International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 14, No. 2, June 2023, pp. 1172~1183
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v14.i2.pp1172-1183

Influence of reactive power compensation from PV systems on electrical grid

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Article Info

Article history:

Received Oct 21, 2022
Revised Dec 9, 2022
Accepted Dec 18, 2022

Keywords:

Distribution energy
Grid-connected
Photovoltaic system
Power quality
PV system

ABSTRACT

The rising electricity consumption, rapid fossil fuel depletion, and a higher shift to the use of renewable or green energy resources have increased the need to integrate renewable and distributed energy resources (DERs), like solar photovoltaic (PV) energy to power the utility grids. In this study, the researchers have determined the effect of PV inverters to offer reactive power to an adapted IEEE 13-node distribution network. Power flow analyses were conducted on MATLAB/Simulink for various reactive power modes of PV inverters to show the effect of the reactive power on the regulation of grid voltage, reduced the total harmonic distortion (THD), and maintain the power factor so as to improve the ability of the system to handle power. The result shows that using a 400 KW PV system in a bus (675) led to a reduction in the power generated from the generator by 11%, and the use of the reactive power capability of PV inverters on-site improved the voltage profile significantly. as well, reduced the voltage THD by 27.09% when injected with reactive power, reduce the current THD by 77.39% When absorbing reactive power, and improved the power factor on-site.

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1. INTRODUCTION

The amount of energy that is supplied to the consumers is dependent on the centralised energy generation system, which uses traditional generators [1]. However, the centralised power generation systems are plagued with many issues like the higher costs of fossil fuels [2], power losses during transmission and distribution, and the negative effect of global warming [3]. As a result, novel concepts and tactics for planning and operating the energy systems must be developed. To address these issues, many organisations have started using distributed generators (DGs) [4]. The introduction of renewable distributed generation (DG) into power systems plays a vital role in emerging electric power systems [5] . Integrating renewable energy resources into existing electrical grids is the way forward for the generation of clean and sustainable energy due to the rapid depletion of fossil fuels, which are traditional energy sources [6]. An abrupt change in the energy demand, as well as a lack of distribution infrastructure due to technological and economic constraints, have resulted in a clear shift toward the implementation of renewable energy resources for power generation.

These changes have prompted power companies to decentralise their electric systems to connect the smaller renewable DG units to a distribution network directly at or near loading points [7]. Integration of renewable energy sources into the power systems could offer economic, environmental and technical advantages to the consumers along with the distribution systems [8]. Sunlight and solar energy, which are among the many types of renewable energy sources that have become popular over the years, can be converted by photovoltaic (PV) systems into electricity, and these systems can be connected to a grid without causing air pollution and other environmental restrictions [9]. Photovoltaic (PV) systems have become the fastest growing power generation system worldwide, according to the renewable energy capacity statistics of the international renewable energy agency (IRENA) (2022). As shown in Figure 1, at the end of 2021, the global renewable energy generation capacity reached 3,064 GW, in 2021, the power generation ability of the renewable energy plants increased by 257 GW (+9.1%). However, solar energy continues to lead this energy expansion by adding 133 GW (+19%) and is followed by wind energy which added 93 GW (+13%) [10]. It is expected that by 2040, photovoltaic technology will become the most important contributor to the generation of electricity among all other candidates for renewable energy.

The PV systems feed actual electric power into the grid via several distribution network locations [11]. Because this is seen to be a cost-effective response to the rising energy demand, it can offer many significant implications for the whole distribution network [12]. This could be attributed to the fact that the irregular supply of PV energy affects the quality, availability and dependability of the complete grid [13]. The IEEE standard for interconnecting distributed resources to the electrical power systems (IEEE Std 1547a-2014) [14] stated that the DERs could aggressively participate in regulating the network voltage at the point of common coupling (PCC) by modifying the active and reactive power generation for the DERs, as well as signing mutually-beneficial agreements with the DERs and the distribution network operators, in order to avoid abnormal voltage overshoots. Thus, rather than the switched capacitors [15], voltage source inverters (VSIs) are utilized in the PV systems as the active local variable compensators [16], [17]. In regions having a higher penetration of PV systems, they offer reactive power that can be easily absorbed by local loads, estimated at the PCC, thereby helping in improving the power factor (PF) [18], [19]. This helps in resolving the voltage regulation problems, enhancing the PF, improving the grid stability and optimizing the power transmission ability by decreasing the transmission losses [20]. Furthermore, this offers a financial benefit to the consumers since there are no equipment costs for controlling the PF [19].

