Performance Comparison of Reactive Power Control Methods of Photovoltaic Micro-inverter

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Abstract. Photovoltaic power generation becomes an important technology in recent years, because of its advantages such as clean energy, pollution reduction, no gas emissions, maintenance and operation requirements are low. So it is a new path for generating electric power. This paper will study the performance comparison of two photovoltaic systems of three-phase grid-connected micro-inverter and study their design methods of reactive power control. The first design is suggested that the photovoltaic PV system based on an interleaved DC-DC boost type converter with its maximum power point tracking control (MPPT) for each boost converter. A voltage source inverter type (VSI) is used as a three-phase micro-inverter. By controlling the direct and quadrature components of inverter output currents, reactive power controlling is achieved at 90.76% efficiency. The second design is suggested that the photovoltaic panel is connected DC-DC converter of an interleaved flyback type. Each sub-converter is controlled by an individual (MPPT). The circuit of active third-harmonic current injection in recent years have received much interest, this technique contributed to get better quality of current injected into the utility grid and to control the reactive power with good efficiency 95.07%. A line-commutate current source inverter type (CSI) with filter is used. The developed micro-inverter of (1000W) offers an expanded range of reactive power control with balanced three-phase output power. Each system design in this study has proven its effectiveness in obtaining control of reactive power and nearly sinusoidal three-phase output currents. The effectiveness of the suggested systems are clarified by using the MATLAB Simulink program and the results of the simulation show the validity of the suggested micro-inverter system.

Keywords: Photovoltaic micro-inverter; Boost converter; Flyback converter; Third-harmonic injection; Reactive power control

1. Introduction

Renewable energies particularly solar, are an interesting and growing alternative electricity generation source in recent years. Solar power is abundant, renewable and pollution-free. It is most commonly available in the midst of increased natural energy interest. Several types of inverter circuits and the corresponding control systems have been studied for PV systems.

The interactive PV systems with the grid can be categorized into the following three sorts: are the central inverter, string inverter and AC modules system [1]. The AC module strategy has been suggested in this paper to overcome the drawback of other types of PV inverter including high tension DC cables, power loss associated with central MPPT, loss mismatch between solar AC modules and loss mismatch between photovoltaic modules and inverter. AC module system, with ranging of low power levels of micro-inverter is used in this paper, there are many advantages of AC module include:
1) Improved the energy harvesting
2) Improved efficiency of the system
3) Lower cost of installation
4) Operation "Plug-N-Play"
5) Increased modularity and flexibility
6) Enable the capacitance of the DC capacitor small [2]

An AC Module displays the integrated of the DC-AC converter and PV module in an electrical system [3] as shown in figure 1.

Figure 1. Parallel connection of AC module inverters.

Several reactive power technique is discussed in the literature, those show the constant power factor (PF) and fixed reactive power (Q) [4] [5]. This paper proposed an improved solar radiation photovoltaic MPPT control algorithm. The three-phase 1000W micro-inverter is designed and can be injected active and reactive power into the grid. The perturbation and observation (P&O) algorithm is applied to extract sun power. It can be used because of its advantage such as:

1) Easy in implementing and very simple in finding true MPP.
2) It can be operated as either an Analog or Digital technique of MPPT.
3) Used more widely and so can provide more information [6].

This paper presented two photovoltaic systems of three-phase grid-connected micro-inverter with two design methods of control of reactive power. The first design method proposed that the system is using a DC-DC boost converter in the DC-DC conversion stage and pulse width modulation voltage source inverter (VSI). Control of reactive power is achieved by regulating the q-component of inverter current in the d-q reference frame of three-phase inverter currents. The second design by using interleaved flyback converter in a stage of DC-DC converter and the third-harmonic current injection circuit for reactive power control with current source inverter (CSI).

