Photovoltaic System Penetration on Voltage Profile, System Loss and Transmission Line Power Flow

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Abstract

In many different ways, solar energy has been studied in many ways. Continuous reduction in the prices of solar photovoltaic systems makes solar energy more efficient compared to other types of renewable energies. The main points of the use of solar panels are subject to high penetration of electric power supply for remote areas. Considering this concept rather than the design and fabrication of transmission lines, it reduces the total power system losses and increases the reliability and overall system stability of the system. However, distributed power generation may cause significant voltage regulation and problems in the power system. This paper examines the effect of high penetration photovoltaic systems on voltage profile, system loss, and transmission lines power flow. The IEEE 9 bus system is considered as a standard test system for analysis. The simulation was carried out with the help of ETAP v16.0.0, which is a very convenient tool for the simulation and analysis of the power system.

Keywords: High penetration photovoltaic; Steady-state analysis; Voltage profile; System loss; Transmission line power flow.

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1. Introduction

Renewable energy is a term used to show the energy from a source that does not end when used.

Wind or solar energy is very important among all forms of energy sources and is concerned throughout the world.

Of course, the reduction in the use of fossil fuel resources and its dependence is essential to reducing emissions and protecting energy in the future. Switching to renewable energies is a promising solution to the current crisis.

The high cost of renewable energy so far has been the main hurdle to its development. But to promote renewable energy installations, policies and regulations will change in all the major countries.

Also, due to recent developments in technology and research, the cost of renewable energy has been steadily decreasing, which is the most important drop in price in the sun, which is 80 % in the last seven years.

The cost of solar photovoltaic systems is owing to dramatic advances in the technology sensing technology.

PV cells are the fundamental elements of the total solar panels generating PV arrays when they are connected. Currently, PV cells are cheaper than before and are still cheaper, resulting in better efficiency of distributed solar generation in the whole power distribution system [1].

High penetration is concentrated on large solar panels in which influence is significant. More than 15 % of the maximum daily load is feeder.

However, this percentage will be different in various studies.

Currently, its impact on the electricity program and its customers has not been implemented in most cases.

The solar panel, which is described below, has exceeded what most experts consider influential scenarios.

Voltage, power quality, and other operational parameters are retained in the range of need with minimum negative effect on distribution and service users.

These case studies are intended to illustrate the success stories by integrating the large PV plants at the distribution level as well as some solutions used by the utility to ensure the safe and reliable operation of the solar system and distribution power system [2].

The solar photovoltaic installations have so far been small in size and quantity and have only been associated at distribution points. But large solar parks of the order of hundreds of MW are coming up and at transmission, the level will be linked.

With such a large increase in the deployment of solar photovoltaics, operators of power systems are expected to address a new set of issues due to the different nature of the generation.

The solar photovoltaic system has the ability to reverse the power flow from the loads to the transmission system and actually has zero or very low reactive power generation [3].

More disadvantages are mentioned in [4-18].

It is expected that large grid photovoltaic plants will be close to conventional plants and help for grid stability management.

Therefore, if built without any advanced controls, large solar PV plants will have an effect on the stability and safety of the grid. It is, therefore, necessary to examine the problems of large solar PV penetration into the power system.

Solar energy (especially PV) and wind energy are two main sources among renewable energy sources that are commercially well established and proven technology for clean energy production.

By the end of 2019, the installed world capacity of photovoltaic (photovoltaic) and wind was 646.8 GW and 655.9 GW, using 1302.7 GW from total renewable installations. Renewable energy-based electricity production has recently increased rapidly, especially solar energy.

Advances in the production of PV panels and the natural PV solar advantages on resources and other technologies have paved the way for such huge growth.

PV solar technology has many advantages over others such as small size, ease of installation, without moving mechanical parts, smooth functioning without noise, need for less maintenance.

Statistical predictions show that solar installations will grow faster in the coming years.

The situation in India is also aimed at making 5 GW of solar energy up to 2022.

Therefore, it is time for studies and analysis of the effect of increasing the influence of solar PV on the grid, which is currently dominated by conventional resources. This will help identify problems related to the high penetration of solar PV to the network.

So far, PV solar installations are small in volume and size only connected at the distribution level.