The basic goal of a power distribution network is to reduce energy losses and improve the transmission process in order to deliver electric energy to the end consumers at the desired quality (THD reduction with <5% as per IEEE 519 standards) [21], efficiency, and reliability [22], [23]. Many scholars have recognized reactive power compensation as a well-known method for reducing power loss while also offering many benefits like PF correction, voltage stability, increased transmission and operating ability of the network lines and devices, and optimization of the voltage profile [24], [25]. These advantages are influenced by different operating limitations and distribution network properties [26].

In this study, the researchers have highlighted the significance of reacting effectively and quickly while controlling the electrical variables that were affected by reactive power flows needed by the loads in the inductive power distribution systems. They have also explained the need to focus on the distribution networks with the distributed resources because these networks are on the track to becoming self-sustaining and capable of generating renewable energy using non-polluting sources in the near future. This paper shows how the inverters in (400 KW) photovoltaic system connected to an electrical grid can used to generate active power, and at the same time, be used for the injection/absorption of reactive power, according to the requirement of the distribution network and the availability of photovoltaic power, and the impact of this on improving the voltage profile of each node to ensure its stability, improve the power factor, release the capacitance in lines and equipment, and improve the quality of the network power because of the existence of a local power compensation control.

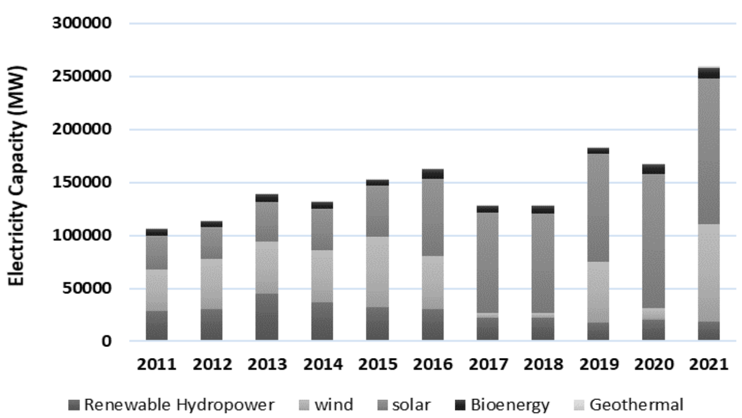

Figure 1. Growth of renewable power capacity

2. SYSTEM DESCRIPTION

In this study, the researchers present the design of the 3-phase grid-connected PV system as shown in Figure 2. The grid-connected PV system with Double-stage power conversion systems. This system includes a PV array, DC-DC boost converter, 3-phase DC-AC inverter and its control, maximum power point tracking (MPPT) algorithm control, LC filter, and the isolation transformer.