The output power provides into the utility grid varies over time. When the power is taken from the photovoltaic panel needs to be fixed value to improve power harvesting. That causes a mismatch between instantaneous input power and the instantaneous output power, so components of energy storage have to be located between the input and the output for balancing instantaneous input power and instantaneous output power [7]. An element is used for power decoupling in the circuit is a capacitor. The capacitor is placed between the PV panels and the inverter. The feasibility of the program is demonstrated by the MATLAB software simulation. The performance comparison contributed to achieve a nearly sinusoidal output currents, a reactive power control injected into the grid, high efficiency, more reliability, reduction in THD, reduction in DC-Link capacitance value. This paper is organized as follows: Section 2 introduces operating principles and the control for tracking MPP and the control scheme of the micro-inverter for first design; Section 3 presents the micro-inverter operating principles and control algorithm for tracking MPP and the control scheme of the third-harmonic injection circuit for second design; Section 4 shows the simulation to verify the presented methods; Section 5 shows the final conclusion of this paper.
2. First design: PV micro-inverter based on boost converter

This section describes a photovoltaic conversion system. In general, five essential elements are used to build solar power systems for grid-connected applications: PV panel that converts energy from the solar radiation to electricity, DC-DC converter for boosting a low voltage generated by a PV panel to a high DC voltage, an inverter (VSI) which converts current to a three-phase AC currents, MPPT and Filter is used to decrease the voltage and current harmonics produced by the inverter.

2.1. MPPT controller

The electric power generated by a photovoltaic panel varies throughout the day because of change in irradiance and temperature. To remove this barrier, the PV power must be tracked by using MPPT controller. P&O algorithm is the wide generally used than other MPPT algorithms. The study is founded the PV output power measurement and the changes in power by influencing the current and voltage of photovoltaic. The tracker works continuously at regular intervals by increasing or decreasing the solar array voltage. P&O compares the value of power previously given with one after disturbances by varying periodically the panel voltage by a small increment step. This cause a variation of the duty ratio of the DC-DC converter in decreasing or increasing and repeating the procedure until full power point is reached [6] [8].

2.2. Circuit configuration

Figure 2, shows a configuration of the circuit of PV inverter connected to the three-phase utility grid.

![Figure 2. Three-phase grid-connected circuit configuration of the micro-inverter PV system.](image)

The system circuit is divided into two stages. The first stage is responsible to increase the input DC voltage and the MPPT closed loop. The location of the boost converter would enhance the overall photovoltaic system installation, permitting various controls of a system by MPP monitoring using the (P&O) algorithm method. The second stage is the DC-AC conversion stage and three-phase filter.

2.3. System control

This section describes the suggested controls of active and reactive power. The control diagram in Figure 3, shows that the inner loop of current control with two control loops including active power and reactive power control. A phase-locked loop (PLL) is used for synchronization between the utility grid and the micro-inverter. The outer loop is represented by the regulation of DC-Link voltage. The DC voltage is estimated and it related to the constant reference voltage. As shown in the Figure, relations of cross-coupling and voltage are feedforward in the loop of inner control, so that active and reactive power injection into the grid can be individually controlled [9].
The direct current component $I_d$ represents the active power component of the output currents that are compared with the output of the voltage PI-control which is $I_d^*$. The reactive current $I_q$ is regulated using PI-controller to determine the necessary reactive power ($Q$). Then the command voltage of the controller circuit is used to generate PWM signals for the micro-inverter switches.

The specifications designed system is shown in table 1. The PV panel is taken under STC of irradiation 1000 W/m$^2$, temperature of 25 ℃ and the PV specifications are shown in table in appendix A.

| Parameters                     | Value | Unit |
|--------------------------------|-------|------|
| Boost output DC voltage         | 420   | V    |
| Grid voltage (line-line)        | 220 (rms) | V    |
| $L_{boost}$                     | 1.5   | mH   |
| $L_f$                           | 3     | mH   |
| Switching frequency ($f_s$)     | 50    | kHz  |
| Rated power                     | 1000  | W    |
| Output frequency                | 50    | Hz   |

3. Second design: PV micro-inverter based on third-harmonic injection technique
In this design, the micro-inverter consists of PV panels each panel of 250W, a DC-DC converter stage that includes four interleaved flyback converter, a third-harmonic current injection circuit and a line-commutated current source inverter (CSI) with square wave control pulses [10][11].
3.1. Circuit configuration

Figure 4, shows the configuration of the circuit of PV system of a three-phase grid-connected with a third-harmonic current injection circuit.

