Hardware Experimental Results

Figure 16 shows the close-up of the PV emulator unit. A digital programmable DC power supply XDC600-10 from Xantrax with maximum voltage of 600 V and current of 10 A is used as the power supply. A single IGBT IXEN60N120 from IXYS is used for the switching with breakdown voltage of 1200 V and current capacity of 100 A. For the gate driver, a gate driver unit based on VLA502-01 from POWEREX is used to drive the IGBT with 5 kHz PWM signal.

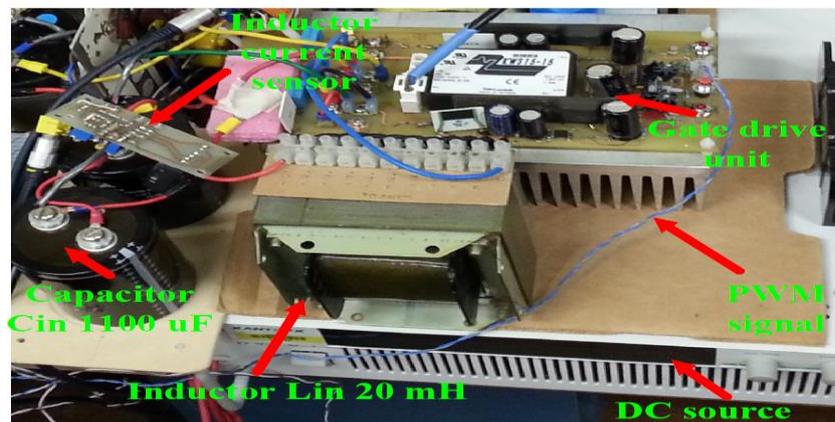
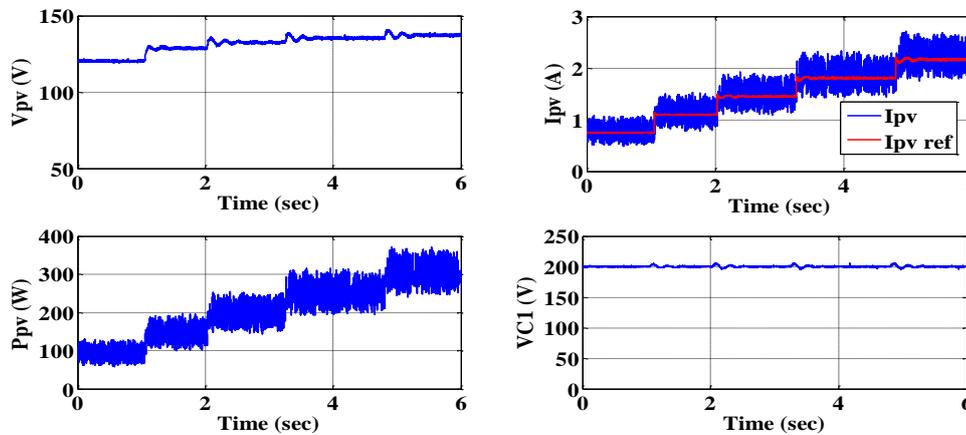


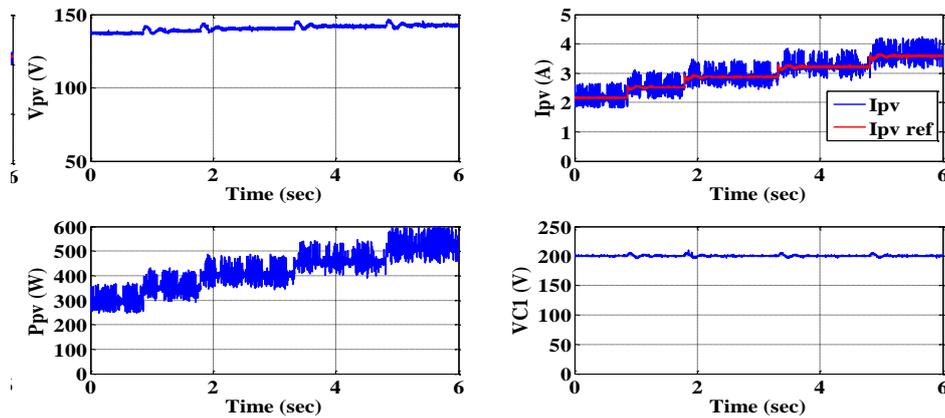
Figure 16. Experiment setup of DC-DC buck based PV emulator