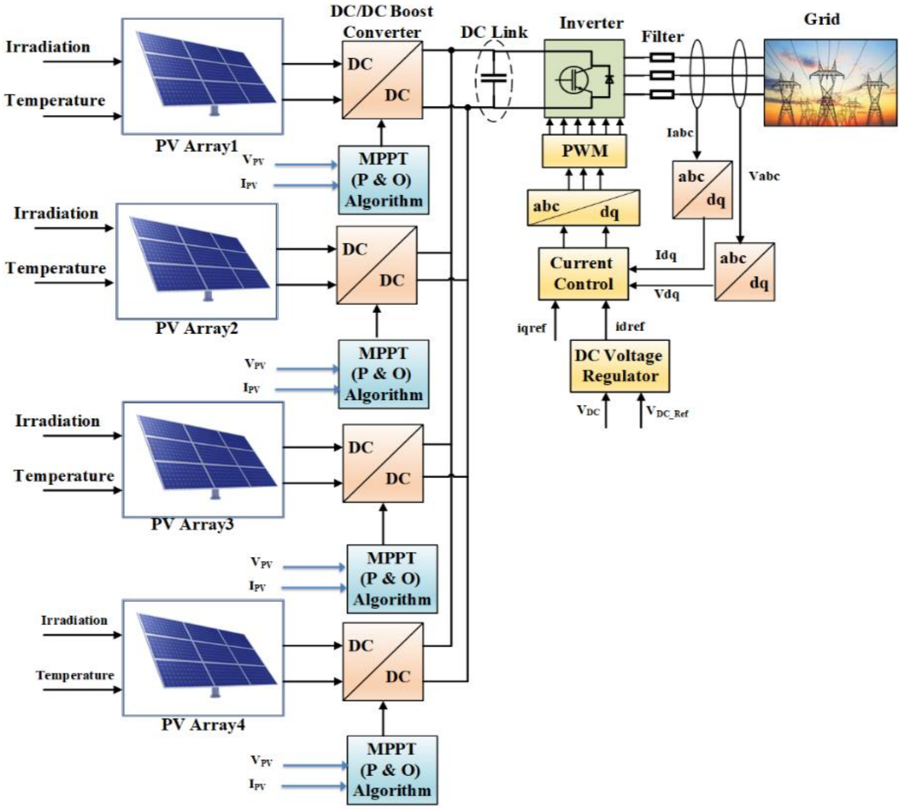

Figure 2. Schematic block circuit diagram of a grid-connected PV system

2.1. PV array modelling

In this paper, the PV system (400 KW) consisted of a four-sun power SPR-305E-WHT-D PV array connected in parallel. Each PV array generated 100 KW, and all the PV arrays were set to operate in standard test conditions (STC) (1000 W/m^2 of solar radiation at a temperature of 25 ^{o}C). The parameters for this model are shown in Table 1.

Table 1. PV module specifications (SUNPOWER SPR-305E-WHT-D)

Parameter	Value
Maximum power (W)	305.226
Voltage at maximum power (V_{mp})	54.7 V
Current at maximum power (I_{mp})	5.58 A
Open circuit voltage (V_{oc})	64.2 V
Short circuit current (I_{sc})	5.96 A
Total no.of cells in series (N_s)	5
Total no.of cells in parallel (N_p)	66
Temperature coefficient of Voc (Kv)	-272.7 mV/^{o}C
Temperature coefficient of Isc(Ki)	61.745 mA/^{o}C
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 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

2.2. DC-DC boost converter

A DC-DC boost converter was used to control and increase the DC output voltage of the PV array and to implement the MPPT. The MPPT algorithm is needed for driving the system such that it can operate at MPP, wherein any changes occurring in the temperature or solar irradiance could amplify or decrease the power in a PV source. The output power is also kept at a higher level to improve the system's efficiency. The MPPT algorithm can be used in a DC-DC converter that modulates the duty cycle for tracking the instant MPP of a PV array. The authors applied the perturb and observe (P&O) algorithm for varying the duty cycle and achieving the maximal active power for a PV array [27].

2.3. DC to AC converter

The researchers designed a 3-phase 3-level voltage source converter having a sinusoidal pulse-width modulation (SPWM)-based PQ controller for the DC to AC conversion in the PV simulation model. The output of the capacitors at the boost converter provided a neutral point, N, for the inverter. The gate signals at the inverter controlled the 'on' and 'off' insulated gate bipolar transistors (IGBT) switches during that period. These signals were generated by the designed inverter control loop, which consisted of a phase-locked loop (PLL), DC voltage control loop, and a current control loop. The PLL and a dq transformer control converted the voltage and current to per unit values. The angle and frequency of the PLL were determined by the grid voltage. This was important for the purpose of grid synchronization. In this model, the 3-phase voltage and the current from abc were converted by the dq transformer to a dq reference frame. This conversion helps in accurately controlling the signals [28]. Also, the DC voltage control loop controls the DC-link voltage at the inverter's input for maintaining the balance of power between the PV array and power grid and ensuring the quality of generated electricity by managing the current injection in the grid. The current control loop helps in regulating the current in a dq reference frame. Furthermore, the pulse width modulator (PWM) and reference voltage convert the voltage in the abc reference frame from the dq frame. The PWM generates the PWM signals after comparing the 3-phase reference signals and triangular waves using a specific frequency value. Additionally, these signals manage the IGBT 'On' and 'Off' switches in the inverter. This inverter generates a 3-phase sinusoidal voltage and current [29].

2.4. LC filter

The increasing use of devices based on power electronics in renewable energy systems has led to an increase in the value of non-sinusoidal voltages and currents. Therefore, it is necessary to create filtering circuits to remove harmonics in the electrical network. The harmonics resulting from the power electronics circuits are the main factor that causes problems for sensitive equipment or loads connected to the network, as the price of filters and THD is also an important consideration in the design stage of systems. The design included the LC filter for filtering the primary PWM signals from an inverter and improving the inverter's power output quality. The configuration of the LC filter's capacitance and inductance on the AC side was based on the cut-off frequency value, which needs to be lower than the value of the lowest-order harmonic frequency in a PWM inverter output voltage [30].

2.5. Isolation transformer with three phases

Isolating transformers have been used for protecting sensitive electronic equipment from electrical breakdowns, eliminating electrical noise, and transmitting power between two circuits that cannot be connected directly. Isolation transformers prevent the transmission of the DC components in the signals while allowing the passage of AC components. 3-phase isolation transformer type has been configured to convert from Delta to Wye since it is highly common in distributed renewable energy-based systems [31].