In this design a small ceramic capacitor instead of a bulky capacitor in the input side of the inverter just for getting a high-frequency input pulse current that is different from the conventional single PV input in [12][13]. The main subject of the various research teams’ attention on operational issues such as the operating activity of the MPPT, improved THD of flyback micro-inverters and the reduction of input capacitors.

As shown in Figure 4, the micro-inverter has four terminal at the input side each terminal connected to one flyback. The developed micro-inverter is connected to the back of one PV panel.

The third-harmonic injection circuit contains a leg of two switches connected from the middle to the third harmonic current inductor that is connected to one phase by the bidirectional switch. Reactive power can be controlled by accurate control of the third-harmonic circuit and provide a three-phase sinusoidal output current. The line commutated CSI includes six inverter switches. Three arms of this inverter will be delayed with 120 degrees angle to generate a three-phase AC supply [14].

3.2. Principle of operation

As shown in Figure 4, each flyback converter with separate MPPT is designed and each converter consists of two sub-converter interleaved with 180° phase shift, this increases the harvesting of energy, more efficiency of the converter and decreases the current ripple.

The operating principles of a third-harmonic injection circuit are explained as follows: for the switches Swa+, Swb+ and Swc+, of the inverter, the connection of switch to the input phase side with the high voltage value. But for the switches Swa−, Swb− and Swc−, the connection of switch to the input phase with the low voltage value. The switches Swy+ and Swy− is working in high switching frequency in the third-harmonic injection circuit, which can be controlled to form the third-harmonic current iy flowing in the inductor of third-harmonic circuit Ly. So the reactive power controlled by controlling the power factor by using a special algorithm [15] [16].

The line commutated CSI operated in synchronized with grid voltages. The DC output points p, n and y are connected to output phase voltage a, b and c. As assume u_a > u_b > u_c at this state, the switch in the upper arm of phase a (Swa+) and the lower arms in phase c (Swc−) and bidirectional switch (Swb±) are operated in ON state to generate DC-link voltage. Table 2, shows the pulses switching states.

| $\theta_{\text{sa}}$ | sector | $\text{Sw}_{\text{y}+}$ | $\text{Sw}_{\text{b}+}$ | $\text{Sw}_{\text{c}+}$ | $\text{Sw}_{\text{y}−}$ | $\text{Sw}_{\text{b}−}$ | $\text{Sw}_{\text{c}−}$ |
|-------------------|-------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| 0$-$π/3           | One   | 0                 | 1                 | 0                 | 1                 | 0                 | 0                 |
| π/3$-$2π/3        | Two   | 1                 | 0                 | 0                 | 0                 | 1                 | 0                 |

![Figure 4. Schematic diagram of three-phase micro-inverter topology construction.](image-url)
2 \pi/3 - \pi  Three  0  0  1  0  1  0  0  0
\pi/3  Four  0  1  0  0  1  0  0  1  0
4 \pi/3 - 5 \pi/3  Five  1  0  0  0  0  1  1  0  0
5 \pi/3 - 2 \pi  Six  0  0  1  1  0  0  0  1  0

3.3. MPPT control of the PV panel
The P&O algorithm for MPPT built on the photovoltaic current control is taken in this work for the three-phase micro-inverter because of the benefits such as good operation performance and small implementing efforts.

In this method, a modified strategy of current perturbation is taken into account instead of the voltage perturbation presented in the traditional method [17], to increase the speed of the MPP tracking.

