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Effect of Reactive Power Capability of the PV Inverter on the Power System Quality

Raghad Adeeb Othman[1], Omar Sharaf Al-Deen Al-Yozbaky[2]
[1,2]College of Engineering, Electrical Department, University of Mosul, Iraq

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ABSTRACT

Distributed generation (DG) based on a photovoltaic system (PV) connected to a power system is a very promising solution to meet the present demand for energy and to reap the advantages of using clean energy. With the exponential increase in the deployment of distributed energy sources based on renewable energy, the reactive power drawn from the grid has increased dramatically compared to the active power. This affects the quality of the power from the network. Reactive power is usually required to regulate the power factor and the grid voltage so as to improve the ability of the system to handle power. In this paper, the reactive power capability of a PV inverter connected to the grid was determined using the MATLAB/Simulink program. The amount of active power and reactive power injected into the network were independently controlled by their reference values. The study showed the effectiveness of the effect of injection/absorption of reactive power on raising/lowering voltage and improving power quality by reducing the Total harmonic distortion of the voltage and current under different operating conditions.

Corresponding Author:

Omar Sharaf Al-Deen Al-Yozbaky,
College of Engineering, Electrical Department,
University of Mosul, Iraq
Email: o.yehya@uomosul.edu.iq

1. INTRODUCTION

The depletion of conventional energy reserves, rising environmental concerns such as pollution and global warming, in addition to the volatility of oil prices, and the increasing demand for electricity worldwide have led to the need to find alternatives to traditional energy sources to overcome the challenges of a sustainable energy supply[1]. Renewable energy-based distributed generation systems have garnered a lot of interest as an alternative energy source that can be used to provide electricity to small or medium-sized businesses and homes. Solar energy has gained global attention for its immense potential and inexhaustible nature [2]. The amount of energy from the sun that reaches the Earth's surface in one day is ten times the total energy consumed by all the people on this planet in one year. PV, which is clean and pollution-free, has great potential for the supply of energy with minimal impact on the environment, in addition to several advantages, including the possibility of generating energy near to consumers to reduce energy losses, increased voltage levels, improved energy quality and reliability, reduced operating costs, and the creation of a more stable network [3] ،[4].

In recent years, the integration of a solar energy system with traditional electrical networks has witnessed a tremendous growth [5], reaching about 700 GW at the end of 2020 [6]. According to the renewable energy capacity statistics of the International Renewable Energy Agency (IRENA) (2022), as shown in Figure.1, China is currently the main producer of solar energy, followed by the United States, Japan and then, Germany. Also, the installed solar energy is estimated by the area shown in Figure. 2. In Asia, the installed solar energy is about 57.07% of the global total, and in Europe it is estimated at 22.79% of the global total, while the Middle East has the lowest installed solar energy of about 1.13% of the global total.

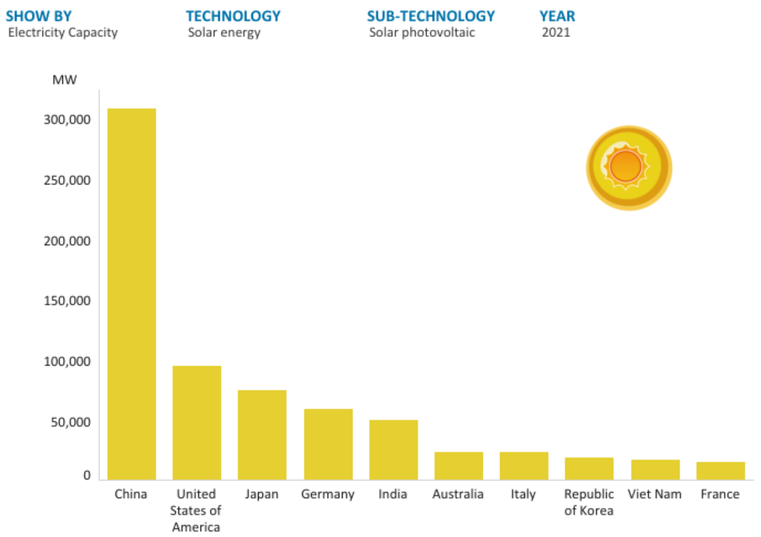

Figure 1. Solar Energy Capacity Growth Worldwide (Country Rankings)

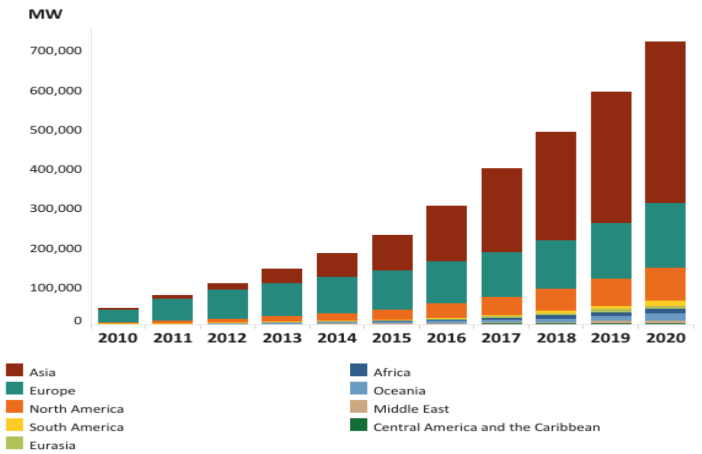

Figure 2. Trends in Solar Energy by Region

The interconnection of these DGs to the conventional grid is usually achieved through the use of power converters. The use of power converters provides significant benefits such as optimal operation and flexible control [7], in addition to the benefits offered by DGs, which include voltage support, reduced losses, high power quality and system reliability. Depending on the characteristics of both the system and the DG, customer bills can also be reduced by reselling the additional energy generated. Nevertheless, the introduction of DGs into the electrical network creates many problems [8] in terms of protection and safety issues, harmonic distortion, and transient issues [9].

In addition, PV systems efficiently inject power into the grid, thereby providing an effective solution to the increasing demand for energy[10]. On the other hand, the irregular supply of Photovoltaic (PV) energy can severely affect the complete distribution network, and also hinder the quality, reliability and availability of the network. Furthermore, if the production of the PV energy is higher than the domestic energy requirement [11], the complete distribution system loses control, and it is likely to reverse the power circulation through a distribution feeder or even a local substation, thereby damaging the utility grid. This can further affect some of the customer utilities that are powered by this distribution circuit, owing to unstable voltage [12].

Reactive power compensation is an actual solution to the challenges of voltage fluctuations and better power quality. Thus, PV inverters can be used as on-site VAR compensators that are responsive to changing loads to provide the reactive power to be absorbed by inductive loads. This could help in decreasing the voltage regulation problems, improving the power factor (PF) and grid stability, along with maximising the power transmission capacity after decreasing the power transmission losses. The customers could also save a lot of money as they would not have to invest in the equipment for controlling the PF [13].

From this perspective, and to study the effect of using a PV inverter to improve the power quality and power factor, and to reduce the Total Harmonic Distortion (THD) of a proposed distribution network, a solar photovoltaic system with a capacity of 100.725 KW was modeled. Using this model, the reactive power of the inverter was investigated in the mode of effective power injection, reactive power injection/absorption and in various environmental conditions using two stages, including the use of a DC-DC boost converter and an AC-DC inverter with a sinusoidal pulse-width modulation (SPWM) controller.

This paper is structured as follows: Section I is the introduction; Section II explains the classification of photovoltaic systems; Section III shows the importance of reactive power in the power grid; Section IV introduces a PV system model; Section IV represents the reactive power capability of the PV inverter; Section V discusses the simulation and results for different cases and conditions of operation; and finally, Section VI extracts the outcomes and gives the conclusions of this research.

2. GRID-CONNECTED PV SYSTEMS

PV systems are divided into 2 categories, The off-grid and on-grid PV systems. The off-grid systems do not depend in their work on the utility network. In the past few years, the on-grid PV systems have become more popular than the off-grid PV systems, thereby accounting for 99% of the overall capacity of the installed PVs. This is attributed to the fact that they can operate parallel to the electric utility grid and require no energy storage systems. Additionally, they resupply the power to the utility grid if the power that is generated exceeds the load requirements [14].

Thus, it is noted that the production of PV energy decreases the utilisation of other sources of energy supplied to the grid, like fossil fuels or hydroelectricity. Furthermore, The on-grid systems are more inexpensive and do not require a lot of maintenance and reinvestment, since they do not use batteries [15].