3. ANALYSIS OF REACTIVE POWER CAPABILITY OF PV PLANT

The rapid expansion of PV systems has raised many concerns among grid operators [32], one of them being the stability of the network voltage [33]. Grid operators have to impose strict operating rules on PV systems in order to maintain the stability of the grid voltage. As a result, they have suggested that PV systems be manufactured with PV inverters that have the ability to control the voltage. PV inverters should have grid support functions that include the ability of the reactive power to stabilize the grid voltage [34]. The power of the inverter determines the amount of reactive power output of PV power plants when inverters are used as a source of reactive power, as in (1).

$$|Q_{inv.}| \leq \sqrt{S_{inv.}^{\ 2} - P_{pv}^{\ 2}} \quad (1)$$

Where $S_{inv.}$ is the inverter rated power, P_{pv} is the instantaneous PV power of the PV array, $Q_{inv.}$ is the inverter reactive power. Q_{Max} is the reactive power limit of the inverter when supplying active power P_{pv} [35]. Figure 3, shows the susceptibility of the inverter to the injection/consumption of reactive power, where the inverter can inject the required reactive power when there is a shortage of reactive power generated by the grid, and can also consume the reactive power to reduce the grid voltage.

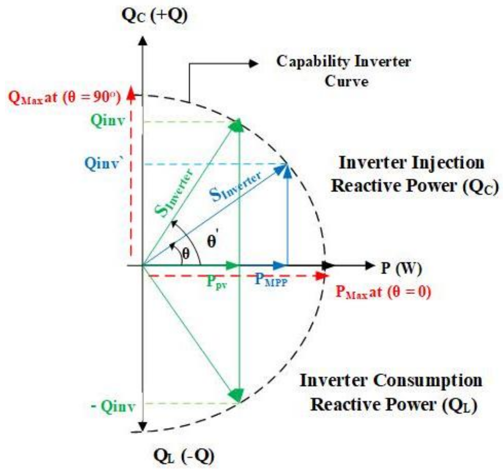

Figure 3. Two-quadrant operation of PV inverter

The power equations of the system in Figure 4 can be derived as follows [36]:

$$P_g = \frac{V_g V_i \sin\delta_i}{X_i} \tag{2}$$

$$Q_g = \frac{V_g (V_i \cos\delta_i - V_g)}{X_i} = \frac{V_g V_i \cos\delta_i)}{X_i} - \frac{V_g{}^2}{X_i} \tag{3}$$

where V_i=Inverter output voltage; δ_i=Phase angle of inverter output; V_g=Voltage of grid bus; X_i=Transformer and line reactance; Q_i=Reactive power of inverter; S_i=Apparent power of inverter; P_g=Active power of a grid busbar; and Q_g=Reactive power of grid busbar. From (2) and (3), it can be deduced that:

$$P_g{}^2 + \left(Q_g + \frac{V_g{}^2}{X_i}\right)^2 = \left(\frac{V_g V_i}{X_i}\right)^2 \tag{4}$$

when Q_g=0

$$P_g = \sqrt{\left(\frac{V_g V_i}{X_i}\right)^2 - \left(\frac{V_g{}^2}{X_i}\right)^2} = \frac{V_g}{X_i}\sqrt{V_i^2 - V_g{}^2} \tag{5}$$

In (4) presents the range of reactive power supplied by the inverter to the busbar linked to a grid:

$$-\left(\sqrt{\left(\frac{V_g V_i}{X_i}\right)^2 - P_g{}^2} - \frac{V_g{}^2}{X_i}\right) \leq Q_g \leq \left(\sqrt{\left(\frac{V_g V_i}{X_i}\right)^2 - P_g{}^2} - \frac{V_g{}^2}{X_i}\right) \tag{6}$$

Inverters typically operate at the rated active power for maintaining the PV system's active power output, hence their inductive and capacitive reactive power output ranges are limited [37]. The system's power flow relationship with a sign convention, as shown in Figure 5, is a critical aspect while analyzing the system.

The inverter's operation is referenced while developing the basic rules for sign convention. The sign is positive if the inverter feeds, and negative if it consumes. As a result, for both the grid and load, the researchers assigned an opposite sign for power injection and consumption [29].