3.4. The control of third-harmonic current injection circuit
An operation of the circuit of third-harmonic injection is related to injecting a suitable third-harmonic current \(i_y\), so the control of current of the third-harmonic circuit \(i_y\) is the key to design a third-harmonic injection circuit. The aim is to control the real third-harmonic current \(i_y\) which track the third-harmonic injection reference current \(i_y^*\). Thus the total output power \((P^*o)\) and \((i_y^*)\) should be found firstly. As shown in Figure 6.

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Figure 5. Block diagram of the MPP tracking controller of the PV system.

Figure 6. Block diagram for control of micro-inverter.
The specifications of this system are shown in table 3. The PV panel is taken under STC of irradiation 1000 W/m² and temperature of 25 °C and its specifications are shown in table in appendix B.

| Parameters                                  | Value   | Unit |
|---------------------------------------------|---------|------|
| Total power rating                          | 1000    | W    |
| grid voltage (Line-line)                    | 220     | V    |
| Output frequency of the inverter            | 50      | Hz   |
| Frequency of switching                      | 50      | kHz  |
| The magnetizing inductance of flyback transformer | 54    | µH   |
| Turn ratio                                  | 6.5     |      |
| Filter inductance                           | 500     | µH   |
| Third harmonic inductor                     | 3       | mH   |

4. Simulation results
The two systems design is simulated using the MATLAB software. For boost micro-inverter, operates in CCM, which simulated with the same system design specification obtained in table 1, and for flyback micro-inverter, operates in CCM, which simulated with the same system design specification obtained in table 3.

4.1. Three-phase grid-connected PV module-integrated micro-inverter based on DC-DC boost converter simulation results
The MATLAB software program is used in this simulation. PV panels operated at a standard solar intensity of (1000 W/m²) and temperature (25°C).

Figure 7, shows the PV output voltage (DC-voltage) \( V_{in} = 72 \text{V} \) with small voltage ripple \( V_{ripple} = 0.621 \text{V} \).

![Figure 7. PV array output voltage.](image)

Figure 8, shows the PV output current, whose value of \( I_{in} = 6.7 \text{A} \) with a small ripple value \( I_{ripple} = 0.12 \text{A} \).

The DC output power of each PV array is shown in figure 9 with 500W for irradiation of 1000W/m² and temperature of \( T = 25^\circ \text{C} \).
Figure 10, shows the drive signal waveform of the IGBT switch of each boost converter. To confirm the PV system at its MPP, the switching cycle varies accordingly. The value of the duty cycle to give maximum power is 0.82857.

The voltage source inverter (VSI) is associated with the following waveforms. The voltage source inverter input is DC voltage shown in figure 11. The DC-DC boost converter regulates its output voltage to match the reference value (420).
The active power and reactive power injected into the grid are proportional to the direct current component (I_d) and quadrature current component (I_q) respectively. Figure 12, shows the direct component response that follows the output of PI-controller of DC voltage loop with a steady-state value of 3.66A, the injected active power is 1000W. Figure 13, shows the quadrature current component which is controlled to zero using a PI controller, this means that no reactive power injected into the grid.

Figure 11. Input DC voltage of three-phase voltage source inverter VSI.

Figure 12. Direct current component I_d.

Figure 13. Quadratic current component I_q.
Figure 14, shows the micro-inverter waveforms that run in full power condition. In this status, each PV array light intensity was defined set at (1000, 1000) W/m² respectively, and the output power of the PV array was estimated were $P_{\text{PV1}} = 500$ W, $P_{\text{PV2}} = 500$ W. Figure 14 (a) shows the voltage of phase $a$ with the current of phase $a$, Figure 14 (b) shows the three-phase output currents. The wanted features are achievable in PV systems, such as near sinusoidal output currents, unity power factor and the separate MPPT. THD of output current is 5.3%.

When the micro-inverter works under full-power condition (1000 W), $I_d = 3.7$A and $I_q = 0.995$A at output reactive power (268Var). Figure 15 (a) shows the voltage of phase $a$ with the current of phase $a$, Figure 15 (b) shows the three-phase output currents. The displacement angle of the inverter output current is $15^\circ$ related to the reactive power that is injected into the grid. THD of output current is
6.477%.