Solar PV systems that are connected to the grid are divided into two categories: (1) Single-stage; and (2) Double-stage power conversion systems. The single-stage power conversion system has a single control over the voltage amplification, grid-injected current, and maximal power point tracking systems. It makes use of a line frequency transformer for adjusting the power based on the weight and size of the device. However, the design of the inverter in the single-stage power conversion system is severely affected by poor power quality, low input voltage, and higher switching stress.

In this study, the researchers adopted the Double-stage power conversion system, wherein Stage 1 included the DC-DC boost converter that increased the PV voltage. Meanwhile, Stage 2 included a VSI voltage source conversion. As Stage 1 boosted the DC-DC converter, no transformer was needed during power conversion. Furthermore, for ensuring that maximal power was extracted in any situation, the researchers implemented a Maximum Power Point Tracking (MPPT) algorithm during the DC-DC converter phase. The output generated in this step was linked to a DC-AC voltage stage inverter that controlled the power transmission based on the requirements of the network [16]. Figure.3 depicts the design of the Double-stage solar energy system.

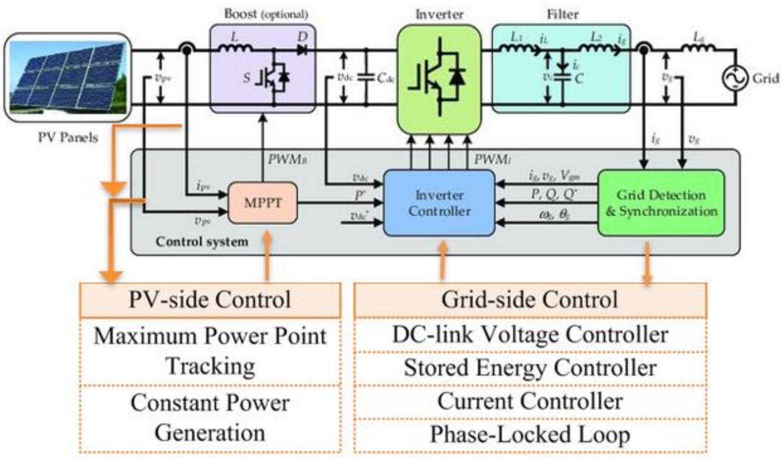

Figure 3. Double Stage Power Conversion

3. IMPORTANCE OF REACTIVE POWER

It is essential to apply the most favourable reactive power compensation process in the electric power generation system for maintaining the optimal engineering and economic conditions in the power system. The concept of reactive power compensation includes a wide and diverse range of system and customer-related issues, which are generally related to the power quality. The recent development of power electronics technology has led to the application of several non-linear loads that have increased the fluctuations in network voltage, thereby decreasing the power quality and affecting the proper working of the equipment. Hence, the reactive power compensation helps in enhancing the network's power factor, stabilising the voltage, decreasing voltage fluctuations, increasing the long-distance transmission ability and reducing power losses. The majority of the power quality issues can be handled by effectively controlling the reactive power [17].

The inductive load consumes reactive power (lagging PF), resulting in a drop in the network voltage profile. The angle between the active power and reactive power (θ) increases with the consumption of reactive power (-Q) by the inductive load, thereby lowering the power factor (Cos θ). This increases the load current and decreases the voltage and a simultaneous loss in network regulation. For compensating the reactive power consumption, reactive power (+Q) is injected, which decreases the value of the angle (θ) to a minimal value (i.e., increase in power factor) and reduces the load current, improving network regulation. It is worth noting that, for deriving the full benefits from the network, the reactive power compensation is done locally [16], as presented in Figure. 4.

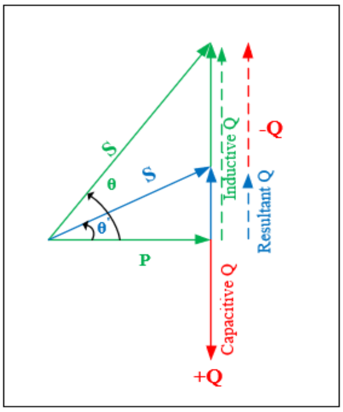

Figure 4. Power Triangle

The reactive power (leading PF) injection, which is generally done with a capacitor bank or FACTS device, elevates the voltage in the network. To maintain the grid voltage as a constant value, an electrical utility should always stabilise the reactive power consumption, locally. The wind power and PV systems are frequently combined to build hybrid power systems for lowering the installation costs. In this scenario, the low-power windmills use induction generators that utilise a lot of reactive power. As a result, a reactive power generation system is needed to improve the system power handling capacity, maintain grid voltage control, and compensate for the reactive power requirements by the wind generators and utility networks.

4. PV SYSTEM COMPONENTS

4.1. PV Array Model

A basic component of a photovoltaic system is the photovoltaic cell, which is a simple P-N junction diode that converts solar radiation into electricity. A group of photovoltaic cells are electrically connected to form a photovoltaic module (PV module). These PV modules are connected to form a panel. In a grid-connected PV system, a group of PV modules are configured in parallel and in series (Nss x Npp modules) to produce a PV array to generate the required current and voltage. The output of the PV array varies according to the inputs represented by solar radiation and temperature, where the standard inputs according to standard test conditions (STC) are 1000 W/m^2 of solar radiation at a temperature of 25^o Celsius[18].

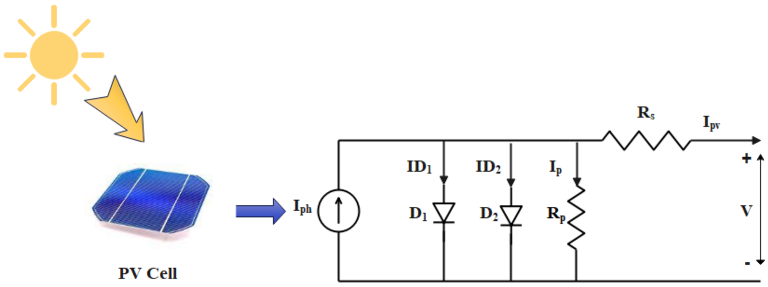

Figure 5. Equivalent Circuit of Solar PV Panel

In this study, the researchers modelled the PV cell circuit after combining the source current (I_{ph}), parallel resistance (R_p), and the series resistance (R_s). Furthermore, for overcoming the limitations of modelling the PV single diode at the high and low voltage values, a photocell was expressed using two diodes, (D_1) and (D_2). Figure.5 depicts the equivalent circuit, wherein D_1 reflects the diffusion process; D_2 denotes the space charge area in the Junction; Rs highlights the initial losses that are caused due to the current flow and contact leads; while R_p indicates the modelled reverse saturation current. The voltage-current properties of the solar cell are depicted using the equations below:

$$I_{pv} = I_{ph} - I_{d1} - I_{d2} - I_p \quad (1)$$

$$I_{pv} = I_{ph} - I_{01}\left[e^{\left(\frac{(V + I.R_S)}{\alpha_1.V_{T1}}\right)} - 1\right] - I_{02}\left[e^{\left(\frac{(V + I.R_S)}{\alpha_2.V_{T2}}\right)} - 1\right] - \frac{V + I.R_S}{R_p} \quad (2)$$

IPV = Photovoltaic current; k = Boltzmann constant = l.38 ×l0-23 J/K; q = charge on an electron = 1.602 ×10 -19 C; Iph = Photocurrent, as a function of irradiation level and junction temperature; I_{01}, I_{02}= Reverse saturation current of the Diodes, D1 and D2.; VT1, VT2 = the thermal voltages of PV module as given by $\left(\frac{N_S.K.T}{q}\right)$, where T = the temperature of the p-n junction in Kelvin; V = Cell output voltage; Ns = number of PV cells connected in series; α1, α2 = Ideality factors of diodes D1, D2;

$$I_{pv} = (I_{scn} + K_i\,\Delta T)\,\frac{G}{G_n} \quad (3)$$

Iscn = short circuit current at standard test conditions (STC); ki = current temperature coefficient; G = irradiation value which affects the panel; Gn = irradiation of the solar panel at 1000 W/m2 s; ΔT = T - Tn, where T = surface temperature of panel and Tn = temperature at STC, i.e., 25 oC. In this paper, a SunPower SPR-305E-WHT-D PV array was designed. The parameters of this model are shown in Table 1, Figure.6 shows the characteristic I-V curve, and Figuer. 7 the characteristic P-V curve.