The DC-DC buck converter is designed to operate at maximum 2 kW power level, with V_{in} 600 V, V_{out_max} 200 V and output current I_{out_max} 10 A with maximum ripple of 20%. Worst case sampling time which is also the switching frequency f_{sw} is made at 5 kHz and duty cycle D_{max} 0.35. In the experimental setup an inductor of 20 mH is used together with two electrolyte capacitor of 2200 uF/450V connected in series to create a 1100uF capacitor value.

Figures 17 to Figure 18 shows the results when insolation value is gradually increased and decreased at various level between 0.2 to 1.0 kW/m² to produce approximately 100W to 500W power from the PV emulator. In all cases capacitor C_l voltage V_{Cl} is well controlled at 200V to enable the MPPT operation. The maximum power point is achieved through the increment and decrement of V_{pv} within a range of 120V to 145V by varying the shoot-through duty ratio d between 0.2 to 0.3. Inductor current I_{pv} is successfully controlled according to the values I_{pv_ref} referred by the I-V lookup table. The power produced by the emulator goes into the inverter and output current of the inverter I_{inv} is proportional to the input power from the emulator output in Figure 19 (a)–(d). Based on the value of inverter phase output current of 6.43 A_{pk-pk} and 10.25 A_{pk-pk} in Figure 19 (a) and (b), the amount of power produced by the emulator is roughly match the power released by the inverter.



(a)



(b)

Figure 17. Variation of emulator output voltage V_{pv} , current I_{pv} , power P_{pv} and control of V_{Cl} for insolation at at (a) 0.2 to 0.6 kW/m² and (b) 0.6 to 1.0 kW/m²

Figure 6-2 Variation of emulator output voltage V_{pv} , current I_{pv} , power P_{pv} and control of V_{Cl} for insolation of 0.6 to 1.0 kW/m².

