

AIMS Energy, 10(2): 236–253. DOI: 10.3934/energy.2022013 Received: 10 February 2022 Revised: 15 April 2022 Accepted: 24 April 2022 Published: 27 April 2022

http://www.aimspress.com/journal/energy

Research article

Impact of photovoltaic grid-tied systems on national grid power factor

in Palestine

Amer Braik¹, Asaad Makhalfih², Ag Sufiyan Abd Hamid³, Kamaruzzaman Sopian¹ and Adnan Ibrahim^{1,*}

- ¹ Solar Energy Research Institute, Universiti Kembangan Malaysia, 43600 Bangi, Selangor, Malaysia
- ² Electrical Engineering Department, Arab American University, Jenin, Palestine
- ³ Faculty of Science and Natural Resources, Universiti Malaysia Sabah, 88400 Kota Kinabalu Malaysia
- * Correspondence: Email: iadnan@ukm.edu.my; Tel.: +60389118581.

Abstract: Residential photovoltaic systems are a cost-effective solution for Palestinians to reduce their power costs while improving the environment. Despite their numerous advantages, these systems have several negative effects on the entire electric grid infrastructure. Increased penetration of photovoltaic (PV) systems, for example, may result in a fall in the power factor of the distribution grid. When the power factor is low, heat production and switch failures are more likely to occur. Even though comparable research has been published in the past, this is the first time PV systems have been investigated in terms of power factors in Palestine. This research serves as a resource for people interested in how photovoltaics (PVs) impact their systems' total power factor. To begin, the researchers in this study presented an intuitive power factor selection criterion for photovoltaic (PV) systems. Second, the article included a proposal for an auxiliary power factor controller. This article's conclusions may be utilized by municipalities, grid operators, and legislators to aid them in planning, forecasting, and accommodating new PV systems in their grids in terms of total power factor, as demonstrated by the results of this study. However, even though the data in this study is drawn from Palestinian sources, it may be applied to other regions because the data sets used are worldwide in scope.

Keywords: PV system; power systems; power factor; solar energy; Palestine

1. Introduction

The photovoltaic (PV) system comprises one or more solar panels connected to an inverter and other electrical hardware, utilizing the energy from the sun to produce electricity. The PV systems significantly differ in size, ranging from small ones used on rooftops to large utility-scale used in generation plants. Palestine is among the countries in the world that receive enough solar radiation. Regardless, Palestine has power shortages, with a large part of its electricity imported from other countries. Besides the inadequate electricity supply, Palestine is among the fastest-growing populations in the region. In the last 25 years, the population has doubled from 2.7 million in 1997 to almost 5.3 million in 2021 [1]. Therefore, the electricity demand is high, and the government has engaged in several strategies to compensate for the shortage. The adoption of PV systems is one of the government's policies already implemented. According to P.E.a.N.R.A, the demand is expected to rise from 1400 MWp to 2335 MWp by 2030 [2]. Studies conducted in the country show that many residential buildings are now connected with PV systems. When implementing this strategy, the relevant stakeholders should pay attention to the concept of the power factor. Power factor is defined as measuring the phase difference between current and voltage in an AC power system.

1.1. Residential PV systems

The deployment of PV systems is regarded as one of the fastest-growing renewable sources of energy in the world today. PV systems have many advantages, including providing a safe and environmentally friendly energy source. Some of the factors that affect the success of this form of energy include the tilting of the solar PV, solar radiation, ambient temperature, wind speed, and dust deposition [3,4]. The Middle East region remains one of the areas in the world receiving high solar radiation [6]. Palestine is one of the countries with the highest solar irradiation potential. The sunshine availability is estimated to be around 3000 hours a year.

Palestine acquires a significant portion of its energy from neighboring countries. For instance, research shows that in 2016, 91% of the electricity used in Palestine was imported [7]. Regardless, electricity is one of the most fundamental needs required in many Palestinian households. Electricity is required for various reasons, including cooling and operating the air conditioning units [8,9]. With a lack of an electricity plant in Palestine, government officials have been prompted to develop PV systems for electricity production. Essentially, this has contributed to too many challenges, prompting the Palestinian government to invest in the PV systems to deal with the challenges. The residential PV systems in Palestine have primarily bettered thanks to the favorable policy. Khatib, T. et al. illustrated that a dominant factor that may determine solar generating success or failure is energy policy [3].