Table 1 PV Module Specifications (SUNPOWER SPR-305E-WHT-D)

Parameter	Value
Maximum Power (W)	305.226
Voltage at Maximum Power (Vmp)	54.7 V
Current at Maximum Power (Imp)	5.58 A
Open Circuit Voltage (Voc)	64.2 V
Short Circuit Current (Isc)	5.96 A
Total No.of Cells in Series (Ns)	5
Total No.of Cells in Parallel (Np)	66
Temperature Coefficient of Voc (Kv)	-272.7 mV/oC
Temperature Coefficient of Isc(Ki)	61.745 mA/oC
Diode saturation current (Io)	6.3076×10-12 A
Parallel resistance (Rp)	393.2054 Ω.
Series resistance (Rs)	0.37428 Ω
Maximum Power (kW) (PV Array)	100.725 KW
Voltage at Maximum Power (Vmp) (PV Array)	273.5 V
Current at Maximum Power (Imp) (PV Array)	368.28 A
Open Circuit Voltage (Voc) (PV Array)	321 V
Short Circuit Current (Isc) (PV Array)	399.432 A

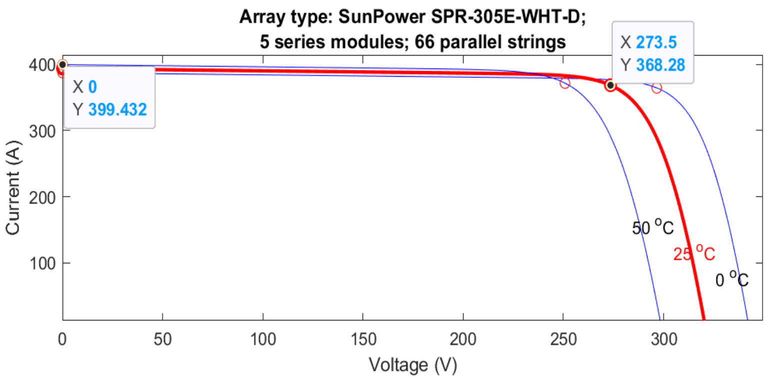

Figure 6. I-V Characteristic Curve of a PV Module

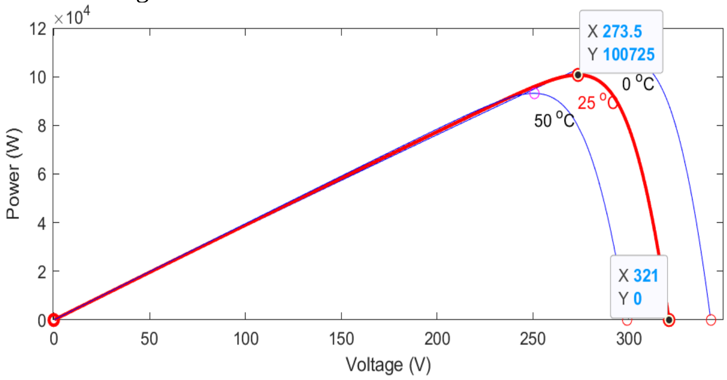

Figure 7. P-V Characteristic Curve of a PV Module

4.2. DC-DC Boost Converter

The output of the PV array served as the input for the DC-DC boost converter to increase the voltage and decrease the current [19]. Here, the researchers used a boost converter to achieve Maximum Power Point Tracking (MPPT) for enhancing and managing the PV array output voltage, as illustrated in Figuer.8. Theoretically, maximum power is transferred from the source to the load when the load impedance matches the impedance of that source. This was achieved by adjusting the duty cycle of a DC-DC boost converter. A duty cycle is described as a ratio of the switch on time to the overall switching period. For extracting the maximal power from a PV array, the duty cycle of a DC-DC boost converter is adjusted to the variable weather conditions. Compared to the different configurations, the boost converter offers many advantages, like cost-effectiveness, simple structure, high efficiency and very reliable.

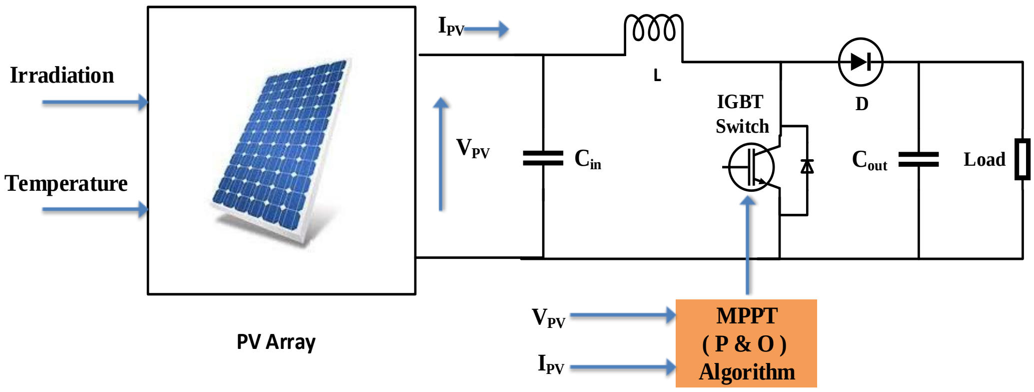

Figure 8. The Schematic of the DC-DC Boost Converter

4.3. MPPT Technique

The efficiency of a PV power generation system can be improved after controlling the PV array such that a maximal amount of available power is generated under varying environmental conditions. The Maximum Power Point Tracking (MPPT) technique is seen to be a self-optimisation procedure that uses algorithms for ensuring that a PV array is operational at the MPP [20]. MPPT is described as the non-linear feature of a solar PV module. It comprises a single maximum power point that is based on the intensity of the temperature and radiation in the cell. The solar panels do not display a high efficiency. Since the PV voltage and current increase at higher radiation levels, it also leads to an increase in the output power of the PV array. However, if the temperature of the cell increases at a steady solar radiation intensity, the PV current increases marginally with a sudden decrease in the PV array voltage which further decreases its output power. Hence, MPPT can be used for enhancing solar panel efficiency. The MPPT is used in the DC-DC converters that connect the load and PV array for optimising the alignment of the system. The MPPT controller has 2 inputs, i.e., output voltage and output current in the solar array. These inputs help in generating the control signals that offer power to the IGBT switches in the DC-DC converter. In the past, several researchers have applied the Perturbation and Observation (P&O) and the Incremental Connectivity (IC) algorithms for MPPT modelling owing to their basic structure. The IC-MPPT algorithm can track the varying conditions faster compared to the P&O MPPT algorithm, however, it needs an expensive and complicated controller and also produces a slightly unstable output power. On the other hand, the output power in the P&O algorithm fluctuates around MPP [21]. In this study, the researchers have used the P&O technique. Figuer. 9 presents the P&O algorithm that is used in the MPPT technique for controlling the PV generator. It displays a basic structure, is cost-effective, easily implemented, requires fewer parameters and can be easily improved to become more efficient [22].