But large solar parks are increasing around 100 MW and are connected to the transmission level. According to the MoE (Ministry of Energy) and SATBA (Renewable Energy and Energy Efficiency Organization), the penetration of the solar at present is about 0.5% (350 MW) from a total of 75000 megawatts (in 2019).

Renewable energy sectors, the day's order and the government's power to upgrade renewable energy across the country have been increasing rapidly.

As discussed in the SATBA, it will be around 6.7 % until 2022.

Until now, the solar PV installations were small in size and quantity and were connected only at the distribution level. But large solar parks of the order of hundreds of MW are coming up and will be connected at the transmission level.

With such an extensive growth in the deployment of solar PV, power system operators are expected to deal with a new set of issues due to the different nature of the generation.

Power operators are expected to face a vast growth in the deployment of solar power plants with a new set of issues due to the different nature of production.

Solar PV has the ability to switch power flow from the load to the system and is now zero or very low.

Solar PV is also connected to the grid as opposed to the thermal power plant at the same time. Hence, they do not contribute to the stability of the network. This is a significant aspect of normal synchronous generators that help in responses due to control frequency [19].

It is also currently protecting the mode of dealing with islanding in the real-time of the plant, which is a network defect.

This will not occur when the power plant capacity is lower, but if the capacity of the power plant is large, it will affect the stability of the network, as it causes imbalance of production and the output of the solar power plant is also highly dependent on weather conditions and seasonal changes.

Hence, if the capacity of the power plant is large, such changes will greatly affect the network [20].

The following is mentioned. Solar power plants are expected to be similar to conventional plants and support network stability management.

As such, large solar power plants that run without certain control will affect the stability and security of the network.

Therefore, it is important to analyse issues related to the large impact of solar PV on the power system.

2. IEEE 9-bus system modelling in ETAP

Small power systems are not realistic to be regarded as a high-penetration PV system since the renewable energy systems significantly affect the bus voltages in such systems.

This paper selects the standard IEEE 9 bus system (Figure 1) for review as the findings are appropriate and the system load flow estimates converge from zero to hundred percent for all forms of PV penetration.