PV generation in most countries depends on the nature and type of policy developed by a country. The policy should pay significant attention to tax reduction, market capacity, financial and fiscal incentives, and technical and non-technical information dissemination. Many Palestinian cities have now embraced the PV electrical systems as the primary mode of electricity generation to serve the deficit experienced by the country.

Currently, 39 MW PV systems have been installed. More than 93 MWp of PV systems are yet to be completed [3]. However, research has shown that Palestine faces significant policy issues that adversely affect the development of PV systems. Some identified areas include poor technical standards, low awareness, and a lack of information dissemination. Therefore, these issues have

contributed to Palestine lagging in its PV electrical systems.

Most of the residential households in Palestine are apartment buildings. Approximately 85% of the household units are owned by the residents [7]. Residential buildings are primarily found in cities, existing in neighborhoods and clusters. As illustrated by Monna, S et al., in Palestine, a 1 kW rooftop system put at optimal tilt and orientation angles generates up to 1635 kWh per year in Hebron, 1613 kWh per year in Jerusalem, 1562 kWh per year in Nablus, and 1557 kWh per year in Gaza city [7]. The outcome is crucial in determining the future of PV in the country. Residential buildings, especially in urban areas, have a high potential to maximize solar energy from the sun. The quality and type of the building remain a critical aspects to consider when determining whether to develop the PV systems.

The use of the grid-connected PV systems culminated in several fundamental aspects influenced by the decreasing PV prices and positive government regulation practices promoting renewable energy sources [10]. Today, residential buildings, municipalities, schools, and private firms have established PV systems. In research by [11], the authors selected PV home systems operating in the last three years. According to the research, the systems yielded 4.81 kWh/kWp per day. Annually, this translates to 1756 kWh/kWp.

As emphasized by the authors in [11], Economic assessments show that increasing the usage of PV household systems is motivating because the payback period is 4.9 years, the cost per kWh produced is 0.43 NIS (0.115 US \$), and the internal rate of return is 25%. Further studies have shown the importance and significance of the PV systems in the national grid. According to studies, the PV system contributes to decreasing losses, high voltage levels, and decreasing power factors [12]. Besides increasing the electricity supply for many Palestinians, it has also improved the environment due to its clean nature. A schematic diagram of a grid-tied PV system can be found in Figure 1.



Figure 1. On-grid PV system block representation.

The PV system is connected to a broader electricity network in a grid-connected version. The inverter is the intermediary between the PV system and the utility grid. The inverter's role is to convert direct current (DC) into alternating current (AC). The connection to residential buildings can take any of the three designs or models explained [14]. Researchers have paid significant attention to the residential PV systems, including their various electrical dynamics. The study by [10] looks at the various aspects of the residential PV systems installed in France. With this research, the author seeks to answer three fundamental questions, including the amount of energy produced, the level of performance, and the parameters that influence its quality [10]. In 2010, the PV systems in France produced an average power level of 1163 kWh/kWp [10]. Besides France, South American countries

like Chile have also experienced a growth in the US of the PV systems as part of their electrical production system [13]. Therefore, the PV systems continue to act as a primary source of electricity for many countries and cities across the globe. The PV system offers individuals an opportunity to generate power in a clean, quiet, and reliable manner.

1.2. Power factor of the PV systems

Power factor is one of the most fundamental concepts in electricity. It is regarded as the phase difference between current and voltage in an AC power system. In resistive loads such as those witnessed in an electric kettle or incandescent bulb, the voltage is in phase with the current creating a unity power factor [16]. However, the same is not valid for the inductive and capacitive loads, such as in an inductive motor or a capacitor bank. The current will lag or lead the voltage leading to a non-unity power factor. In a non-unity power factor, the load utilizes both active and reactive power. As shown in Eq 1, the active power is the true power and is directly involved in the work: [17].

$$PF = \cos\left(\tan^{-1}\frac{Q}{P}\right) \tag{1}$$

Most PV systems have a unity power factor, which means that they strictly produce active power [16]. However, research shows that this reduces the power factor in the real sense, and the grid is compelled to supply less active power with the same level of reactive power.