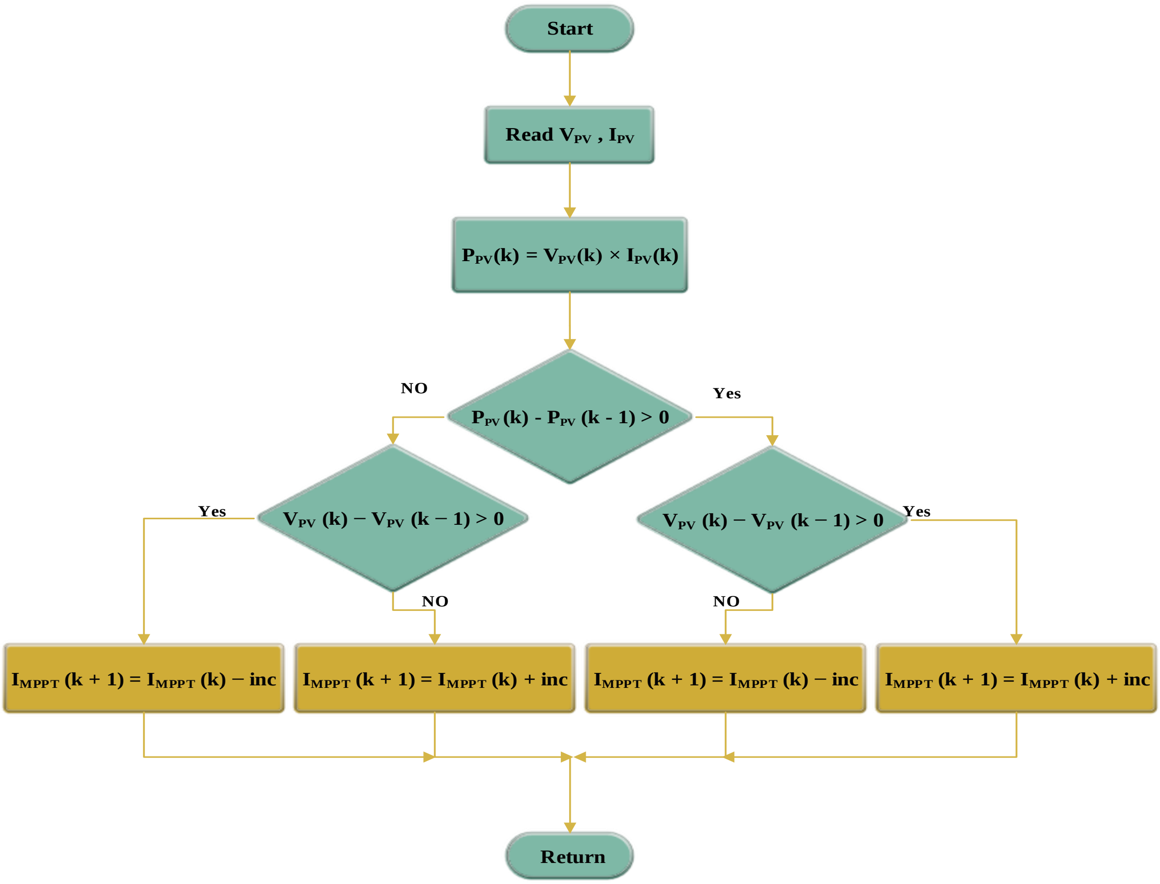

Figure 9. Flowchart of P&O MPPT Technique

This algorithm helps in determining the connection between the output voltage and power in the PV module. In this technique, the voltage of the PV module terminal is periodically disturbed and the output power of the PV array is compared to the earlier perturbation cycle [23]. When the operating voltage in the PV module is changed and output power increased, the operating point in the control system shifts in that direction; otherwise, it shifts in the opposing direction. The current and voltage values in the PV array are estimated and the voltage and current output help in determining the actual power of this PV module. Thereafter, it determines the state and assesses if P = 0 or not. When this condition is satisfied, the trigger point is seen to be the MPP. On the other hand, if the condition is not satisfied, it checks a different condition, i.e., if $\Delta P > 0$. If this condition gets fulfilled, the algorithm determines if $\Delta V > 0$. When that condition is also fulfilled, it is noted that the operating point lies on the left side of MPP. If the condition of

ΔV > 0 is unsatisfied, the operating point is seen to lie on the right side of the MPP. This procedure is constantly repeated until MPP is reached, as depicted in Figure 10.

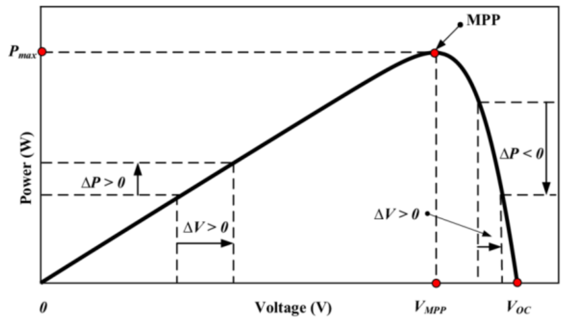

Figure 10. Curves of P&O MPPT Technique

4.4. Voltage Source Inverter (VSI) Model with Controller Model

In the case of Double-stage grid-connected PV systems, the DC-AC inverter or VSI is primarily used for converting the PV array's output power from the DC to AC, synchronising the grid while also controlling the DC output voltage in the boost converter. A 3-phase Voltage Source Inverter (VSI) in the on-grid PV system is equipped with an Insulated Gate Bipolar Transistor (IGBT), Gate Turn-Off thyristor (GTO) or a Metal Oxide Semiconductor Field-Effect Transistor (MOSFET). The inverter topologies are categorised into 2 types, i.e., single-level and multi-level inverters. The single-level inverter presents many advantages like cost-effectiveness, higher efficiency, better performance, more reliability and a basic structure. However, the multi-level inverter can accept the input voltage variations, Although it, displays an isolated and complicated structural topology with high-frequency transformers that extract power from the source, despite the low DC voltage.

Figuer.11 presents the design of an inverter controller system that generated the Pulse-Width Modulation (PWM) for synchronising the grid and PV system. The control system included a DC voltage regulator, Phase Lockup Loop (PLL) block, current controller block, and the PWM signal generation block.

The PLL could convert the 3-phase time-varying system into all components of a DC system, with voltage components ([Vd, Vq] and current components [Id, Iq]. The system measured the DC components in addition to the phase angle of the grid that is used for grid synchronisation [24]. The DC voltage regulator generates the current reference of Id, which further produced an instantaneous PV power from an inverter as the active power. Controlling the grid-side converter (3-phase PV inverter) was vital in regulating the DC link voltage so that the power balance between the power grid and PV array can be maintained. This also ensured the power quality that is generated after controlling the injected current in the grid. The current controller output produced the Vd and Vq references depending on the Id references and Iq references using the measured Id, Iq and Vd, Vq values from PLL. The PWM signal is produced depending on 3 modulating signals that are produced by Vd and Vq. The Iq current reference is generated from a reactive power controller for regulating the voltage at the Point of Common Coupling (PCC), within admissible limits, after generating a relevant reactive power from the inverter [12].

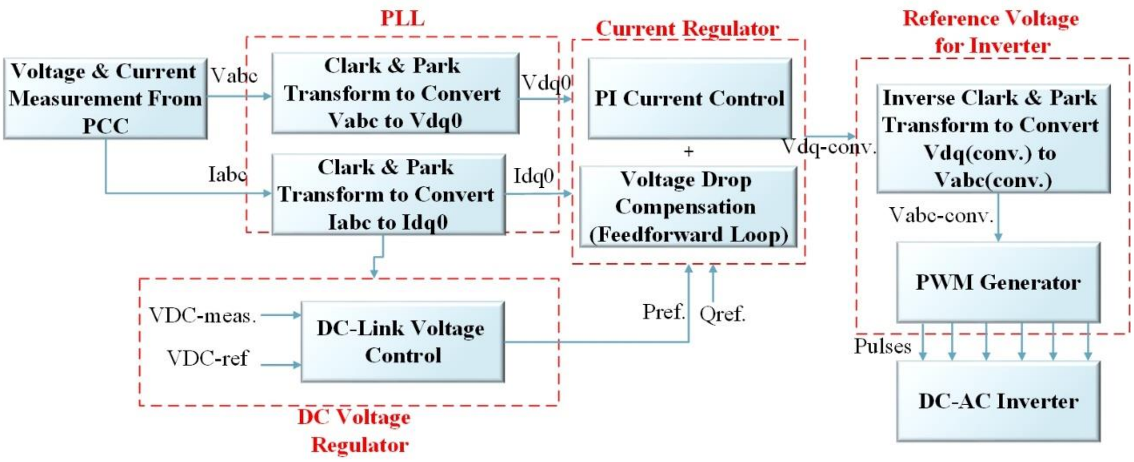

Figure 11. VSI Controller Model

The reactive power controller guides the inverter for offering or absorbing reactive power depending on the necessary conditions. The reactive power control is related to the voltage behaviour at PCC and is affected by the drawbacks of this inverter [25]. The voltage at PCC is measured constantly and the algorithm estimates the accurate Iq reference based on the instantaneous PV power for determining the voltage and improving the PF at PCC. The researchers set the value of the reactive power reference at 0 in the algorithm since the power is injected at the power factor of 1 [16].

4.5. Inverter with Reactive Power Capability

The power grid can be made more reliable and efficient through the use of advanced inverters, combined with distributed generation. The PV system provides reactive power for 24 hours, irrespective of the time of the day, without decreasing the real power output.

As long as the provision of reactive power is properly offset, there will be an important shift in the driving of these utilities as reactive power is dynamically supplied where it is most needed near the loads. The researchers in Oak Ridge National Lab noted that the distributed voltage control was significantly better than the centralised voltage control. Regulation of the distributed voltage presents an efficient system, without any power outages. The advanced inverters are programmed to override the minor voltage fluctuations, which eliminates the need for additional network disconnections. As the advanced inverters were cost-effective compared to the conventional voltage regulation options, the customers and utilities are served better by the implementation of a novel technology.

In this work, the power quality of the inverter was investigated by analysing its reactive power injection/consumption capability under different operating conditions. Figuer.12 shows the reactive power capability of the inverter. The inverter was able to operate in the (+Q) mode when there was a shortage of reactive power generation by the grid where reactive power is required. The inverter was also able to operate in the (-Q) mode to reduce the grid voltage, where P, Q, and S were the active, reactive and apparent power, respectively of the inverter. The inverter produced a maximum active power (S = Pmax) when the reactive power was zero at Unity Power Factor (UPF). The inverter was only able to produce a maximum reactive power (S = Qmax) when the active power was zero and θ = 90 degrees.

