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A REVIEW ON IMPACT OF LARGE SCALE PV CONNECTED SYSTEM ON GRID AND INVESTIGATING THE INSTABILITY PARAMETERS

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Abstract
The installation of residential solar systems in India is a solution that can help lower the country's electricity expenditures while also being beneficial to the environment. These systems, despite the many benefits they offer, are associated with a number of drawbacks that affect the infrastructure of the whole electric grid. A decrease in the power factor of the distribution grid may be one of the potential side effects of increased penetration of photovoltaic (PV) systems, for example. When the power factor is low, there is an increased likelihood of heat production as well as switch failures. In spite of the fact that previous study of a similar nature has been published in the past, this is the first time that PV systems have been evaluated in India in terms of their power factors. People who are interested in learning how photovoltaics (PVs) influence the total power factor of their systems might use this research as a resource. In the beginning of this investigation, the researchers proposed a straightforward power factor selection criterion that may be used for photovoltaic (PV) systems. Second, the piece included a suggestion for an auxiliary power factor controller in its conclusion. According to the findings of this research, the conclusions of this article might be used by municipalities, grid operators, and legislators as a tool to assist them in the planning, forecasting, and accommodating of new PV systems in their grids in terms of total power factor. This would be the case because of the findings of the study. However, despite the fact that the data utilized in this investigation come from Indian sources, it is still possible to employ the findings in other parts of the world because the data sets that were utilized cover the entire planet.
Key words: PV system; power systems; power factor; solar energy; India.

1 Introduction

In order to convert the energy from the sun into usable power, the photovoltaic (PV) system consists of one or more solar panels, which are then connected to an inverter and several other pieces of electrical equipment. The photovoltaic (PV) systems come in a wide range of sizes, with the smallest being installed on rooftops and the largest being installed in utility-scale power plants. India is one of the countries across the world that gets an adequate amount of radiation from the sun. In spite of this, India suffers from power shortages, with a significant proportion of its electricity coming from imports from foreign nations. In addition to having an insufficient quantity of energy, India has one of the most rapidly expanding populations in the area. The population almost reached 5.3 million in 2021, having more than doubled from 2.7 million in 1997 to that number in the past 25 years [1]. As a result, there is a high demand for power, and the government has implemented a number of different initiatives in an effort to make up for the deficit. One of the initiatives that the government has already put into action is encouraging people to use photovoltaic (PV) systems. According to P.E.a.N.R.A., it is anticipated that the demand would increase from 1400 MWp to 2335 MWp by the year 2030 [2]. According to research carried out throughout the nation, a significant number of residential structures are currently wired for photovoltaic systems. When putting into action this approach, all of the necessary stakeholders should keep in mind the power factor notion. In an alternating current (AC) power system, measuring the phase difference between the current and voltage is what is meant by the term "power factor."

1.1 Residential PV systems

PV systems are among the fastest-growing renewable energy sources. PV systems offer clean, safe energy. Solar PV tilting, solar radiation, ambient temperature, wind speed, and dust deposition impact this energy source [3,4]. Middle East sun radiation remained strong [6]. India has significant sun irradiation. The average annual sunlight is 3000 hours.

India relies on neighboring nations for electricity. India imported 91% of its power in 2016 [7]. Electricity is a basic requirement for many Palestinian homes. Air conditioning and cooling require electricity [8,9]. India lacks a power plant, therefore officials have developed PV systems to generate electricity. This has caused too many issues, pushing the Palestinian government to invest in PV systems. The favorable policy has improved residential PV systems in India. Khatib, T. et al. showed that energy policy may make or break solar power [3].

Most nations' policies determine PV generation. Tax reduction, market capacity, financial and fiscal incentives, and technical and non-technical information distribution should be prioritized. To address the power shortfall, several Palestinian cities have adopted PV electrical systems.

39 MW PV systems exist. Unfinished PV installations exceed 93 MWp [3]. However, policy difficulties in India hinder PV system growth, according to study. Technical standards, awareness, and information distribution are issues. These concerns have slowed India's PV electricity systems.