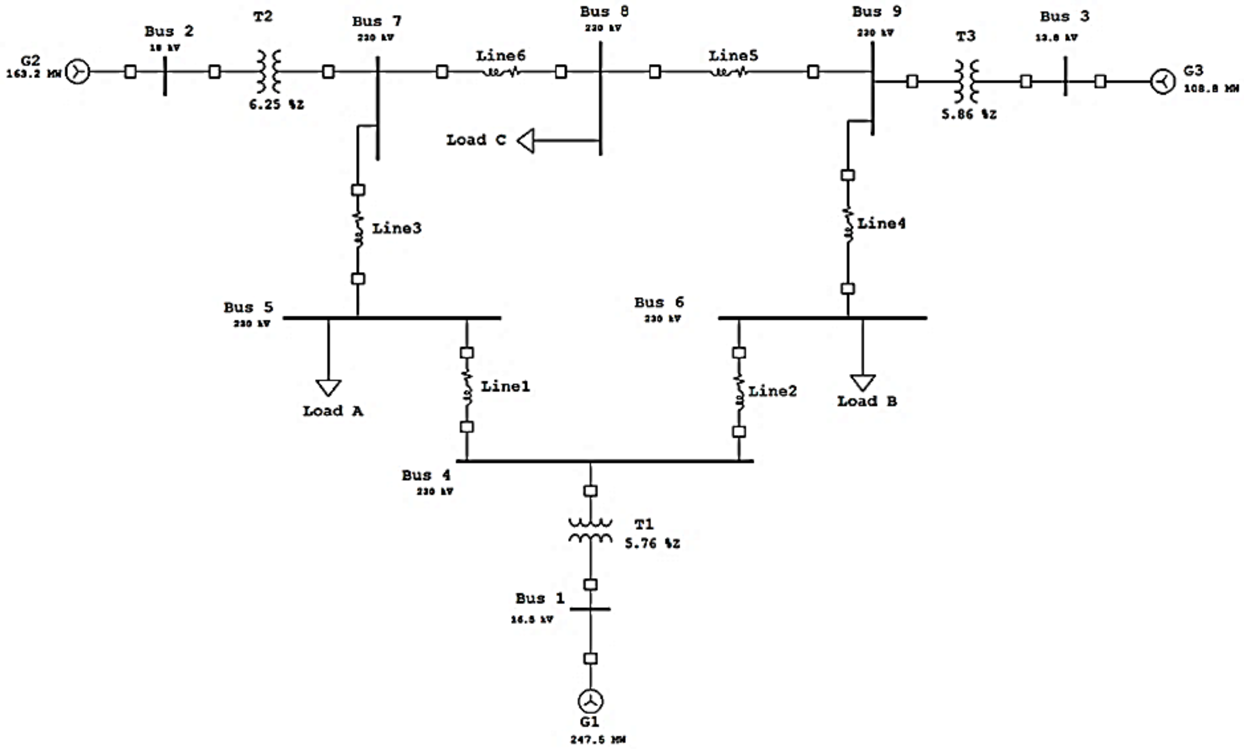

Figure 1. IEEE 9-Bus system

Figure 1 displays the standard 9 bus system used in this paper for study, which involves three generators linked to three separate buses in the looped network.

Generator 1 is considered to be the swing bus and Generator 2 and Generator 3 is considered to be the type of voltage control bus.

Nevertheless, there are many drawbacks to operation in the high PV penetration process.

Lack of solar energy during daylight time, the need for storage devices to supply power at night, safety and synchronization with the classic power systems and space needed for photovoltaic farms are some of the problems that restrict high-penetration photovoltaic systems.

Load flow results for the IEEE 9-Bus system as shown in Table 1.

Table 1. IEEE 9-Bus system load flow results control

General	
Generation Cat	Design
Diversity Factor	Normal Loading
Buses	9
Branches	9
Generators	3
Loads	3
Load-MW	319.337
Load-MVar	22.64
Generation-MW	319.337
Generation-MVar	22.64
Loss-MW	4.661
Loss-MVar	-92.212

3. Photovoltaic penetration of the IEEE 9-bus system

In ETAP, the complete test IEEE 9-bus system was first developed. Then, using the PV array base, a model of a typical solar PV plant is created.

Several small 200 Watt PV panels are combined in series and parallel combinations to achieve a PV array with a maximum output of approximately 21.8 MW and a DC bus voltage of approximately 1000V (V dc). Every PV array have an approximately 11kV and 26.2 MVA inverter unit with an AC rating.

Several of these PV arrays were created and pooled into a popular 11kV bus called a solar bus.

The solar bus consists of 11 solar arrays with the power of 21.8 MW, the total power of the solar bus is 240 MW.

The solar bus output is then provided to a transformer station, which increases the voltage produced by 11kV to 230kV, which would be suitable for penetration into the transmission bus.

This solar bus is connected to Bus No. 5, into the IEEE 9-bus network, as shown in Figure 2.