The reactive power could be controlled by changing the value and angle of the inverter output voltage, and the directional control of the inverter voltage was attained by changing the Iq reference to control the reactive power output of the inverter. One of the most important advantages of using an inverter to generate/absorb reactive power is the possibility of operating the inverter in the VAR mode at low levels of solar radiation subject to climatic conditions. Thus, it improves the use of solar photovoltaic energy and reduces the additional cost to compensate for the reactive capacity.

The P-Q relationship of the inverter is given in Equation (4),

$$Q_{inv.} = \sqrt{S_{inv.}^{\ 2} - P_{pv}^{\ 2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

where $S_{inv.}$ is the capacity of the inverter, P_{pv} is the instantaneous PV power of the PV array, and $Q_{inv.}$ is the reactive power of the inverter.

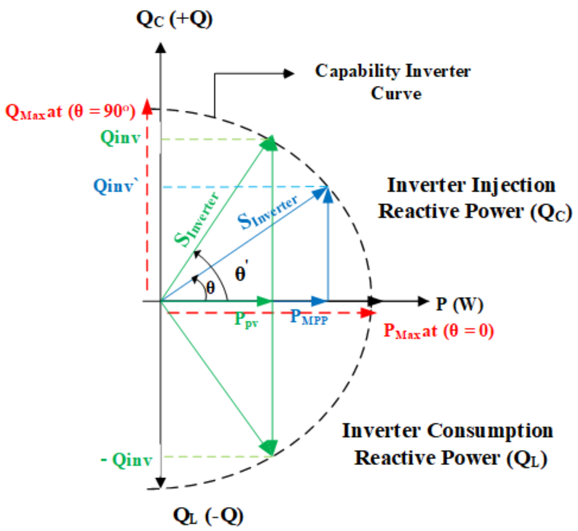

Figure 12. Two Quadrant Operation of P.V. Inverter

5. SIMULATION AND RESULTS

The model of the Double-stage grid-connected photovoltaic system in MATLAB/Simulink is shown in Figuer.13. The model consisted of a 100-KW PV array [SUNPOWER SPR-305E-WHT-D] connected to a DC boost transformer for maximum power point tracking using a P&O algorithm. Then, the system was connected to a 3-level NPC inverter with two capacitors connected in series with a value of 12,000 µF for each capacitor to form a DC-link between the two stages, and to reduce distortion in the inverter output voltage, An LC filter was used. The output of the inverter was connected to the distribution network via a transformer (260/25K) V.

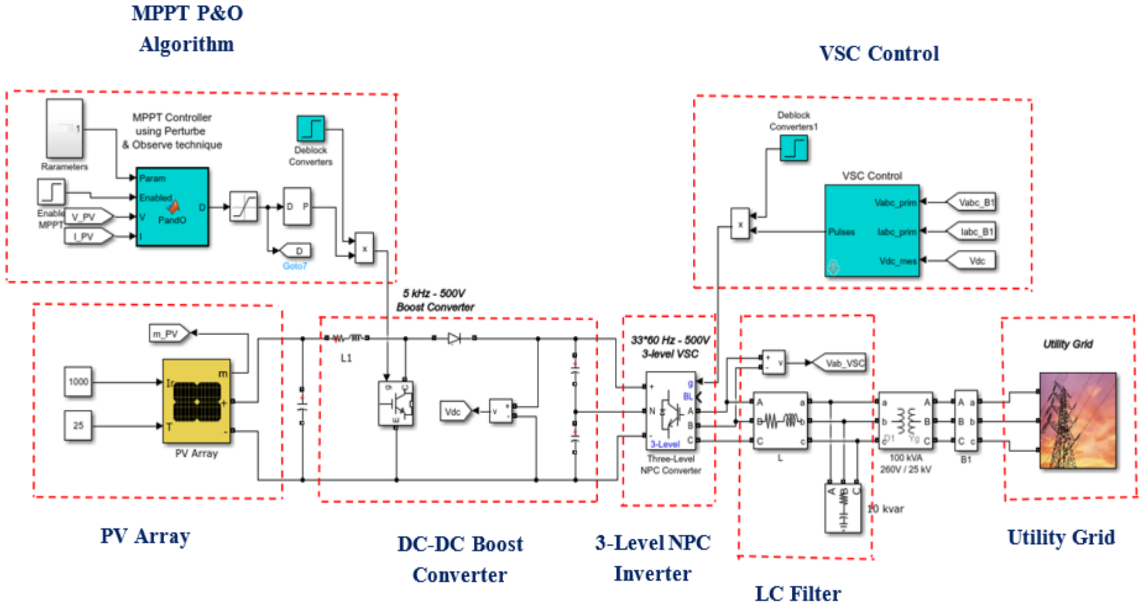

Figure 13. Simulation Model of The Three-Phase Grid-Connected PV System

At STC, and without the reactive power of the inverter having any effect on the grid, Figuer.14 shows the per phase (RMS) voltage and current at PCC, Figuer.15 shows the inverter output voltage, and Figuer. 16 shows the active and reactive power at PCC

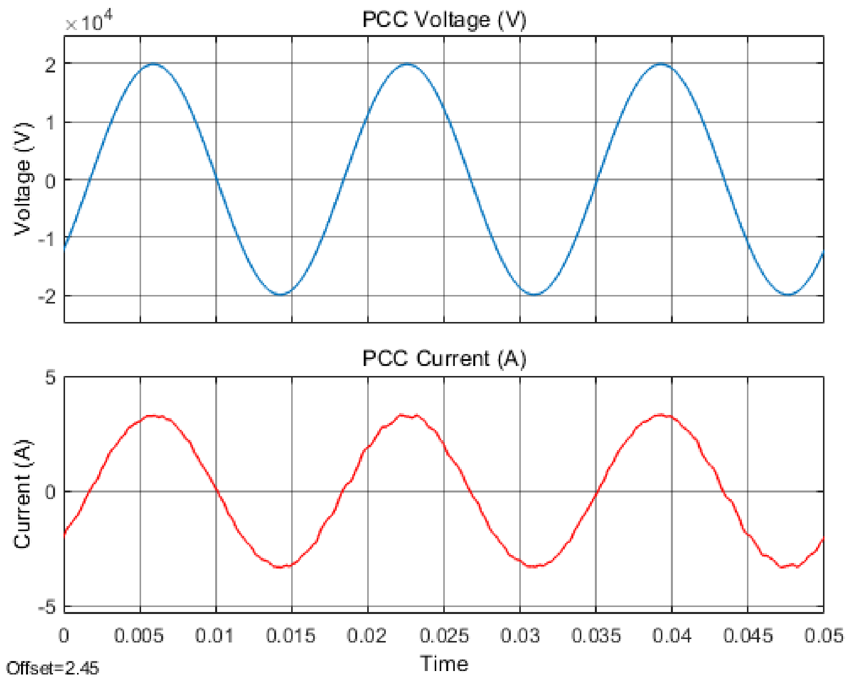

Figure 14. PCC Voltage & Current at STC Without Reactive Power Compensation

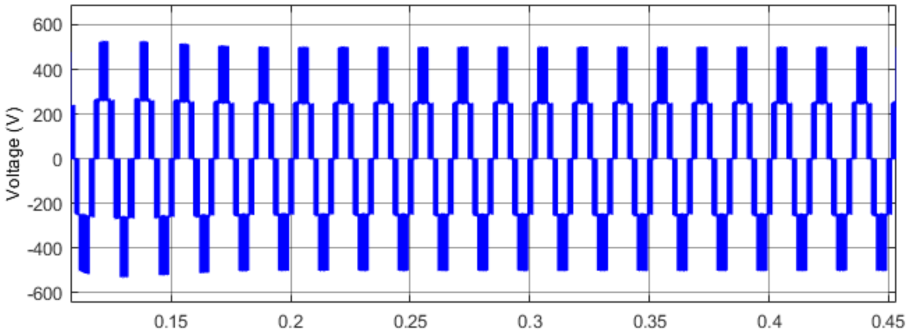

Figure 15. Inverter Output Voltage at STC Without Reactive Power Compensation

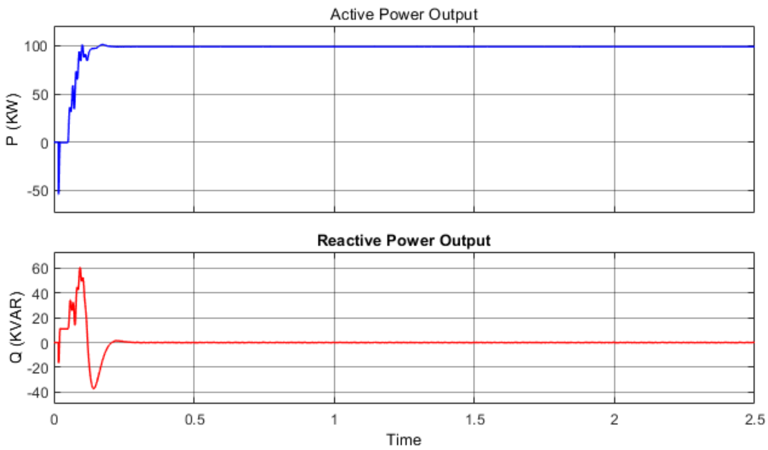

Figure 16. Active & Reactive Power in PCC at STC Without Reactive Power Compensation

In this work, the reactive power reference to represent the reaction power injection mode varied from (0 to -1). Similarly, the reactive power reference varied from (0 to 1) when observing the maximum reactive power consumed by the inverter. Figuer. 17 and Figuer. 18 show the active and reactive power at PCC, at injection reactive power values of QRef. = - 0.2, QRef. = - 1, respectively. Figuer. 19 and Figuer.20 show the active and reactive power at PCC at absorption reactive power values of QRef. = 0.2, QRef. = 1, respectively.