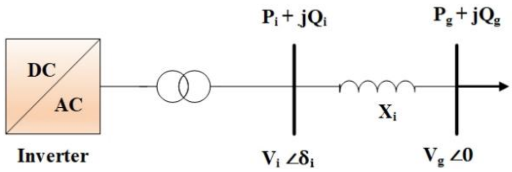

Figure 4. PV power plant equivalent circuit

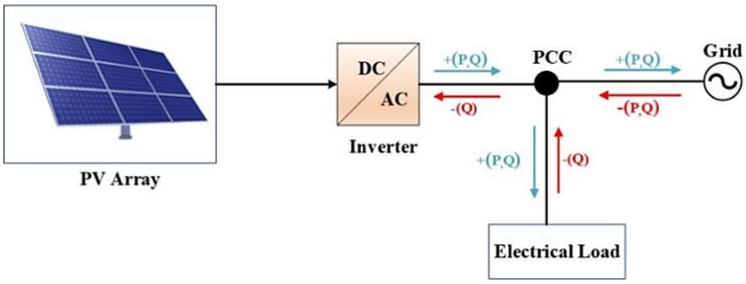

Figure 5. The system power flow characteristic

4. DESCRIPTION OF THIS DISTRIBUTION NETWORK

Software developers and field engineers can use the test systems developed by the IEEE distribution systems analysis subcommittee to validate their studies. Here, the researchers used the IEEE 13-bus distribution feeder module for determining the impact of the PV transformers' reactive power capacity, as illustrated in Figure 6. This small and highly-loaded test feeder had very interesting characteristics. The voltage level of the short and adequately loaded grid was 4.16 kV.

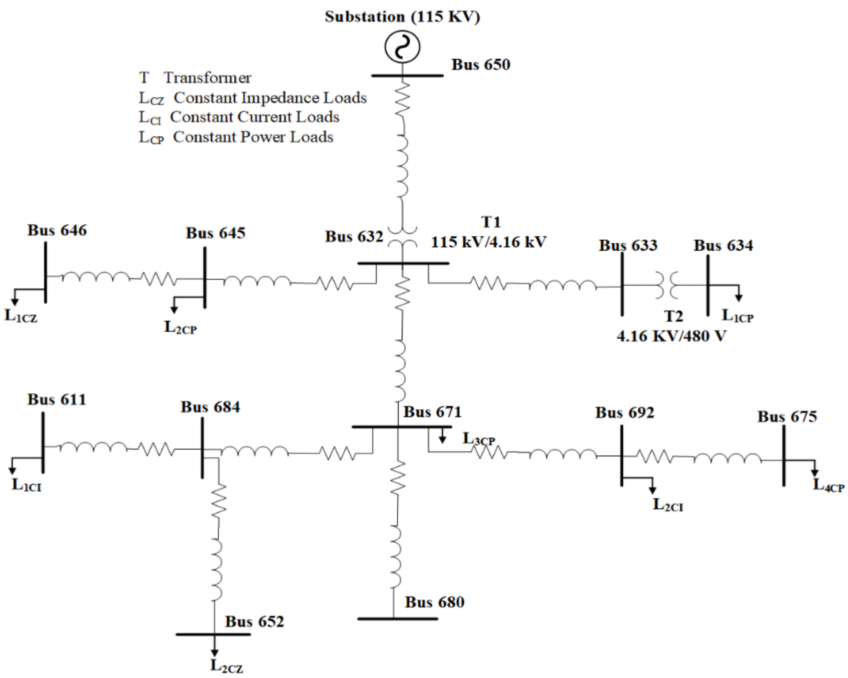

Figure 6. IEEE 13-bus distribution feeder

The goal of the system was to test and compare techniques for handling the unbalanced 3-phase radial systems. This system included 13 buses, 10 overhead and underground lines, a transformer (Y 115/4.16 kV), voltage regulator unit, generation unit, in-line transformer (YY 4.16/0.480 kV), 2 shunt capacitor banks, unbalanced spot and distributed loads [38]. The loads can be three-phase (balanced or unbalanced) or single-phase loads. These loads are modelled specifically as shown in Table 2.

During the modelling of the distribution grids, removing the voltage regulator and replacing it with the swing generator with specified characteristics is particularly useful. This would simplify the model without sacrificing accuracy. In this study, the voltage regulator was left out of the IEEE 13-bus test grid since the DGs could vary the voltage levels. The generator's voltage was set at 4.16 kV and it was connected to the distribution lines directly. Two shunt capacitor banks were also excluded from the design.

Table 2. List of codes used to describe various loads

Code	Connection	Model
Y-PQ	Wye	Constant KW and KVAR
Y-I	Wye	Constant Current
Y-Z	Wye	Constant Impedance
D-PQ	Delta	Constant KW and KVAR
D-I	Delta	Constant Current
D-Z	Delta	Constant Impedance

5. SIMULATION RESULTS

In this study, simulations of the modified IEEE 13-bus test grid model with a 400-KW PV system were carried out using the MATLAB/Simulink application to analyze the impact of the reactive power capability of the PV inverters, as shown in Figure 7. Case 1: A power flow analysis was performed at steady-state operating conditions on the modified IEEE 13-bus test grid without a PV system being connected to any of the buses. The slack bus (bus 632) generated an active power of 3477.2 KW, and reactive power of 2224.8 KVAR. The results of the voltage and power of the buses are shown in Tables 3 and 4. It turned out that the voltage of (bus 675) was the weakest among the other buses due to the heavy loads that were connected to it, and therefore, it required a large amount of power from the generator to operate the load.