Apartments house most Indian homes. Residents own 85% of residential units [7]. Neighborhoods and clusters of residential dwellings dominate cities. In India, a 1 kW rooftop system at ideal tilt and orientation angles generates 1635 kWh per year in Hebron, 1613 in Jerusalem, 1562 in Nablus, and 1557 in Gaza city [7]. PV's national destiny depends on the outcome. Urban residential constructions may maximize solar energy. PV system development depends on building quality and type.

The deployment of grid-connected PV systems was impacted by falling PV prices and supportive government regulation of renewable energy [10]. Residential structures, governments, schools, and private enterprises have PV systems. [11] Examined three-year-old PV house systems. The systems produced 4.81 kWh/kWp each day, according to studies. 1756 kWh/kWp annually.

The payback period is 4.9 years, the cost per kWh generated is 0.43 NIS (0.115 US $), and the internal rate of return is 25%. Further research has revealed the national grid's PV system's value. PV systems reduce losses, power factors, and voltage [12]. Its clean nature has helped the environment and provided power to many

India. Figure 1 shows a grid-tied PV system design.

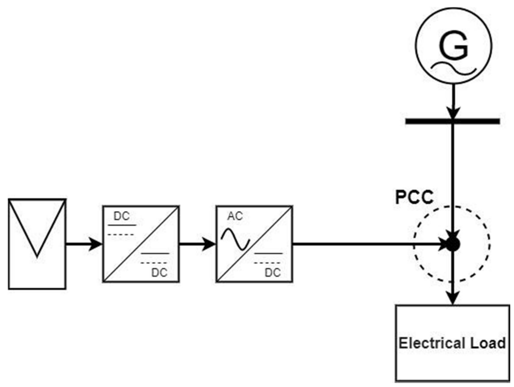

Figure 1. On-grid PV system block diagram.

Grid-connected PV systems link to the power grid. Inverters connect PV systems to utility grids. Inverters convert DC to AC. The three concepts can be used to residential structures [14]. Researchers have studied home PV systems' electrical behavior. [10] Examines French household PV installations. This research tries to address three key questions: energy production, performance, and quality characteristics [10]. French PV installations averaged 1163 kWh/kWp in 2010 [10]. PV systems have also grown in South American nations like Chile [13]. Thus, PV systems continue to power numerous countries and towns worldwide. PV systems enable clean, quiet, and reliable electricity generation..

1.2 Power factor of the PV systems

Power factor is an essential electrical concept. It is the phase difference between AC power system current and voltage. A unity power factor is achieved in resistive loads like an electric kettle or incandescent bulb [16]. Inductive and capacitive loads, such inductive motors and capacitor banks, are different. Non-unity power factor occurs when current lags or leads voltage. Loads use active and reactive power in non-unity power factors. Eq 1 shows that active power is genuine power and directly involved in work: [17].

$$F = \cos(\tan\text{-}1\ ) \qquad (1)$$

Most PV systems create active power [16]. However, research reveals that this affects actual power factor, forcing the grid to offer less active power with the same reactive power.

PV systems usually lower power factor, resulting in fines if not corrected [19]. The load immediately receives active electricity from the solar system. Thus, utility active power demand decreases. However, load reactive power stays constant [20]. Grid power factor decreases. Reducing power factor penalizes the grid operator for consumers. However, research has identified numerous power factor-reducing methods [19]. Inverter manipulation is the main technique. Stakeholders should focus on the active-reactive power ratio. This controls active and reactive power to the load [20]. Capacitors may also rectify power factor. Capacitors decrease current magnetization. Power factor improvement reduces voltage loss, utility bills, and environmental damage [20]. Due to reduced cable and other component stress, a lower power factor extends equipment life..