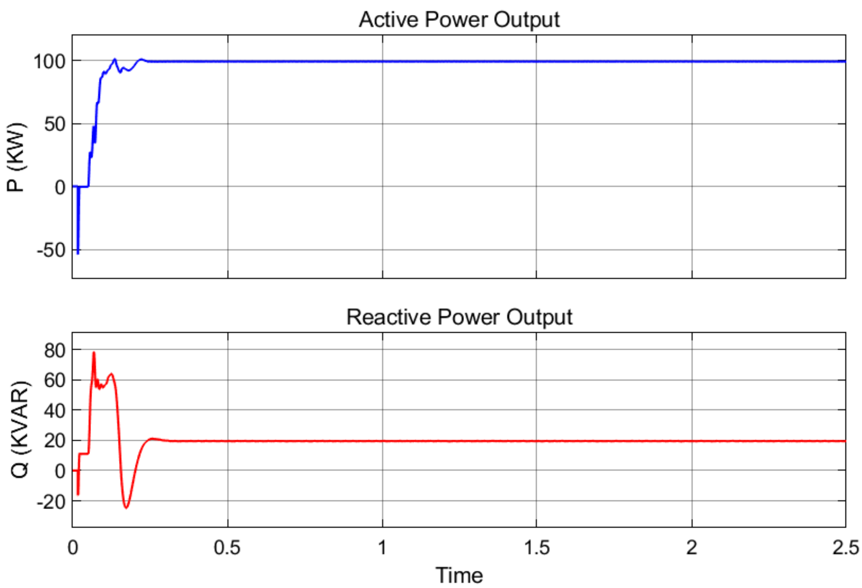

Figure 17. Active & Reactive Power in PCC at STC at QRef. = - 0.2

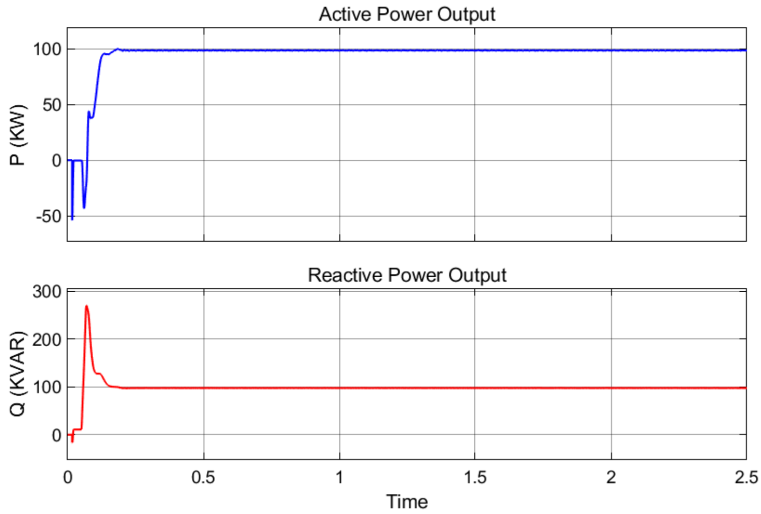

Figure 18. Active & Reactive Power in PCC at STC at QRef. = - 1

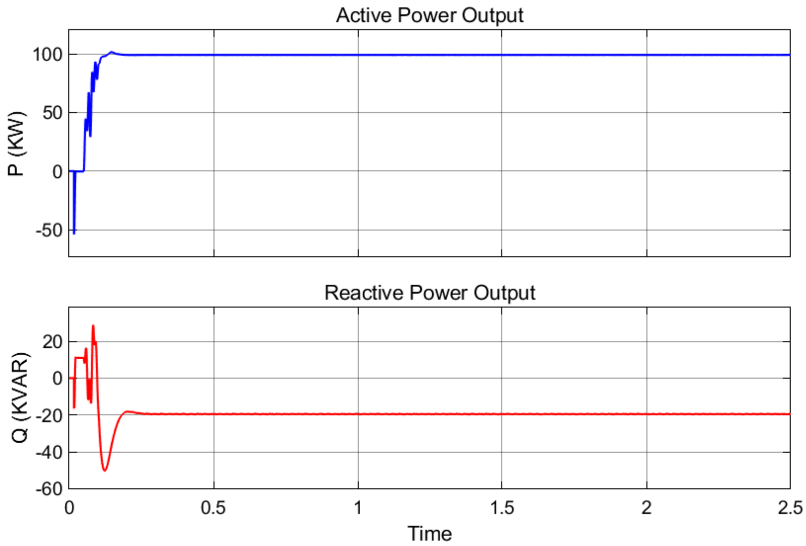

Figure 19. Active & Reactive Power in PCC at STC at QRef. = 0.2

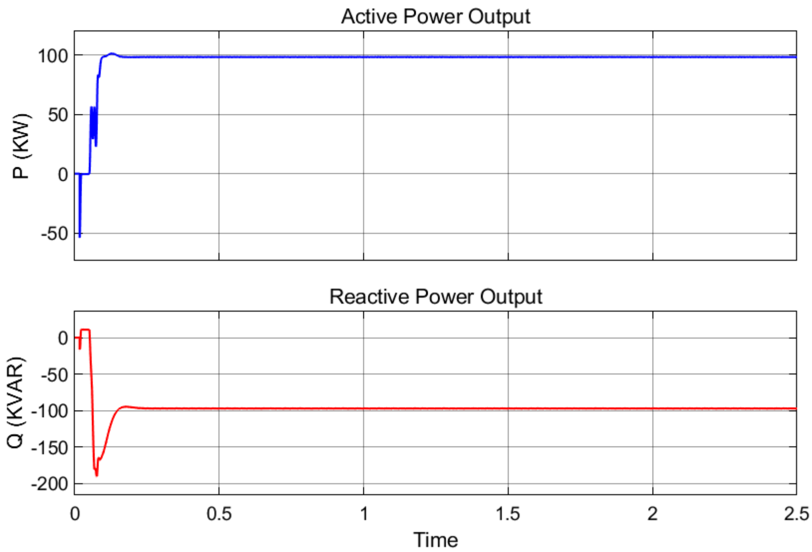

Figure 20. Active & Reactive Power in PCC at STC at QRef. = 1

Table 2 presents the influence of the reactive power injection mode/absorption mode in the inverter on the power factor, as presented in Figure. 21. The voltage total harmonics distortion (THD) also turned out to be within the permissible limit of the IEEE STD 519-1992 as shown in Figure. 22. The current harmonics were high if the reactive power reference was set at 0 (at UPF), and this was decreased if the system was operated in a reactive power injection mode /absorption mode as shown in Figure.23. Thus, it was noted that the inverter's reactive power Effectively affected on the grid output's power quality.