![Micro-inverter waveforms](image)

**Figure 15.** Micro-inverter waveforms with output reactive power of 268Var and phase displacement angle 15° (a) output phase voltage and output phase current (b) three-phase output currents.

When the micro-inverter operate under full-power condition (1000 W), \(I_d = 3.67A\) and \(I_q = 2.142A\) at output reactive power (577Var). Figure 16 (a) shows the voltage of phase a with the current of phase a. Figure 16 (b) shows the three-phase output currents. The displacement angle of the inverter output current is 30°. THD of output current is 6.9%.

![Micro-inverter waveforms](image)

**Figure 16.** Micro-inverter waveforms with output reactive power of 577Var and phase displacement angle 30° (a) output phase voltage and output phase current (b) three-phase output currents.
Figure 17 (a) shows voltage and current of phase a, Figure 17 (b) shows output three-phase currents when The micro-inverter works under full-power condition (1000 W), $I_d = 3.66$ A and $I_q = -0.994$ A at output reactive power (-268 Var) and the displacement angle of the inverter output current is -15° with THD of output current is 7.23%.

![Figure 17](image_url)

**Figure 17.** Micro-inverter waveforms with output reactive power of -268 Var and phase displacement angle -15° (a) output phase voltage and output phase current (b) three-phase output currents.

Figure 18 (a) shows the dynamic response of reactive power when a change from 0 Var to 268 Var to 577 Var and active power at full power rated and Figure 18 (b) shows the three-phase output currents through this change.

![Figure 18](image_url)

(a)
4.2. Three-phase grid-connected photovoltaic micro-inverter based on third-harmonic injection technique simulation results

The MATLAB software program is used in this simulation. PV panel operated at a standard solar intensity of (1000 W/m²) and temperature (25°C).

Figure 19, shows the PV output voltage $V_{in} = 30.7V$ with small voltage ripple $V_{ripple} = 0.436V$.

Figure 20, show the PV output current, whose value of $I_{in} = 8.15A$ with a small ripple value $I_{ripple} = 0.47A$. 
The output power of each PV panel is shown in figure 21 with 250W for irradiation of 1000W/m² and temperature of T = 25°C.

![Figure 21. PV panel output power.](image)

Figure 22 a&b shows the drive signal waveform of the MOSFET switches of a DC-DC flyback converter. To ensure the PV system at its maximum power point, the switching cycle varies accordingly. The value of the duty ratio is (0.596). Each sub-converter with phase shift 180°.

![Figure 22. The gate drive signal (a) Gate signal of subconverter1 (b) Gate signal of subconverter2.](image)

The value of duty ratio of flyback converter switch in steady state is shown in Figure 23. Figure 24, shows the average value of primary input current and the reference of PV current from **Figure 23. Duty ratio D in a steady state.**
the MPP tracker.

Figure 24. PV panel current and reference current.

Figure 25. shows the sector waveform generated in the system and Figure 26 shows the gate drive signal of third-harmonic current injection upper switch and lower switch.

Figure 25. Six sectors of design.

Figure 26. The gate drive signal of third-harmonic current injection circuit (a) for an upper switch (b) for a lower switch.
The current source inverter (CSI) is associated with the following waveforms. The current source inverter input voltage and three-phase output voltage shown in Figure 27.

![Figure 27. DC-link voltage and three-phase output voltages of micro-inverter.](image1)

The three-phase output current of the micro-inverter with third harmonic current injection is shown in Figure 28 at a rated power of 1000W. The measured third-harmonic current $i_y$ and the reference of the third-harmonic current injection estimated by math function $i_y^*$ are shown in Figure 29.