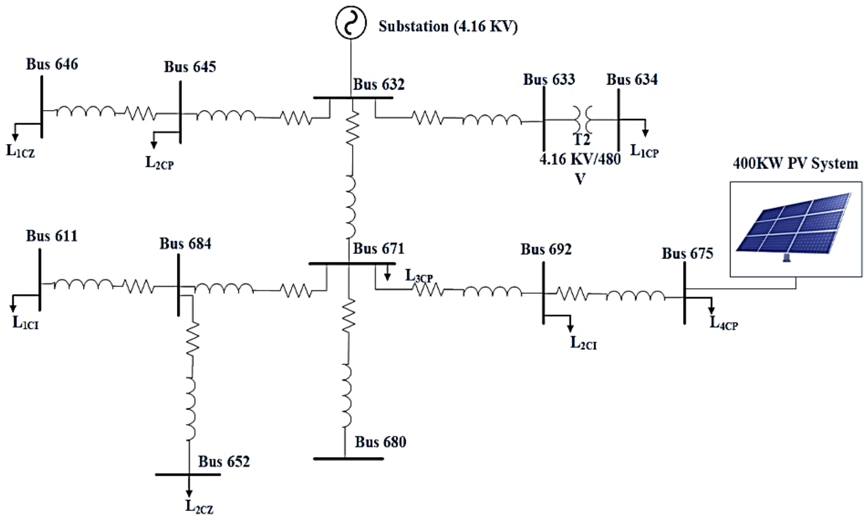

Figure 7. Modified IEEE 13-bus distribution feeder with PV system for bus 675

Case 2: A 400 KW PV system at unity power factor (UPF) was added to (bus 675), while the PV generation at STC and load was in steady-state conditions. The PV system delivered only active power at unity power factor, and it was equal to the apparent power (S) rating of the inverter. The inclusion of the PV system in the distributed generation reduced the power generated by the generator from 3477.2 KW to 3095 KW by 11%, as shown in Figure 8. This is one of the most important goals of using photovoltaic systems in distribution networks. It was also noted that connecting to the photovoltaic system led to an increase in the voltages in the buses near the site, as shown in Figures 9 and 10, shows the effect of the PV system connected to (bus 675) on the reactive power system.

Table 3. Voltage profiles of each bus when the generation was only at the slack bus

Buses	Voltage Phase A	Phase B	Phase C	Bus voltage
Bus 632	1.0210	1.0420	1.017	1.0267
Bus 633	1.018	1.04	1.015	1.0243
Bus 634	0.9939	1.022	0.9959	1.0039
Bus 645	0	1.033	1.015	1.024
Bus 646	0	1.031	1.013	1.022
Bus 671	0.9839	1.046	0.9643	0.998
Bus 675	0.9764	1.047	0.9608	0.994
Bus 680	0.9839	1.046	0.9643	0.998
Bus 684	0.982	0	0.9611	0.971
Bus 692	0.9839	1.046	0.9643	0.998
Bus 652	0.9765	0	0	0.9765
Bus 611	0	0	0.9579	0.9579

Table 4. Active Power and reactive power at each bus when the generation was only at the slack bus

Buses	Phase A Active power (P)	Phase A Reactive power (Q)	Phase B Active power (P)	Phase B Reactive power (Q)	Phase C Active power (P)	Phase C Reactive power (Q)
Bus 632	1,215	794.3	974.2	558.2	1,288	872.3
Bus 633	162.9	114.9	121.8	92.95	1,21.8	93.07
Bus 634	160	110	120	90	120	90
Bus 645	0	0	-331.7	-125.8	-79.43	-137.8
Bus 646	0	0	-161.5	-0.5617	-79.16	-137.5
Bus 671	1,026	596	456.8	296.5	931.8	516.2
Bus 675	477.9	187.2	66.92	59.05	281.3	205.6
Bus 680	0	0	0	0	0	0
Bus 684	-122.9	-82.23	0	0	-160.6	-75.84
Bus 692	481.1	189.9	66.77	59.03	282.7	205.8
Bus 652	-122.1	-82.	0	0	0	0
Bus 611	0	0	0	0	-160.2	-75.38