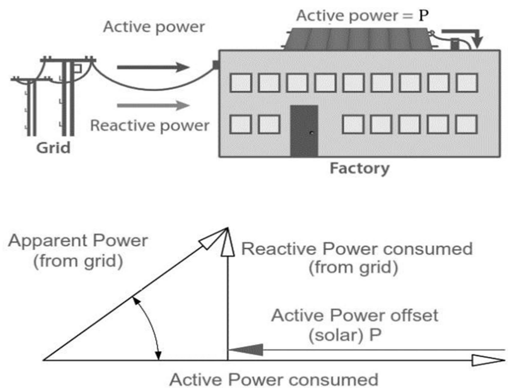

Figure 2. Production plant schematic [25].

1.3 Choosing the correct power factor of PV systems

A grid-connected PV system's power factor selection is now critical [26]. If not addressed, solar energy integration may lower the electrical infrastructure's power factor (PF), resulting in fines. Since the solar system produces and delivers only active energy, less grid energy is needed to create the same reactive energy [26]. Solar companies must minimize kVAR penalty [27]. Installing a specific SCADA system with a Power Factor Correction device can rapidly and successfully fix this problem [27]. Power factor compensators can avoid the penalty.

Power factor fines and settings vary per electricity distributor in India. The North Electricity Company estimates a solar energy system's power factor at 0.92, lower than the national average [28]. This would limit solar energy systems' energy production when it's unnecessary. Technical investigations should also be done before decreasing power factor for specific systems. The excessive design may harm this facility's network or loads. However, after fourteen trial days of PV system commissioning, the Jerusalem District Electricity Company operates and checks the station to assess the effect of connecting it to the network and gather data for proper evaluation [29]. The firm alerts the facility owner if necessary, evaluating each project. In the Al-Nuwaimah Plant, a 7.5-megawatt solar power plant control system was asked [30] to continually alter the power factor to meet the network's condition without hurting it or its equipment. Municipal authority regulation does not provide technical requirements for assessing inverter power factor [31]. These authorities make up 32.5% of India's power distributors [3]. Not researching the network's condition before joining the solar energy system and establishing the inverters' reactive power requirements makes these sections unstable.

Power factor and its adjustment are important for large-scale PV power installations and the grid [31]. Power grids need reactive power. Reactive power must match consumption. Capacitive loads raise voltage, whereas inductive loads lower it [18]. Most grid-connected PV inverters only create active power, lowering power factor since the grid delivers less active power but the same reactive power [32]. Since electrical grid systems depend on voltage management and monitoring, PV plant power factor regulation is vital. Thus, PV plant connection point voltage demand requires power factor correction. It helps integrate dispersed sources [33].

Local laws determine how solar plants handle reactive powers.

2 Methodology

The yearly temperature and irradiance data are shown as a function of time in Figure 3. As was said before, India enjoys a satisfactory quantity of available irradiance and temperatures that are just right. As a consequence of this, solar power is currently considered to be one of the most promising forms of renewable energy. The findings and conclusions have been derived from the meteorological data collected in Palestine. As can be seen in Figure 5, solar irradiance and temperature are analyzed on a weekly timescale using data collected every half an hour.

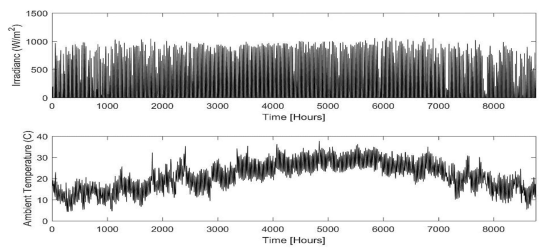

Figure 3. Indian temperature and irradiance data.

2.1 Model Build Up

ETAP 19.0.1 was used in the construction of the model so that it could be used for load flow analyses. The Electrical Transient Analyzer Programmed (ETAP) is a modelling and simulation programmer for electrical networks. It is used by power systems engineers to construct a "electrical digital twin" in order to investigate the dynamics, transients, and protection of electrical power systems. Additionally, in the context of Simulink, an averaged model has been developed. The latter is used to mimic the effect of modifying the power factor of the inverter on the total active and reactive power flow. Figure 4 is a representation of the sub-network model that includes a transformer and takes place in a typical Indian village. A total of five service feeders were used to distribute the PV systems. We took the average of the lengths of the wires and measured them with lumped loads at the terminals. The active and reactive power profiles for the lumped loads are illustrated in Figure 5.