Generally, the PV systems negatively influence the overall power factor, resulting in penalties, especially when corrective measures are not taken [19]. When the solar system produces energy, the active power is harnessed and fed directly to the load. Consequently, this results in lowering the active power demand from the utility. However, the reactive power emanating from the load largely remains the same [20]. The outcome is a reduction in the power factor at the grid connection. From a consumer perspective, reducing the power factor yields penalties for the grid operator. However, research has shown that several ways exist that could be used to reduce the power factor [19]. The primary strategy used revolves around the manipulation of the inverter. Stakeholders should pay significant attention to finding the most appropriate ratio between the active and reactive power. Essentially, this enables them to control the amount of active power that reaches the load, including the reactive power [20]. Capacitors could also be used in the correction of the power factor. The role of the capacitors is to reduce the magnetization of the current. Improving the power factor has many benefits, including environmental protection, reducing electricity bills, and reducing voltage drop [20]. A reduced power factor also means that the equipment has an extended life, thanks to the reduced burden on cables and other additional components.



Figure 2. Schematic diagram of a facility producing at unity PF [25].

1.3. Choosing the correct power factor of PV systems

Choosing the suitable power factor is now considered one of the crucial design points of a grid-connected PV system [26]. The integration of solar energy may have a detrimental influence on the electrical infrastructure's overall power factor (PF), resulting in fines if remedial measures are not implemented. Since the solar system produces and provides solely active energy, less active energy from the grid is needed to produce the same amount of reactive energy that the solar system produces and provides [26]. Solar enterprises must reduce the likelihood of an increase in kVAR fines and penalties [27]. Adopting a Power Factor Correction device may quickly and effectively remedy this problem by installing a special type of available SCADA system [27]. Alternatively, a power factor compensator may be installed to avoid the penalty.

In Palestine, there are several electricity distributors, each with its own set of rules and regulations regarding power factor penalties and settings. For example, the North Electricity Company decides that the power factor of a solar energy system is 0.92, which is lower than the national average [28]. This would have significant limitations, as it would reduce the actual amount of energy produced by solar energy systems in cases where there is no need to reduce its value. In addition, reducing the power factor for some systems should be based on technical studies for each case. The oversized design might have a negative impact on the network or the loads in this facility. On the other hand, after fourteen trial days of PV systems commissioning, the Jerusalem District Electricity Company operates and examines the station to determine the effect of connecting it to the network and gather the information on the ground for accurate evaluation [29]. If necessary, the company notifies the facility's owner, with each project being evaluated separately. For example, it was requested to establish a 7.5-megawatt solar power plant control system in the Al-Nuwaimah Plant [30], which would continuously modify the power factor to consistently meet the condition of the network without harming it or causing any problems to the network or its equipment. Nevertheless, there are no technical criteria for measuring the power factor of inverters under the legislation governing municipal authorities [31]. This paper mainly focuses on such authorities, which account for approximately 32.5% of the total share of electricity distributors in Palestine [3].

These parts of the network are susceptible to instability, which is achieved by not studying its status before connecting the solar energy system and determining the amount of reactive power that the inverters must compensate the network with.

In large-scale PV power plants, the power factor and its correction are relevant both from the perspective of the plant and the grid [31]. The supply of reactive power is vital in a power grid. The amount of reactive power generated must closely balance that which is being consumed. A leading power factor due to capacitive loads causes a rise in voltage, while a lagging power factor due to inductive loads causes a reduction in the voltage [18]. However, most grid-connected PV inverters only produce active power, reducing the power factor as the grid supplies less active power but the same reactive power [32]. Further, emphasize the significance of regulating the power factor of PV plants, given that controlling and monitoring voltage is a crucial aspect of electrical grid systems. Accordingly, power factor compensation is a crucial step in attaining voltage demand in the connection point of PV plants. It is also a reliable way of easing the integration of distributed sources [33]. However, the method of handling reactive powers of photovoltaic plants depends on local legislative expectations.

2. Methodology

Figure 3 shows the annual temperature and irradiance values as a function of time. Palestine, as previously stated, has adequate amounts of irradiance and moderate temperatures. As a result, solar energy is one of the most promising renewable energy sources. The findings and conclusions are based on Palestinian meteorological data. Half-hourly data sets of solar irradiance and temperature are evaluated for one week, as shown in Figure 5.