![Figure 28. Three-phase output current and injected third-harmonic current injection circuit](image2)
Figure 30, shows the waveforms of the full rated power condition of the micro-inverter, at which the output currents of the PV panel are set with PV power of each panel at $P_{PV1} = 250\text{W}$, $P_{PV2} = 250\text{W}$, $P_{PV3} = 250\text{W}$, $P_{PV4} = 250\text{W}$ respectively. Also, the wanted output displacement angle $\phi$ is 0. Figure 30 (a) shows the output voltage and output current of phase a, and figure 30 (b) shows the three-phase output current. The three-phase currents are nearest to sinusoidal waveform shape and in the equal phase with a three-phase output voltage. In this condition, the micro-inverter output power is 1000W and the unity power factor. THD of output current is 2.46%.

Figure 29. Waveforms of the micro-inverter working in full-power condition. (a) Output phase voltage and output phase current (b) three-phase output currents.
Figure 3.1. Micro-inverter waveforms with output reactive power of 268 Var and phase displacement angle 15° (a) output phase voltage and output phase current (b) three-phase output currents.

Figure 3.1, states that the suggested micro-inverter system can control the reactive power and the output current near sinusoidal. The figure shows the micro-inverter operated at the rated power of 1000W and the reactive power of 268 Var and the expected displacement phase angle is 15°. The THD of output current is 2.9%. Figure 3.1 (a) shows the output voltage with an output current of phase a. Figure 3.1 (b) shows the three-phase output currents.

Figure 3.2, shows the micro-inverter operated at a rated power of 1000W and reactive power of 577 Var and displacement phase angle of 30°. The THD of output current is 5.43%. Figure 3.2 (a) shows the output voltage with an output current of phase a, Figure 3.2 (b) shows the three-phase output currents.
When the micro-inverter is operated at the rated power of 1000W and the expected reactive power -268Var and displacement phase angle of -15°. The THD of output current is 5.41%. Figure 3 (a) shows the output voltage with an output current of phase a, Figure 3 (b) shows the three-phase output currents. The proposed system has good performance and simple in construction.

![Micro-inverter waveforms with output reactive power of 577Var and phase displacement angle 30° (a) output phase voltage and output phase current (b) three-phase output.](image)

**Figure 32.** Micro-inverter waveforms with output reactive power of 577Var and phase displacement angle 30° (a) output phase voltage and output phase current (b) three-phase output.

![Micro-inverter waveforms with output reactive power of -268Var and phase displacement angle of -15° (a) output phase voltage and output phase current (b) three-phase output currents.](image)

**Figure 33.** Micro-inverter waveforms with output reactive power of -268Var and phase displacement angle of -15° (a) output phase voltage and output phase current (b) three-phase output currents.
Figure 3(a) shows the dynamic response of reactive power when it changes from 0Var to 268Var to 577Var output current and Figure 3(b) shows the three-phase output currents during this change.

![Figure 3](image)

**Figure 3.** Dynamic response of reactive power during reactive power change (b) three-phase output currents during reactive power change.

Table 4 shows the comparison between two systems method of micro-inverter, the first method is based on DC-DC boost converter and the second is based on flyback converter and third-harmonic injection circuit technique.

| parameters                                                                 | Three-phase grid-connected PV module-integrated micro-inverter based on the DC-DC boost converter | Three-phase grid-connected photovoltaic micro-inverter based on third-harmonic injection technique |
|----------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
| THD of output current at full active power and zero reactive power          | 5.3%                                                                                             | 2.46%                                                                                           |
| THD of output current at 268Var and full active power and phase displacement angle of 15° | 6.477%                                                                                            | 2.9%                                                                                           |
| THD of output current at 577Var and full active power and phase             | 6.9%                                                                                             | 5.43%                                                                                           |
displacement angle of 30°
THD of output current at -268Var and full active power and phase displacement angle of -15°
Efficiency at full active power
DC-Link voltage at full active power
DC-Link current at full active power
Power factor at rated power and zero reactive power

7.23% 5.41%
90.76 % 95.07%
420V 297V
2.3643A 3.3A
0.9943 1

The table shows the THD of each system is estimated for full active power and zero reactive power, it obtained that the second system is best in THD value than the first system. The table shows the THD value of the system at full active power and different reactive power of (268Var, 577Var and -268Var), also the second system is best in THD value. By compared the efficiency of each system, the second system is more efficient than the first system.