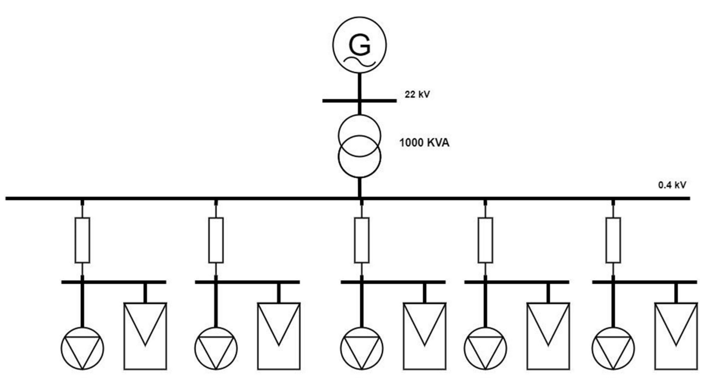

Figure 4. ETAP model block diagram.

Table 1. ETAP model parameters.

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

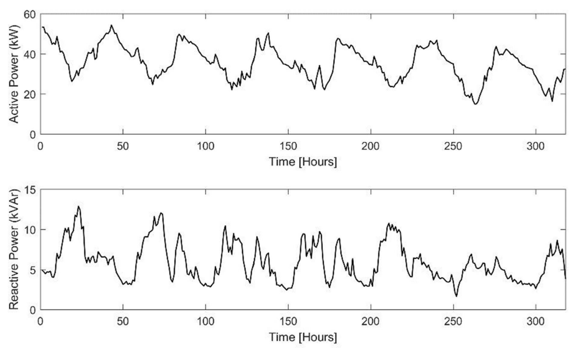

Figure 5. Load profile of a dominant residential network in India.

2.2 Investigated scenarios

The power factor of photovoltaic (PV) systems that are linked to the power grid has been researched with regard to the electric sub-network in terms of its impact on the total value of the power factor at the connection point. In addition, it was suggested that solar energy systems with a total capacity of 150 kilowatts be installed, with that power being split evenly among the five service feeds. After determining a single number for the power factor of all solar systems, we ran 12 alternative scenarios and found that each one improved the total capacity of the systems. For illustration purposes, the following table, which can be seen below, displays the many situations that may be addressed by modifying the power factor of all PV installations on the grid from 1 to 0.9 leading power factor.

Table 2. PV design by feeder capacity (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

3 Results and discussion

The findings are presented in three distinct sections here. The first thing that has to be done is to investigate the impact that changing the power factor of the PVs would have on the total power factor of the PCC. Second, a lookup table for the power factor of photovoltaic systems is provided. This table aids municipalities and electric network operators in establishing the power factor that is best for PV installers to employ. At long last, an intuitive power factor control block has been conceived and explained.

3.1 The impact of PV's power factor

As indicated, a grid-connected PV system's power factor is important. If all linked systems have a unity power factor, the point of common connection (PCC) power factor will fall, especially at peak periods. Eq 2 gives the PCC power factor for one system.:

FCC = o rt n [od](2)
rdV

Alternately, this ratio may alternatively be interpreted as the percentage of the entire PV capacity that is represented by the average load. As can be seen from Figure 6, increasing the installed capacity of PV by maintaining the power factor of all systems at a universal power factor might result in a decrease in the overall power factor of the network. On the other hand, the impact is delayed and a leading power factor is involved. For example, if all of the systems have a leading power factor of 0.95, the network operator has a wider range to accept additional photovoltaic cells (up to 80 percent of the total load).