Figure 3. Meteorological data of irradiance and temperature in Palestine.

2.1. Model Build Up

For load flow studies, the model has been built with ETAP 19.0.1. The Electrical Transient Analyzer Program (ETAP) is a modeling and simulation software for electrical networks that power systems engineers use to generate an "electrical digital twin" to examine electrical power system dynamics, transients, and protection. An averaged model has also been built in the Simulink environment. The latter is used to simulate changing the inverter power factor on the overall active and reactive power flow. Figure 4 shows the sub-network model consisting of a transformer in a typical town in Palestine. PV systems were distributed over five service feeders. Lengths of the cables were averaged with lumped loads at the terminals. Figure 5 shows the active and reactive power profiles for the lumped loads.



Figure 4. ETAP model block diagram.

Table 1. E	FAP model	parameters.
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Parameter	Value
Medium Voltage	22 kV
Low Voltage	0.4 kV
Transformer Capacity	1000 kVA
Transformer X/R Ratio	13
Service Line Length	200 m
Service Line Impedance	0.705 + j0.406 Ω/km



Figure 5. Load profile of a dominant residential network in Palestine.

2.2. Investigated scenarios

The electric sub-network has been investigated in terms of the power factor of PV systems connected to the power grid on the overall value of the power factor of the connection point. Moreover, it was proposed to install solar energy systems with 150 kilowatts distributed across the five service feeders. The total capacity of the systems increased through 12 different scenarios after the power factor value for all photovoltaic systems was fixed. As an example, Table 2 below depicts the different scenarios addressed by adjusting the power factor of all PV installations on the grid from 1 to 0.9 leading power factor.

Table 2. Considered PV configuration in terms of connected capacity at each feeder in (kW).

Scenario No.	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5	Total Power (kW)
1	10	0	0	0	0	10
2	10	10	0	0	0	20
3	10	10	10	0	0	30
4	10	10	10	10	0	40
5	10	10	10	10	10	50
6	20	10	10	10	10	60
7	20	20	10	10	10	70
8	20	20	20	10	10	80
9	20	20	20	20	10	90
10	20	20	20	20	20	100
11	30	20	30	20	20	120
12	30	30	30	30	30	150

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3. Results and discussion

The findings are broken down into three sections. The first step is to look at altering PVs' power factor on the PCC's total power factor. Second, a PV power fac-tor lookup table is given, which assists towns and electric network operators in determining the optimal power factor for PV installers to use. Finally, a suggested intuitive power fac-tor control block is described.

3.1. The impact of PV's power factor

As mentioned earlier, choosing the proper power factor for a grid-connected PV system could be crucial. For instance, if all connected systems are operating at a unity power factor, a decrease in the overall power factor at the point of common connection (PCC) is expected, especially at peak times. For a single system, the power factor at the PCC is given in Eq 2:

$$PF_{PCC} = cos \left[arctan \left[\frac{Q_{load}}{P_{grid} - P_{PV}} \right] \right]$$
(2)

The grid will deliver part of the real power to the load, but all reactive power will be drawn from the grid. Hence, as seen from the grid side, the total power factor will decrease at peak generation times. Power factor degradation worsens with increasing PV generation at the unity power factor. For this reason, it can be noted how important it is to reconsider the unity power factor arrangements for integrated PV systems. Figure 6 depicts how the power factor at the PCC behaves when PV integration is increased concerning the maximum active power of the connected loads. Where the load ratio r is given by dividing the total installed PV capacity by the maximum load from Figure 5 is shown in Eq 3:

$$r = \frac{\text{Installed PV Capacity } (kW_p)}{\text{Maximum Active Load } (kW)}$$
(3)

Alternatively, this ratio can also be the proportion of the total PV capacity of the average load. From Figure 6, it is quite clear how increasing the installed PV capacity by fixing the power factor of all systems at a universal power factor can degrade the overall power factor of the network. However, it has a delayed effect with a leading power factor. For instance, having all systems at a leading power factor of 0.95 gives the network operator a broader range to accept more PVs (as high as 80% with respect to the overall load).