Table 2 Analysis of The Reactive Power Ability of the Grid-Connected PV Inverters in The Different Inverter Modes at STC Conditions

QRef.	PPV (KW)	P at PCC (KW)	Q at PCC (KVAR)	Phase Voltage (R.M.S) at PCC (KV)	Power Factor	THD Voltage (%)	THD Current (%)	Inverter Mode Operation
-1	100.713	98.49	97.55	14.09	0.7105	0.05493	1.919	Injection Reactive Power (+Q)
-0.9	100.713	98.54	78.80	14.09	0.7470	0.06317	2.528	
-0.7	100.713	98.69	68.25	14.08	0.8225	0.06036	2.626	
-0.5	100.713	98.89	48.9	14.08	0.8967	0.05634	2.633	
-0.3	100.713	99.01	29.38	14.07	0.9588	0.05267	2.644	
0	100.713	99.09	0.09	14.07	1	0.04617	2.422	Unity Power Factor
0.3	100.713	98.99	-29.23	14.06	0.9592	0.05357	2.698	Absorption Reactive Power (-Q)
0.5	100.713	98.92	-48.65	14.06	0.8974	0.05542	2.583	
0.7	100.713	98.73	-68.18	14.05	0.823	0.05516	2.346	
0.9	100.713	98.59	-87.56	14.05	0.7477	0.04620	1.715	
1	100.713	98.52	-97.31	14.05	0.7115	0.04523	1.551	

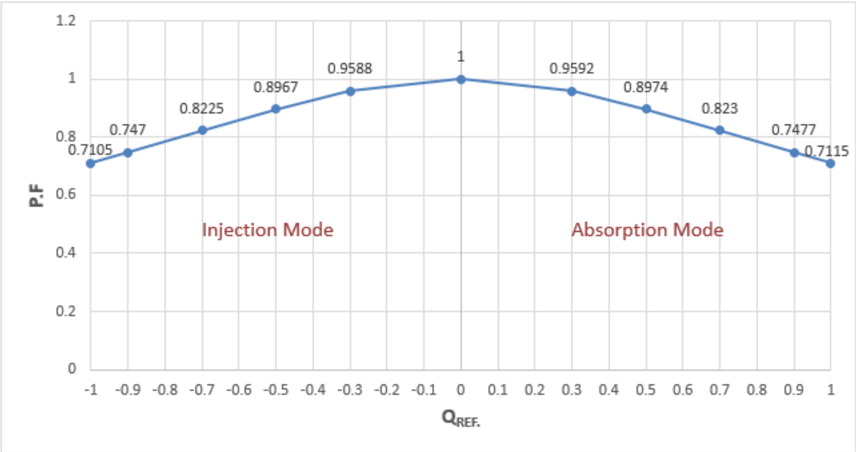

Figure 21. Relation Between Qref. (Injection/Absorption) & Power Factor at STC

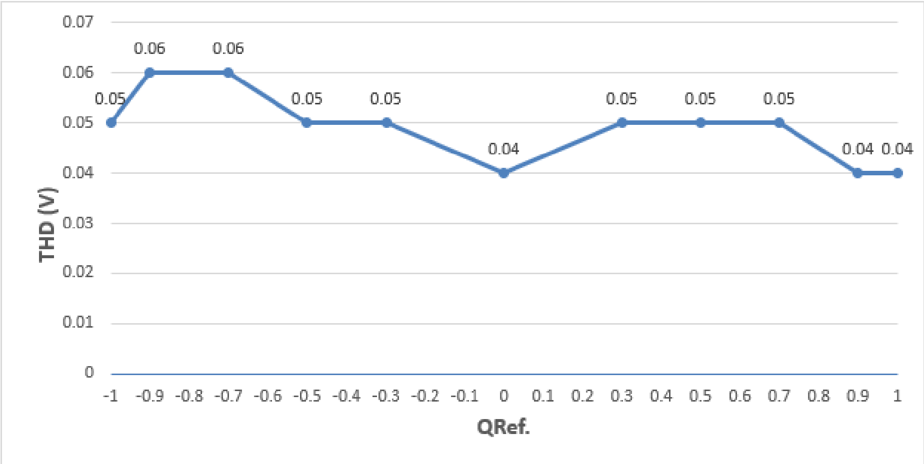

Figure 22. Relation Between QRef. (Injection/Absorption) & Voltage THD at STC

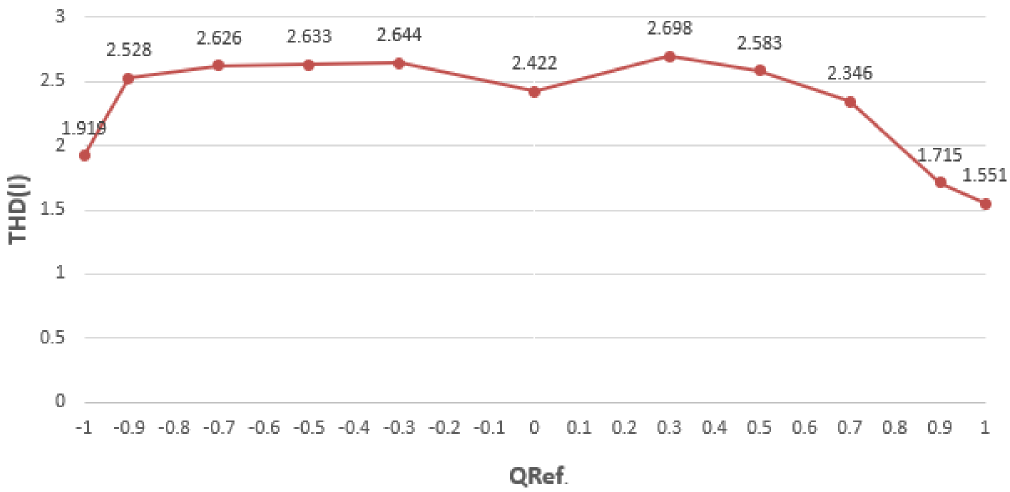

Figure 23. Relation Between QRef. (Injection/Absorption) & Current THD at STC

It was noted from the results shown in Figuer. 24 that the injection of reactive power to the grid led to an increase in the grid voltage profile, and the absorption of reactive power led to a decrease in the grid voltage. This type of local reactive power compensation results in grids with better voltage regulation and stability.

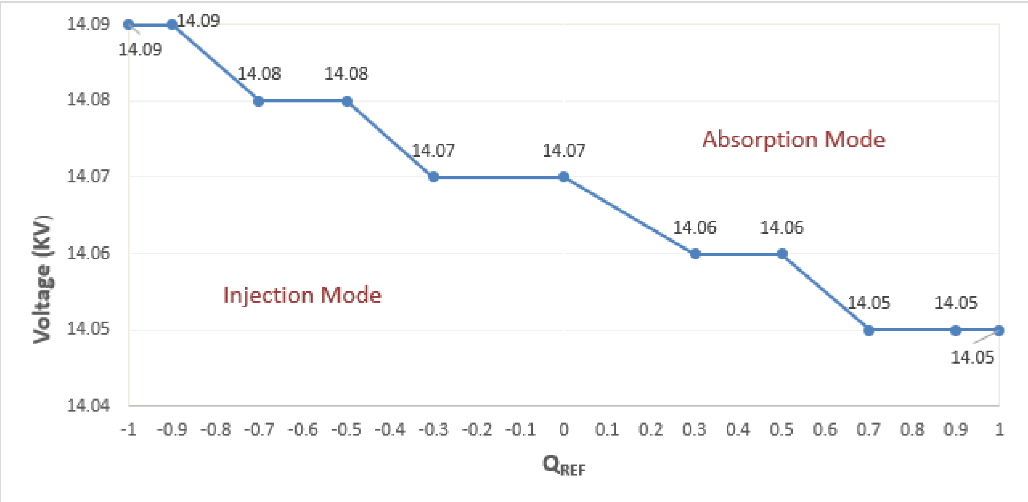

Figure 24. Relation Between QRef. (Injection/Absorption) & PCC Voltage at STC

It was clear from Table 2 and Table 3 that the PV that was connected to a inverter was able to inject the reactive power at a maximum inverter capacity when the PV power was available or in a night mode (PV power was unavailable).

Table 3 Reactive Power Capability Analysis of Grid-Connected PV Inverter in Different Inverter Mode at Night Mode Irradiation

QRef.	PPV (KW)	P at PCC (KW)	Q at PCC (KVAR)	Phase Voltage (R.M.S) at PCC (KV)	Power Factor	THD Voltage (%)	THD Current (%)	Inverter Mode Operation
-1	0	-0.93	97.55	14.08	-0.009245	0.05793	2.996	Injection Reactive Power (+Q)
-0.8	0	-0.69	78.13	14.08	-0.008592	0.05680	3.68	
-0.5	0	-0.54	48.83	14.07	-0.01077	0.04641	4.652	
-0.2	0	-0.38	19.56	14.07	-0.01836	0.04105	9.86	

During the VAR mode, as shown in Table 4, the inverter also injected a maximum reactive power of 97.55 KVAR at 2.996 % of THD of the current. This improved the utilization of the system since the P.V. inverter was also able to produce power at night for the regulation of the grid voltage.

As shown in Table 4, there was considerable total harmonics distortion (THD) of the current when the level of solar irradiation was low in the PV array or there was low power in the injection mode. The THD of the current was higher in the low-power mode (in the evening), as shown in Figuer. 25.