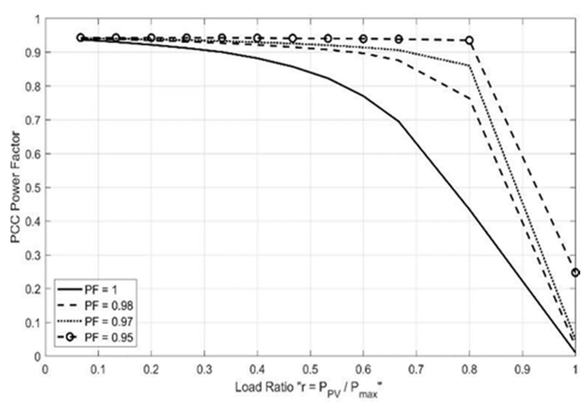

Figure 6. PV vs. PCC power factor.

Figure 7 presents the plot in three dimensions. This figure presents the power factor of the PCC as a function of the power factor of the PV and the total capacity of the PV that has been installed. It offers a glimpse into how much photovoltaic energy at a particular power factor will be acceptable. For instance, the upper section does a sweep of all of the potential combinations of the PV power factor and its relative total capacity, which ultimately results in an overall PCC power factor of 0.90 or higher. On the other hand, combinations that are not acceptable are denoted by the regions that are located at the slope of the graph. Because of these combinations, the overall power factor is significantly lower than 0.50. These findings are gaining widespread attention as PV integration rates continue to climb in countries like India. When it comes to the PCC power factor, network operators and governments are more worried than they have ever been. Before obtaining a license to build a photovoltaic system, some people are already asking for a comprehensive analysis of the system's impact. However, such studies are in their infancy and are not yet capable of addressing the entire influence that the power factor of PV has on the power factor of PCC. As a result, those who are interested in power factor evaluation should consider this study to be an outstanding source of reference.

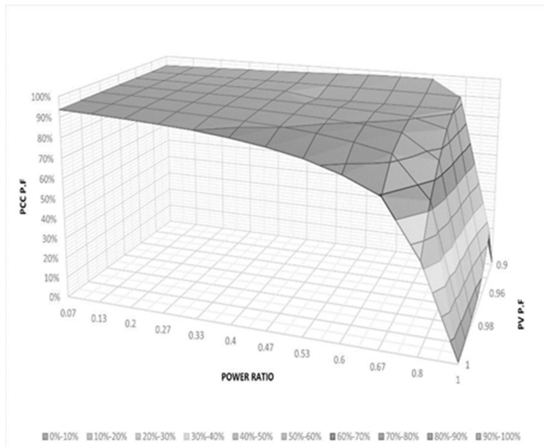

Figure 7. PCC power factor vs PV power factor.

3.2 PV's power factor selection

In this part, a lookup table is developed to assist network operators and municipalities in determining the optimal power factor values for any additional PV systems that are added to their respective grids. The numbers that are shown in Table 3 were determined on the basis of Figure 7. The power ratio parameter is represented in the first column to the left and it compares the peak power of the PV system to the peak power demand within the network that is being considered. However, the first row contains information on the power factor of the correct PV system, which needs to be chosen in order to obtain the total power factor that is displayed in the table. The lookup table that has been developed is useful as a criterion for decision-making even in situations when extensive grid impact analyses are not applicable. It is especially noticeable in smaller settlements, when residents are unable to obtain data on a grid size or pay for expensive investigations. In the event that there is an excessive penetration of PV, it can also assist anticipate the future overall power factor. For example, increasing more beyond fifty percent of the total capacity can significantly lower the overall grid power factor.

Table 3. PV penetration lookup table..

Power Rat	1	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%

Figure 8 shows real-time data from two identical photovoltaic (PV) systems with different inverters' power factors, which may be used to demonstrate how power factor changes affect PV system output. The power factor 0.92 system generates reactive power in parallel. Peak demand lowers the power factor at the connecting point., this reactive power might be of great assistance. At low generation periods, however, there is a possibility that this surplus reactive power will have an impact that is counterproductive.