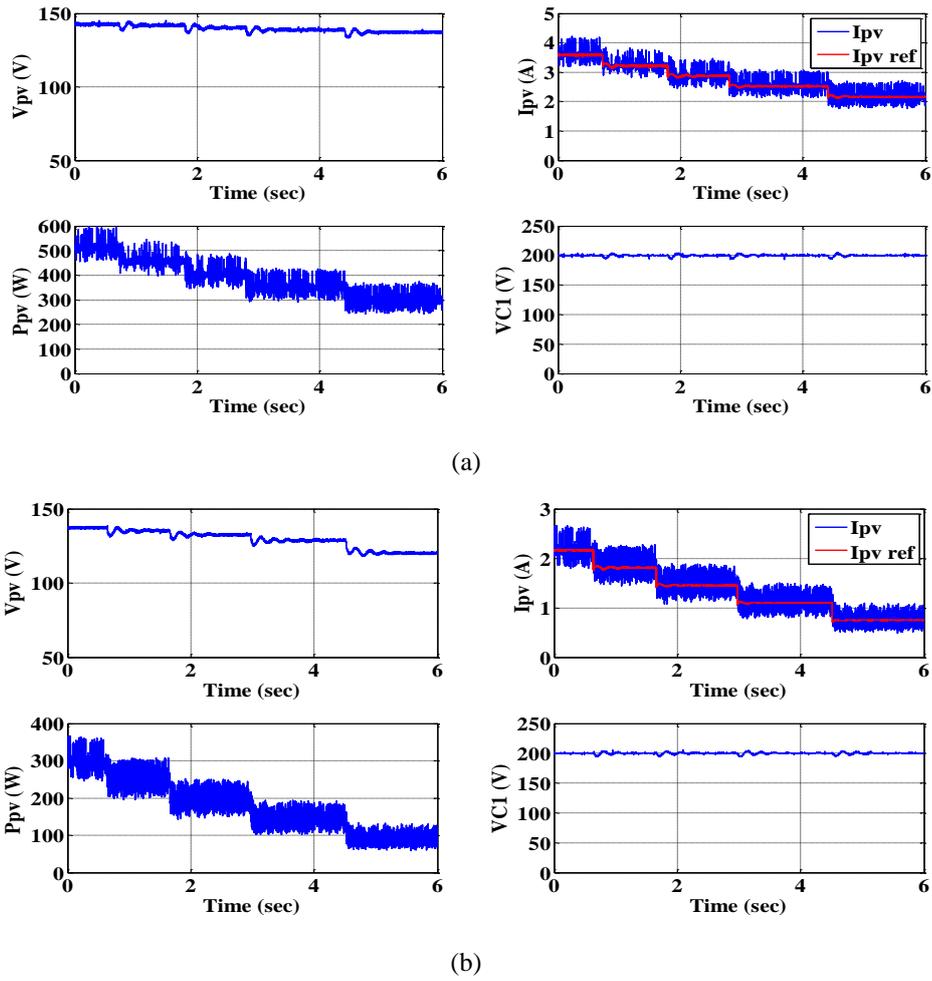


Figure 18. Variation of emulator output voltage V_{pv} , current I_{pv} , power P_{pv} and control of V_{CI} for insolation at (a) 1.0 to 0.6 kW/m^2 and (b) 0.6 to 0.2 kW/m^2

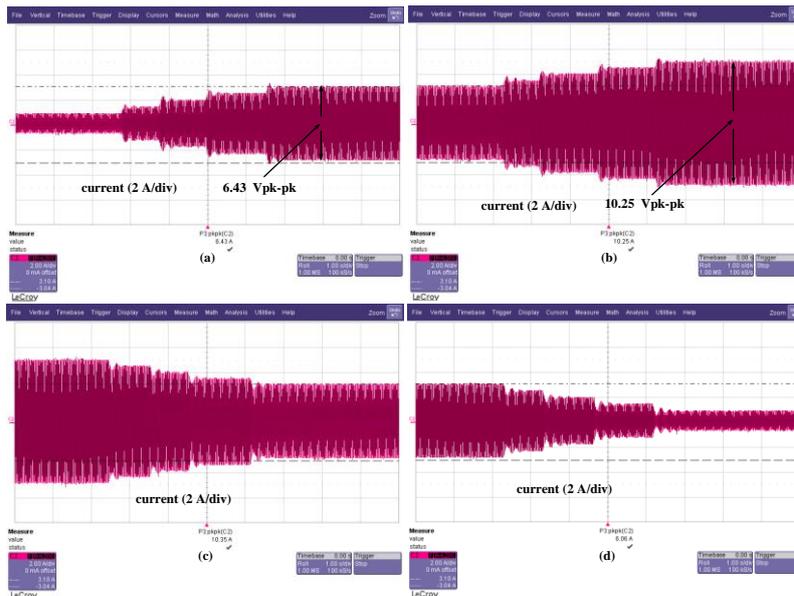


Figure 19. Variation of inverter output phase current I_{inv} as insolation is increases and decreases (a) 0.2 to 0.6 kW/m^2 (b) 0.6 to 1.0 kW/m^2 (c) 1.0 to 0.6 kW/m^2 and (d) 0.6 to 0.2 kW/m^2

4. CONCLUSION

The paper presents the design and development of PV emulator for use with the grid-connected quasi-Z-source inverter system. The integration with the qZSI is unique with the elimination of the DC-DC boost converter as normally applied in the conventional VSI topology. The PV emulator is modelled and the I-V characteristics are obtained from the commercially available PV panel product. The overall system of the grid-connected qZSI is configured at two distinct power levels of 5 kW and 0.5 kW to show functionality over wide range operation. Based on both simulation and experimental verification results, the PV emulator satisfactorily operates as a current source for the inverter with the MPPT functions well as expected.

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