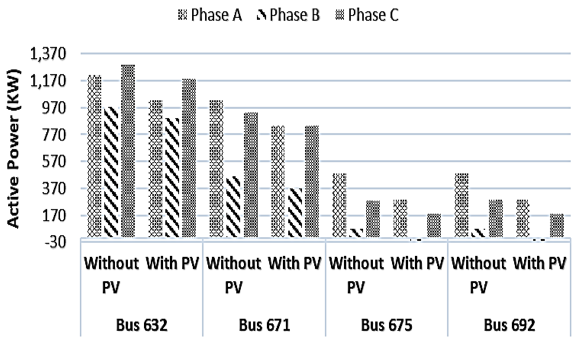

Figure 8. Comparison between active power without and with a PV system at UPF

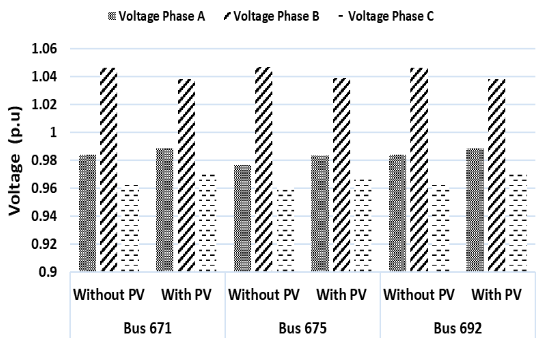

Figure 9. Comparison between voltage without and with a PV system at UPF

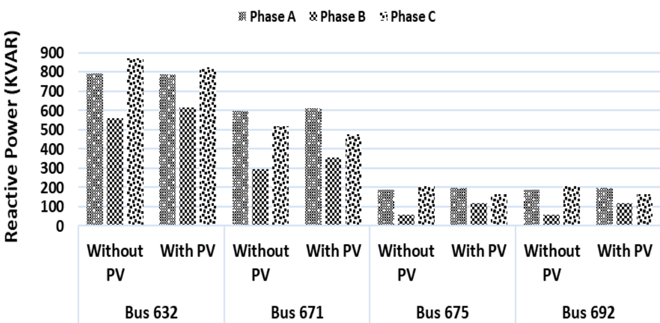

Figure 10. Comparison between reactive power without and with a PV system at UPF

Case 3: The effect of the injection/absorption of reactive power from a 400 KW PV system on (bus 675) at STC and loads in steady-state conditions was demonstrated. The reactive power reference was adjusted from 0 to -1, indicating that the reactive power injection mode was selected. When the inverter consumed the reactive power, the reactive power reference shifted from 0 to 1. The per-phase voltage of (bus 675) is shown in Figure 11, for reactive power injection values of $Q_{Ref.}$ = -0.5 and $Q_{Ref.}$ = -1, as well as reactive power absorption values of $Q_{Ref.}$ = 0.5 and $Q_{Ref.}$ = 1. The results showed that the reactive power injection into the grid increased the bus voltage, while the reactive power absorption decreased the bus voltage.

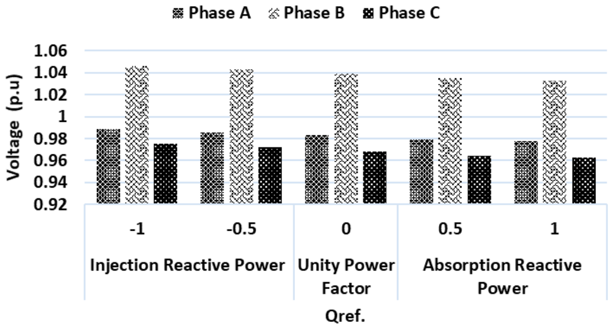

Figure 11. Voltage of bus 675 from reactive power injection/absorption compensation

Grids with greater voltage regulation and stability will result from this sort of grid-connected inverter having a local reactive power compensation. Figure 12, shows the active power of (bus 675) at reactive power injection values of $Q_{Ref.}$ = -0.5 and Q_{Ref} = -1, and reactive power absorption values of $Q_{Ref.}$ = 0.5 and $Q_{Ref.}$ = 1, which indicates that the change in the active power value was dependent on the amount of reactive power injection/consumption. Figure 13, show the reactive power of (bus 675) at reactive power injection values of $Q_{Ref.}$ = - 0.5 and $Q_{Ref.}$ = - 1, and reactive power absorption values of $Q_{Ref.}$ = 0.5 and $Q_{Ref.}$ = 1. It was obvious that the reactive power compensation by the PV inverter decreased the flow of reactive power in the grid to improve the performance of the system. Thus, the PV inverter was able to increase the reactive power required for heavy loads.