Figure 6. PCC power factor behavior against PV power factor.

The 3D plot is shown in Figure 7. This figure gives the PCC power factor as a function of the PV power factor and the total installed PV capacity. It gives an insight into how much PV at a given power factor will be permissible. For example, the upper area sweeps all possible combinations of the PV power factor and its relative total capacity, resulting in an overall PCC power factor of 0.90 and higher. On the other side, unacceptable combinations are given by the areas at the slope of the graph. These combinations give an alarming overall power factor of less than 0.50. These findings are being widely noticed with the PV integration surge in areas like Palestine. Network operators and municipalities are more concerned about the PCC power factor than ever. Some are already requesting a complete grid impact study before getting the license to install a PV system. Nevertheless, such studies are still immature to fully address the effect of the PV power factor on the PCC power factor. Thus, this paper is considered an excellent reference for interested parties in power factor assessment.



Figure 7. PCC power factor behavior against PV power factor.

3.2. PV's power factor selection

This section develops a lookup table to help network operators and municipalities decide on the best power factor settings for any added PV systems added to their grid. Based on Figure 7, the values shown in Table 3 were established. In the first column to the left, the power ratio parameter represents the PV system's peak power to the peak power demand within the network under consideration. However, the first row refers to the proper PV system's power factor, which should be selected to get the overall power factor shown in the table. The proposed lookup table serves as a good decision-making criterion where no exhaustive grid impact studies are applicable. It is evident in small villages where they cannot acquire grid-scale data or cannot afford costly studies. It can also help predict the future overall power factor if excessive PV penetration occurs. For instance, adding more than 50% of the overall capacity can drastically reduce the overall grid power factor.

PV PF	1	0.00	0.00	0.07	0.04	0.05	0.01
Power Ratio		0.99	0.98	0.97	0.96	0.95	0.91
5.0%	94.0%	94.1%	94.2%	94.2%	94.3%	94.3%	94.5%
10.0%	93.4%	94.8%	94.0%	94.1%	94.2%	94.3%	94.7%
15.0%	92.8%	93.4%	93.7%	93.9%	94.1%	94.3%	94.9%
20.0%	92.2%	93.1%	93.5%	93.8%	94.0%	94.3%	95.2%
25.0%	91.5%	92.7%	93.2%	93.6%	94.0%	94.2%	95.4%
30.0%	90.6%	92.3%	92.9%	93.4%	93.8%	94.2%	95.7%
35.0%	89.5%	91.7%	92.5%	93.2%	93.7%	94.2%	96.0%
40.0%	88.2%	91.1%	92.2%	93.0%	93.6%	94.2%	96.3%
45.0%	86.4%	90.5%	91.7%	92.7%	91.8%	94.1%	96.7%
50.0%	84.0%	89.4%	91.1%	92.3%	91.0%	94.1%	97.1%
55.0%	80.8%	88.0%	90.4%	91.9%	91.0%	94.0%	97.4%
60.0%	77.0%	86.3%	89.7%	91.4%	91.0%	94.0%	97.7%
65.0%	71.6%	83.8%	88.2%	90.8%	91.0%	93.9%	97.7%
70.0%	63.5%	78.4%	85.0%	89.5%	91.0%	93.8%	92.8%
80.0%	43.5%	63.6%	76.3%	86.0%	91.0%	93.5%	76.7%
90.0%	22.3%	32.8%	39.7%	45.5%	51.7%	59.1%	39.0%
100.0%	1.1%	2.0%	3.0%	5.0%	12.4%	24.7%	1.3%

Table 3. A lookup table for PV power factor concerning total PV penetration.

To elaborate on how fixing the power factor at a constant value could affect the output of a PV System, Figure 8 shows real-time data from two identical PV systems at different inverters' power factors. As can be seen, the system with a 0.92 power factor has an in the parallel generation of reactive power. This reactive power can be helpful at peak times when the power factor at the connection point is expected to decrease. However, there could be a counterproductive effect of this excess reactive power at low generation times.



Figure 8. Active and Reactive power for two PV systems with different PF settings.