Table 4 Capability Analysis of Grid-Connected PV Inverter at Different Irradiation at QRef. = 0

Irradiation (W/m2)	PPV (KW)	P at PCC (KW)	Q at PCC (KVAR)	Phase Voltage (R.M.S) at PCC (KV)	Power Factor	THD Voltage (%)	THD Current (%)
800	80.44	79.36	-0.08	14.07	1	0.04950	3.263
600	60.06	59.35	-0.06	14.07	1	0.04345	3.543
400	39.67	39.09	-0.01	14.06	1	0.04537	5.789
200	19.4	19.0	-0.01	14.06	1	0.03546	8.354
100	9.433	9.07	-0.06	14.06	1	0.03808	19.73

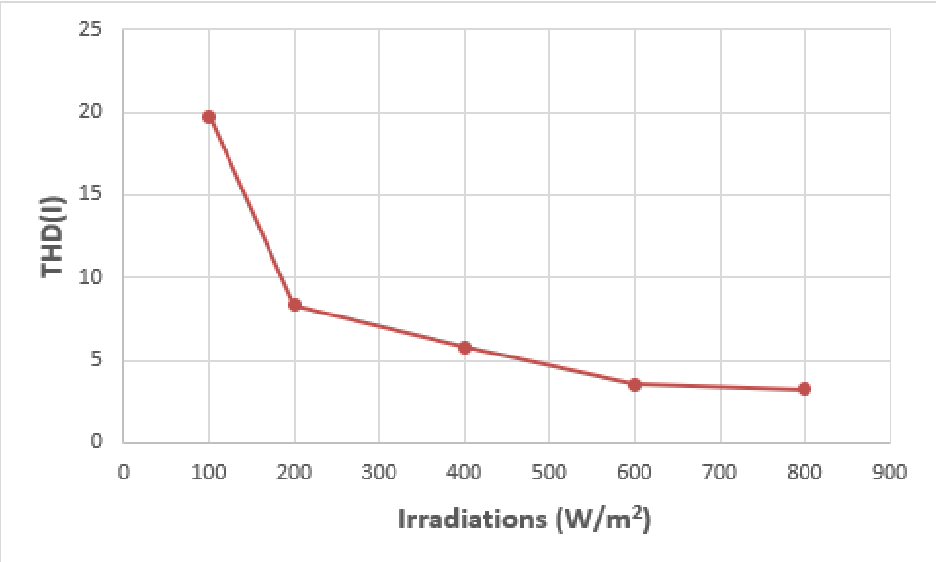

Figure 25. Relation Between Solar Irradiations & Current THD

Therefore, the necessary harmonics compensation should be made when operating at low power levels. The highest current harmonics in this mode was 19.73% at a solar irradiation of 100 W/m2.

6. CONCLUSION

In this study, the researchers analysed the 100-kW solar PV system that was connected to the grid, for determining the active and reactive power ability of the system during daytime. They operated this system in the VAR mode only if the PV power was unavailable. They simulated the PV power system using the MATLAB/Simulink software and then analysed all the system characteristics. The reactive power injection enhanced the grid voltage, while the positive reactive power mode reduced the grid voltage. The researchers noted that the reactive power mode was beneficial if the local grid voltage was to be regulated. The quality of the power in the PV inverter in both modes was analysed. The THD value of the voltage remained within the permissible limit of 0.05%. The THD value of the current was also within the permissible limit in the reactive power consumption/ injection mode. The power quality was poor at 19.73% (higher THD of the current) when the inverter operated at low power generation and low solar irradiation.

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REFERENCES

[1] Ram JP, Manghani H, Pillai DS, Babu TS, Miyatake M, Rajasekar N. Analysis on solar PV emulators: A review. Renew Sustain Energy Rev. 2018;81(May 2016):149–60.

[2] Sudhakar Babu T, Prasanth Ram J, Sangeetha K, Laudani A, Rajasekar N. Parameter extraction of two diode solar PV model using Fireworks algorithm. Sol Energy. 2016;140:265–76.

[3] Cabana K, Candelo J, Castillo R, De-La-Hoz-Franco E. Voltage sensitivity analysis to determine the optimal integration of distributed generation in distribution systems. Int J Electr Comput Eng. 2019;9(1):55–65.

[4] Sankar RRS, Kumar JSV, Rao MG. Adaptive fuzzy PI current control of grid interact PV inverte. Int J Electr Comput Eng. 2018;8(1):472–82.

[5] Parida B, Iniyan S, Goic R. A review of solar photovoltaic technologies. Renew Sustain Energy Rev. 2011;15(3):1625–36.

[6] Nwaigwe KN, Mutabilwa P, Dintwa E. An overview of solar power (PV systems) integration into electricity grids. Mater Sci Energy Technol. 2019;2(3):629–33.

[7] Gayatri MTL, Parimi AM, Pavan Kumar A V. A review of reactive power compensation techniques in microgrids. Renew Sustain Energy Rev . 2018;81(August 2017):1030–6.

[8] Ren BY, Tong XQ, Tian S, Sun XD. Research on the control strategy of inverters in the micro-grid. Asia-Pacific Power Energy Eng Conf APPEEC. 2010;(09):0–3.

[9] Radwan E, Nour M, Baniyounes A, Al-Olimat KS, Awada E. Direct control of active and reactive power for a grid-connected single-phase photovoltaic inverter. Int J Power Electron Drive Syst. 2021;12(1):139–50.

[10] Kalaf AA, Alyozbaky OS, Alghannam AI. A modern technique to manage energy profile in Iraq: Virtual power plant (VPP). J Phys Conf Ser. 2021;1973(1):1–10.

[11] Tonkoski R, Lopes LAC. Voltage regulation in radial distribution feeders with high penetration of photovoltaic. 2008 IEEE Energy 2030 Conf ENERGY 2008. 2008;(Lv).

[12] Kolhe ML, Rasul MJMA. 3-Phase grid-connected building integrated photovoltaic system with reactive power control capability. Renew Energy . 2020;154:1065–75.

[13] Dhaneria A. Grid connected PV system with reactive power compensation for the grid. 2020 IEEE Power Energy Soc Innov Smart Grid Technol Conf ISGT 2020. 2020;

[14] Kouro S, Leon JI, Vinnikov D, Franquelo LG. Grid-connected photovoltaic systems: An overview of recent research and emerging PV converter technology. IEEE Ind Electron Mag. 2015;9(1):47–61.

[15] Zeb K, Uddin W, Adil M, Ali Z, Umair M, Christo N, et al. A comprehensive review on inverter topologies and control strategies for grid connected photovoltaic system. Renew Sustain Energy Rev. 2018;94(November 2017):1120–41.

[16] Kalaivani BVL. Modeling and Power Quality Analysis of Grid Connected PV Inverter with Active and Reactive Power Injection Mode. J Electr Eng Technol. 2021;16(3):1375–87.

[17] Zhou X, Wei K, Ma Y, Gao Z. A review of reactive power compensation devices. Proc 2018 IEEE Int Conf Mechatronics Autom ICMA 2018. 2018;2020–4.

[18] Gonzalez D, Paja CAR, Montes AJS, Zuluaga EIA, Carrejo CE. Modeling and control of grid connected photovoltaic systems. Rev Fac Ing. 2012;3(62):145–56.

[19] Atiq J, Soori PK. Modelling of a grid connected solar PV system using MATLAB/simulink. Int J Simul Syst Sci Technol. 2017;17(41):45.1-45.7.

[20] Banu IV, Beniuga R, Istrate M. Comparative analysis of the perturb-and-observe and incremental conductance MPPT methods. 8th Int Symp Adv Top Electr Eng ATEE 2013.

[21] Hlaili M, Mechergui H. Comparison of Different MPPT Algorithms with a Proposed One Using a Power Estimator for Grid Connected PV Systems. Int J Photoenergy. 2016;2016.

[22] Elgendy MA, Zahawi B, Atkinson DJ. Evaluation of perturb and observe MPPT algorithm implementation techniques. IET Conf Publ. 2012;2012(592 CP).

[23] Sahnoun MA, Ugalde HMR, Carmona JC, Gomand J. Maximum power point tracking using P&O control optimized by a neural network approach: A good compromise between accuracy and complexity. Energy Procedia [Internet]. 2013;42:650–9.

[24] Banu IV, Istrate M. Study on three-phase photovoltaic systems under grid faults. EPE 2014 - Proc 2014 Int Conf Expo Electr Power Eng. 2014;(Epe):1132–7.

[25] Kumar V, Singh M. Reactive power compensation using derated power generation mode of modified P&O algorithm in grid-interfaced PV system. Renew Energy. 2021;178:108–17.