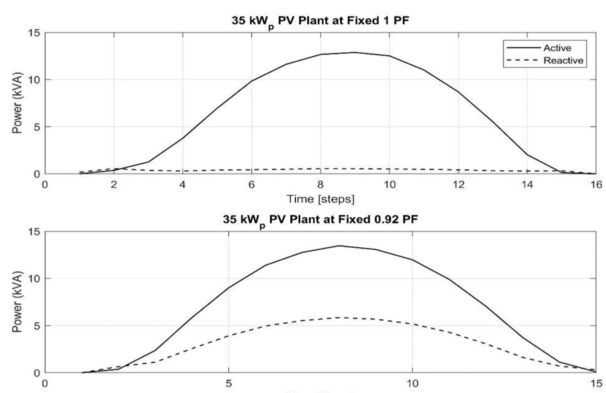

Figure 8. Active/Reactive power for two PV systems with differing PF settings.

3.3 Suggested Auxiliary power factor controller

As was established, configuring the PV system to operate with a constant power factor may only be beneficial during certain times of the day, notably during times of peak generation. Figure 9 illustrates the inverter's maximum capacity, which is measured in kilovolt-amperes (kVAs). When the power factor is adjusted to a value of one, the inverter will only inject active power up to the limit of its capacity. When the inverter runs at a power factor that is not unity, however, the result is that there is a reduction in the amount of active power that is injected. As a result, a power factor controller that is interactive has the potential to be more realistic. A controller of this type is accountable for ensuring that the power factor at the PCC as a whole is constantly monitored. After that, it takes action by transmitting an instruction to the inverter, which tells it to charge the power factor in order to keep a suitable one at the PCC.

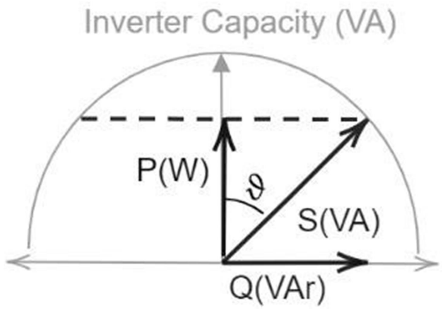

Figure 9. Inverter active and reactive power.

Figure 10 is an illustration of a power factor controller that has been suggested. This intelligent controller detects a decline in the PCC power factor that falls below a particular limit in order to carry out its function. As a consequence of this, it issues a command to the inverter telling it to reduce its power factor by a certain amount (for example, 0.01).

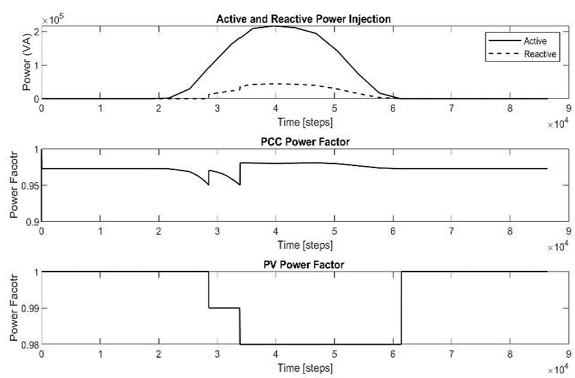

Figure 10. PV controller block schematic.

If the PCC power factor rises beyond the limit, the controller will respond by raising the inverter power factor by an increment of the same size. Figure 11, which may be found below, demonstrates how the injection of pure active power is accompanied by a reduction in the power factor of the PCC. As a result, the controller is able to detect when the power factor has reached its maximum of 0.95 and sends a signal to the inverter to reduce it by 0.01%. As a consequence of this, an increase in the total power factor is experienced as a result of the injection of reactive power into the grid. Utilizing this kind of controller could be helpful in more ways than one. First, it provides an additional degree of flexibility in dealing with the intermittent nature of both load and generation. Second, it functions as a tool for economic optimization, allowing consumers to avoid fines related to high reactive power use. This is one of its many benefits. In addition to this, it makes the most out of the active power generation even when there is no requirement for a leading power factor. Figure 12 illustrates how a fixed power factor can waste a significant amount of energy, particularly at periods other than the peak demand. This helps explain the previous point.

Figure 11. Proposed power factor controller performance.