The first stage in the second system, using flyback converter makes isolation between converter and PV panels, compared with the first system with no isolation. Also, the second system with fewer losses because it is not used PWM.

So, the second system is good in performance achieved a nearly sinusoidal output currents, a reactive power control, high efficiency, more reliability, reduction in THD, reduction in DC-Link capacitance value and show that balanced grid current can be guaranteed when compared with traditional reactive power topology of a PV system.

5. Conclusion
The design of control of reactive power for a three-phase micro-inverter is described by taken two systems design with different methods. In the first system design, the converter is composed of the interleaved DC-DC boost converter. A VSI is used as an integrated micro-inverter with a sinusoidal PWM strategy. Proper control of the associated boost converter such as DC voltage regulator and current controller allows injecting a three-phase current with desired reactive power control to the grid. In the second system design a second topology concept of a PV system, which presented the capability of control of reactive power for three-phase micro-inverter grid-connected. Four interleaved flyback converter are used in the DC-DC converter stage. The third-harmonic (3rd) injection circuit is used for controlling the third-harmonic injection current hence, an expected power factor correction is achieved. A line-commutated CSI inverter is designed for converting the direct current from a flyback converter to three-phase output currents that can be injected into the grid. The micro-inverter is can be operated with full power level (1000W). This proposed system is suitable for AC module PV system application and the micro-inverter has the ability to inject active and reactive power into the grid. The results using MATLAB Simulink environment show the validity of the design of the PV micro-inverter system and good dynamic performance of all controlled variables.

The simulation results shows that the suggested micro-inverter achieved the nearest sinusoidal three-phase output currents, a reactive power control. The second system is good in performance achieved nearly sinusoidal output currents, a reactive power control, high efficiency 95.07%, more reliability, reduction in THD of output current at full active power and zero reactive power is 2.46%, THD of output current at 268Var and full active power is 2.9%, THD of output current at 577Var and full active power is 5.43%, THD of output current at -268Var and full active power is 5.41%, reduction in DC-Link capacitance value and show that balanced grid current can be guaranteed when compared with traditional reactive power topology of a PV system in the first design.
Appendix A

Table. PV panel specifications.

| Parameters                                  | Value | Unit |
|---------------------------------------------|-------|------|
| Maximum power ($P_{\text{max}}$)            | 250   | W    |
| Current at maximum power point ($I_{\text{max}}$) | 6.96  | A    |
| Voltage at maximum power point ($V_{\text{max}}$) | 36    | V    |
| Short circuit current ($I_{\text{sc}}$)      | 8     | A    |
| Open circuit voltage ($V_{\text{oc}}$)       | 40.7  | V    |
| Shunt resistance ($R_{\text{sh}}$)           | 1000  | Ω    |
| Series resistance ($R_{\text{se}}$)          | 0.008 | Ω    |
| Temperature coefficient of $V_{\text{oc}}$   | -0.36099 | %/deg.C |
| Temperature coefficient of $I_{\text{sc}}$   | 0.102 | %/deg.C |
| Diode ideality factor                       | 1.2   |      |

Appendix B

Table. PV panel specifications.

| Parameter                                                      | Value     | Unit |
|---------------------------------------------------------------|-----------|------|
| Maximum power ($P_{\text{max}}$) for each PV panel           | 250       | W    |
| Current at maximum power point ($I_{\text{max}}$)             | 8.15      | A    |
| Voltage at maximum power point ($V_{\text{max}}$)             | 30.7      | V    |
| Short circuit current ($I_{\text{sc}}$)                       | 8.66      | A    |
| Open circuit voltage ($V_{\text{oc}}$)                        | 37.3      | V    |
| Shunt resistance ($R_{\text{sh}}$)                            | 224.1886  | Ω    |
| Series resistance ($R_{\text{se}}$)                           | 0.23724   | Ω    |
| Temperature coefficient of $V_{\text{oc}}$                    | -0.36901  | %/deg.C |
| Temperature coefficient of $I_{\text{sc}}$                    | 0.086998  | %/deg.C |
| Diode ideality factor                                         | 1.019     |      |