Figures 14 and 15, show the impact of reactive power on the voltage THD and current THD in (bus 675) at reactive power injection values of $Q_{Ref.}$ = - 0.5 and $Q_{Ref.}$ = - 1, and reactive power absorption values of $Q_{Ref.}$ = 0.5 and $Q_{Ref.}$ = 1. It inferred that the current harmonics were high when connected PV system to the grid (at UPF), voltage THD reduced when it operated in the reactive power injection mode by 27.09%, and the current THD reduced when it was operating in the reactive power absorption mode by 77.39%. So, which makes the THD turn out to be within the permissible limit of the IEEE STD 519-1992 [39]. Thus, we conclude that the reactive power capability of the inverter improves the power quality of the grid.

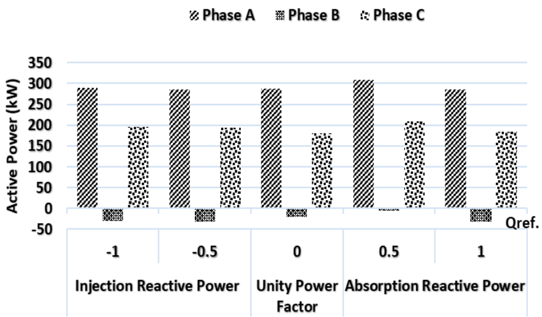

Figure 12. Active power in bus 675 from reactive power injection/absorption compensation

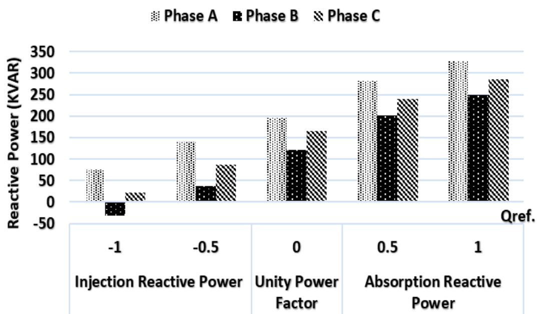

Figure 13. reactive power in bus 675 from reactive power injection/absorption compensation

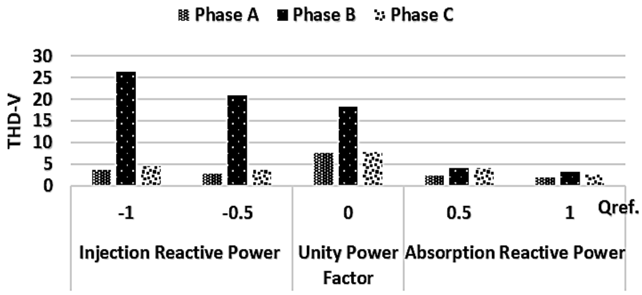

Figure 14. Voltage THD from reactive power injection/absorption compensation

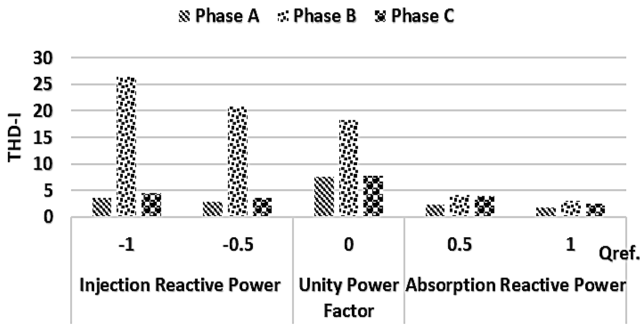

Figure 15. Current THD from reactive power injection/absorption compensation

6. CONCLUSION

In this study, highlighted the requirement for reactive power injection by PV inverters for improving the voltage profile and power quality of the distribution system. They designed a modified IEEE 13-node test system for analyzing the voltage profile and active power of a system with or without PV, at the PF value of unity, along with the effect of the PV inverter on the injection/absorption of the reactive power on the system. A majority of the DERs are linked to the micro grid or utility grid with the help of the electronic electric interface, which generates both the active and reactive types of power, by properly controlling the interface of an inverter. A dramatic improvement was noted in the voltage profile when the full capacity of the PV inverter's reactive power was used, and the voltage THD and current THD were reduced, while the PF at PCC was improved. The results demonstrate that employing PV with PF = 1, reduced the generator's power output by 11% and improved the voltage profile significantly on-site by utilizing the reactive power capabilities of PV inverters. Additionally, when reactive power was injected, the voltage THD was reduced by 27.09%, the current THD was reduced by 77.39% When absorbing reactive power, and the PF was increased on-site.

ACKNOWLEDGEMENTS

The authors would like to thank University of Mosul, College of Engineering, Electrical Department, for the support given during this work.

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