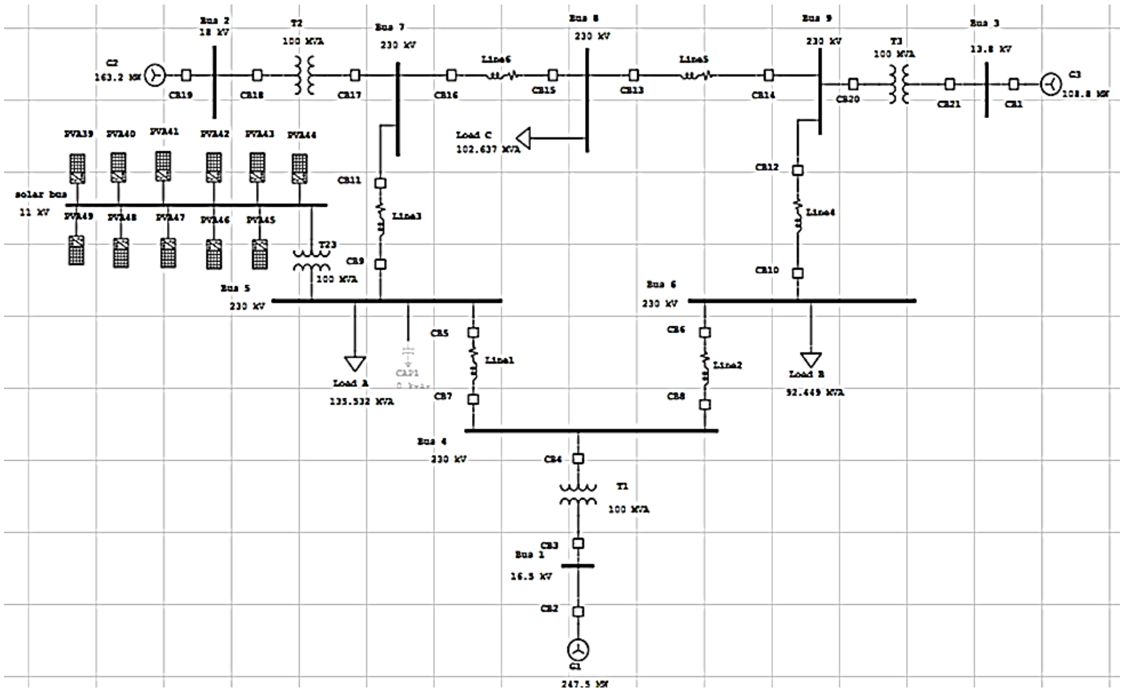

Figure 2. IEEE 9-Bus system containing solar bus

4. Steady state analysis

With 0 percent solar penetration, the IEEE 9-bus system model without solar integration was considered as the base case.

Then the solar power plant was first incorporated into bus 5 (case 1) as it is associated with the largest load and highest voltage drop. For calculating the percentage of solar PV penetration, the base case slack bus power (Generator G1) was taken as a benchmark.

The energy pumped into the grid via bus-5 by the solar PV plant is slowly increased from approximately 0 percent to approximately 100 percent in steps of 10 percent.

In each step, load flow calculation was performed, and different parameters were noted.

Steady-state power flows are observed in lines, bus voltages, generation details, and system losses. With the incorporation of solar PV into other buses, namely bus 6 (case 2) and bus 8 (case 3), the process is repeated.

4.1. Effect of Solar PV Penetration on Steady-State Voltages

Three separate instances of solar PV integration are considered for the study, namely penetration on bus 5, bus 6 and bus 8. For all three cases, full bus data are considered for all solar PV penetration rates from 0 MW to 240 MW.

Regarding the penetration rate, the bus voltages are plotted. The 11kV solar bus voltage is also considered.

The plots of Voltage profiles for the IEEE 9-Bus system containing solar bus at Bus 5, 6 and 8 are as shown in Figures 3, 4 and 5.

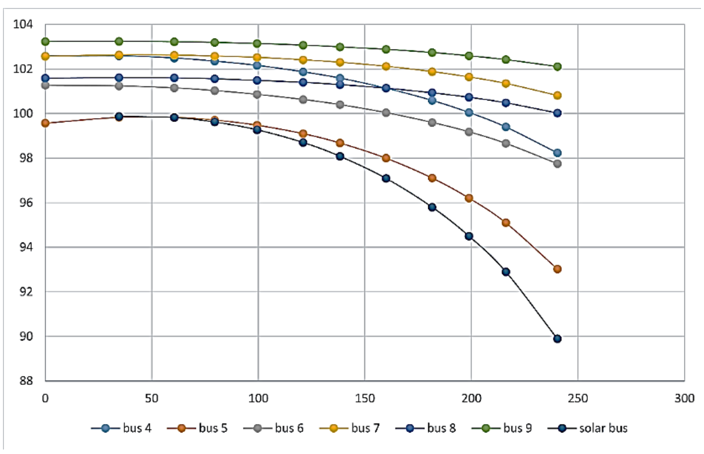

Figure 3. Voltage profiles for IEEE 9-Bus system containing solar bus at Bus 5 (case 1)