3.3. Suggested Auxiliary power factor controller

As concluded, setting the PV system on a constant power factor may only be helpful for specific periods, specifically at peak generation times. As shown in Figure 9, the inverter has a maximum capacity in terms of kVAs. When the power factor is set at unity, the inverter injects only active power at its maximum capacity. However, it means that less active power is injected when the inverter operates at something other than a unity power factor. Hence, an interactive power factor controller can be more realistic. Such a controller is responsible for monitoring the overall power factor to maintain a proper one at the PCC.



Figure 9. Active and reactive power capacity of an inverter.

A proposed power factor controller is shown below in Figure 10. This intuitive controller works by detecting a decrease in the PCC power factor below a specific limit. Consequently, it commands the inverter to decrease its power factor by an increment (e.g., 0.01).



Figure 10. Suggested PV block diagram of power factor controller.

If the PCC power factor increases above the limit, the controller goes back by increasing the inverter power factor by the same increment. Figure 11, shown below, shows how the injection of pure active power comes with a decrease in the PCC power factor. Thus, the controller senses the limit of 0.95 and sends a signal to the inverter to decrease the power factor by 0.01. As a result, the total power factor experiences an increase as reactive power is injected into the grid. Using such a controller could help in more than one way. First, it adds an element of flexibility with load and generation intermittency. Second, it serves as an economic optimization tool, where customers can avoid penalties concerning excessive reactive power consumption. Moreover, it maximizes the active power generation when there is no need for a leading power factor. To elaborate on the latter, Figure 12 shows how a fixed power factor can waste much energy, especially at times other than the peak.



Figure 11. Performance of the suggested power factor controller.



Figure 12. PF influence on output energy from the PV system.

This refers to utilizing the suggested power factor controller could encourage municipalities and grid operators to consider such controllers as a superior way to overcome power factor compensation. Such controllers can be found commercially with various construction. For example, the power factor monitoring and control system has been used in several solar power plants in Palestine, with the Skytron system being used for the first time in a solar power plant with a peak capacity of 992 kW on the roof of the National Aluminum and Profile Company (NAPCO) factory in 2019. This technique is used in two ground-based solar power facilities in the Palestinian territories of Birzeit and Ya'bad [34,35]. Many aspects of the station's performance, particularly the power factor, are controlled by the device, which is constantly working to change the value of the inverters to ensure the highest production and the highest efficiency of the station without affecting the power factor of the PV system. These data are taken from a 1 MW PV plant in Birzeit, Palestine. It is evident how at low generation, time step 35, the inverter increases its power factor since there is less need for reactive power.



Figure 13. PCC power factor behavior against PV power factor.

When it comes to distributed generation (DG) using renewable energy (RE) sources, there are several obstacles to overcome, the most prominent of which is the impact of intermittency, as well as technological concerns deriving from grid connections [36]. The photovoltaic array, for example, feeds electrical energy directly into the electrical grid (also known as grid-tied systems), such as a solar-powered system [37]. Due to the unpredictability of solar radiation, this kind of system is regarded as an unstable energy source. Although challenging to forecast, the performance of these systems is vitally significant in many associated aspects such as system sizing and control [38]. Because the integration of distributed generation into a power system is not considered in the initial network design, certain technical consequences of PV integration into a power system might occur [39]. Moreover, various factors can be analyzed and studied as the impact of connecting PV plants to the national grid, such as the evaluation of the harmonics generated by the PV inverter and the influence of these harmonics on the current harmonic spectrum of the current injected by the PV system at PCC bus [40].

4. Conclusions

The increased penetration of PV systems in Palestine requires an in-depth study to consider their impact on the national grid. Overall grid power factor comes as one of the essential criteria to be considered when any grid impact study is performed. This paper's extensive literature review of the power factor importance and its side effects was delivered. Besides, a lookup table was developed to help grid operators choose the proper power factor for any PV system added to the grid. All data used in this study are actual data to increase the validity of the findings. It was also found that an auxiliary power fac-tor controller can be even more helpful and less stressful for designers to improve power factor.

Acknowledgments

The author would like to thank the Solar Energy Research Institute, UKM for the lab facilities. This research was funded by Universiti Kebangsaan Malaysia (UKM), research grant Program Translational MRUN Rakan-RU-2019-001/4.

Conflict of interest

The authors declare no conflict of interest

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