Reference

[1] Li Q and Wolfs P 2008 A review of the single phase photovoltaic module integrated converter topologies with three different DC link configurations *IEEE Trans. power Electron* 23 1320–33

[2] Bielskis E, Baskys A, and Valiulis G 2020 Controller for the grid-connected microinverter output current tracking *Symmetry (Basel)* 12 112

[3] Rodriguez C and Amaratunga G 2008 Long-lifetime power inverter for photovoltaic AC modules *IEEE Transactions on Industrial Electronics* 55 2593–2601

[4] Fawzy T, Premm D, Bletterie B, and Gorsek A 2011 Active contribution of PV inverters to voltage control—from a smart grid vision to full-scale implementation *Elektrotechnik und Informationstechnik* 128 110–115

[5] Howlader A, Sadoyama S, Roose L, and Sepasi S 2018 Distributed voltage regulation using Volt-Var controls of a smart PV inverter in a smart grid: An experimental study *Renewable Energy* 127 145–157

[6] Liu F, Kang Y, Zhang Y, and Duan S 2008 Comparison of P&O and hill climbing MPPT methods for grid-connected PV converter *3rd IEEE Conference on Industrial Electronics and Applications* 804–807

[7] Hu H, Harb S, Kutkut N, Batarseh I, and Shen Z 2012 A review of power decoupling techniques for microinverters with three different decoupling capacitor locations in PV systems
IEEE Transactions on Power Electronics 28 2711–26
[8] Parveen N and Rupesh K 2016 Design and simulation of interleaved DC-DC boost converter for three-phase loads using solar panel International Conference on Computation of Power, Energy Information and Communication 514–519
[9] Huang T, Shi X, Sun Y, and Wang D 2013 Three-phase photovoltaic grid-connected inverter based on feedforward decoupling control International Conference on Materials for Renewable Energy and Environment 2 476–480
[10] Wang H et al 2017 Topology and modulation scheme of a three-level third-harmonic injection indirect matrix converter IEEE Transactions on Industrial Electronics 64 7612–22
[11] Zhang G, Wang H, and Zhang C 2020 Modulated Model Predictive Control for 3TSMC IEEE Energy Conversion Congress and Exposition 4173–77
[12] Li Y and Oruganti R 2011 A low cost flyback CCM inverter for AC module application IEEE transactions on Power Electronics 27 1295–1303
[13] Nanakos A, Tatakis E, and Papanikolaou N 2012 A weighted-efficiency-oriented design methodology of flyback inverter for AC photovoltaic modules IEEE Transactions on Power Electronics 27 3221–33
[14] Feng J, Wang H, Xu J, Su M, Gui W, and Li X 2017 A Three-Phase Grid-Connected Micro-Inverter for AC Photovoltaic Module Applications IEEE Transactions on Power Electronics 33 7721–32
[15] Wang H et al 2015 Two-stage matrix converter based on third-harmonic injection technique IEEE Transactions on Power Electronics 31 533–547
[16] Lu C, Zhou B, Lei J, and Shan J 2019 Active Damping Control Strategy of Hybrid Active Third-Harmonic Injection Matrix Converter via Modifying Third-Harmonic Injection Reference Current and Output Reference Current 22nd International Conference on Electrical Machines and Systems 1–6
[17] Mohapatra A, Nayak B, and Saiprakash C 2019 Adaptive Perturb & Observe MPPT for PV System with Experimental Validation IEEE International Conference on Sustainable Energy Technologies 257