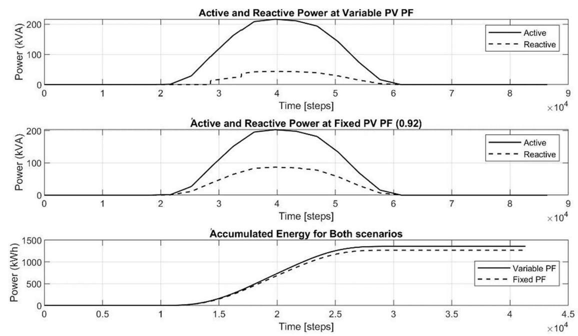

Figure 12. PF affects PV system output.

This is in reference to the use of the proposed power factor controller, which might persuade municipalities and grid operators to consider such controllers as an improved method to circumvent power factor adjustment. These controllers are readily available on the commercial market and come in a variety of constructions. Indian solar power facilities use the power factor monitoring and control system. The Skytron technology was initially used in a 992 kW solar power plant on the top of the National Aluminium and Profile Company (NAPCO) factory in 2019. This approach is used by ground-based solar power facilities [34,35]. Most importantly, the gadget controls the station's power factor. It continually adjusts the inverters to maximise production and efficiency without altering power factor at the connection point. Such a controller may change the PV system's power factor as shown below. A 1-MW photovoltaic (PV) plant in Birzeit, India, took these measurements. At a low generation time step, 35, the inverter increases its power factor since reactive power is less needed...

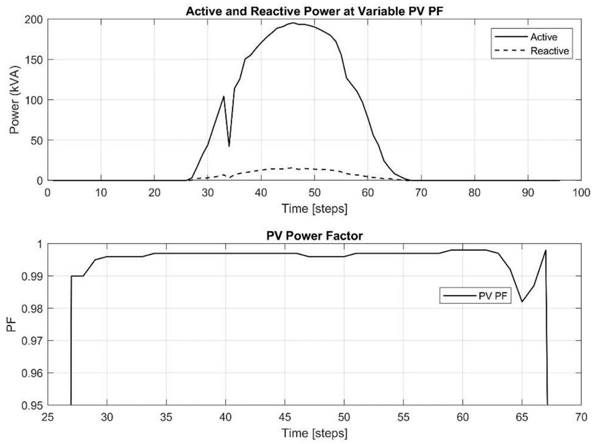

Figure 13. PV vs. PCC power factor.

There are several obstacles to overcome when it comes to distributed generation (DG) using renewable energy (RE) sources. The most evident of these obstacles is the impact of intermittency, as well as technological issues resulting from grid connections. [36]. There are also a number of other difficulties. For instance, a photovoltaic array, which is an example of a solar-powered system, is capable of feeding electrical energy directly into the electrical grid, which is also referred to as a grid-tied system [37]. This sort of technology is considered an unreliable source of energy due to the unpredictability of the sun's radiation. The performance of these systems is crucially important in many connected elements such as system sizing and control [38], despite the fact that it is difficult to foresee how well they will operate. Certain technical repercussions may be brought on by the incorporation of PV into a power system due to the fact that the incorporation of Distributed generation is not considered during network design [39]. Connecting PV facilities to the national grid also affects several things. The current harmonic spectrum of the PV system's current injected at PCC bus is affected by the PV inverter's harmonics [40].

4 Conclusions

The growing prevalence of photovoltaic (PV) systems in India calls for a comprehensive investigation on the effects these systems will have on the country's electrical infrastructure. The overall power factor of the grid is one of the main parameters that must be taken into consideration during any grid impact research that is carried out. The detailed literature study that was presented in this paper on the relevance of the power factor and its side effects was covered. In addition, grid operators were provided with a lookup table to assist them in selecting the appropriate power factor for every photovoltaic system that was added to the grid. For the sake of increasing the validity of the findings, this study only makes use of actual data in all of its data collection and analysis. An auxiliary power factor controller was also found to be considerably more beneficial and less stressful for designers in their efforts to increase power factor.

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