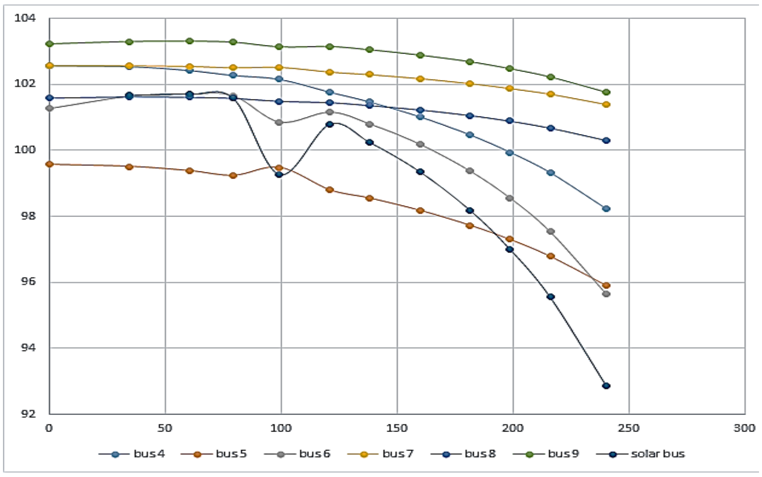

Figure 4. Voltage profiles for IEEE 9-Bus system containing solar bus at Bus 6 (case 2)

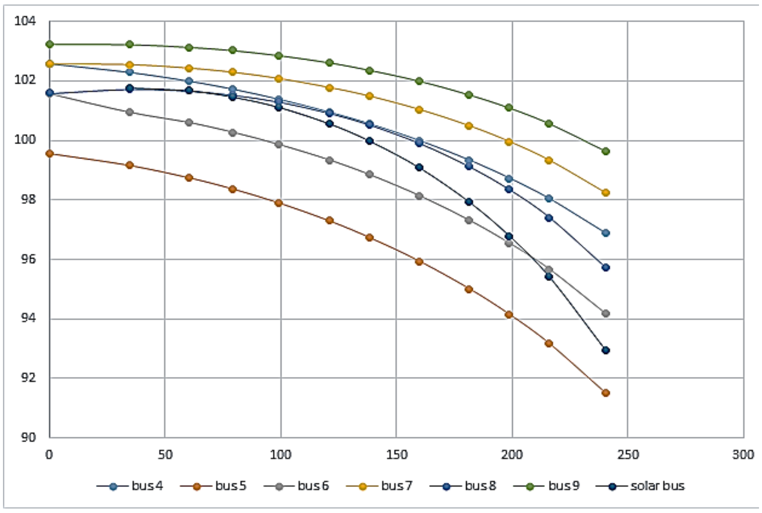

Figure 5. Voltage profiles for IEEE 9-Bus system containing solar bus at Bus 8 (case 3)

As seen in Figures 3, 4, 5, in the plot of bus voltages, the voltage profile seemed to be improving initially as the solar penetration is increasing but it starts dropping beyond a certain percentage.

A similar trend of voltage variation is observed in all three cases. The voltage starts collapsing as the solar penetration beyond a certain point causes the line drop to increase. But the intensity of variation in voltages varied with the location of penetration.

The maximum variation in bus voltages is 6.8% in Case 1 and 6.05% in Case 2 and 8.07% in Case 3.

Buses 1, 2 and 3 are omitted from the story because throughout the penetration they are constant. This is due to Bus 1 being modelled in swing mode and Bus 2 & 3 being modelled in voltage control mode.

The peak point of the curve also varies with the location of penetration. Hence, solar PV penetration into the system can only be allowed up to the point where the voltage profile improves.

In cases 1 and 2 the voltage in most of the buses seemed to be improving and after that, it collapses.

Case 3 was even severe with almost all bus voltages were starting to collapse right from the beginning and many voltages were close to steady-state voltage limits.

The variation was also severe compared to the other cases. The minimum voltage in case 1, 93 % and in case 2, is 96 % and in case 3, is 93 %.

Hence, it is seen from the study that among the three cases, PV injection at bus 6 (case 2) was better as it allowed for more penetration with less severe variation in voltages.

4.2. Effect on the System Loss

The system losses in both MW (real power) and MVAR (reactive power) are observed for all rates of penetration.

It is possible to identify optimum penetration level with regard to system losses from the system loss profile and it is also possible to identify the best penetration position from this analysis.

As shown in Figure 6, initially, the real power losses fell to a point and began to increase for further penetration. In cases 1 and 2 the losses initially decrease slightly and then increase. In case 3, system losses increasing right from the start.

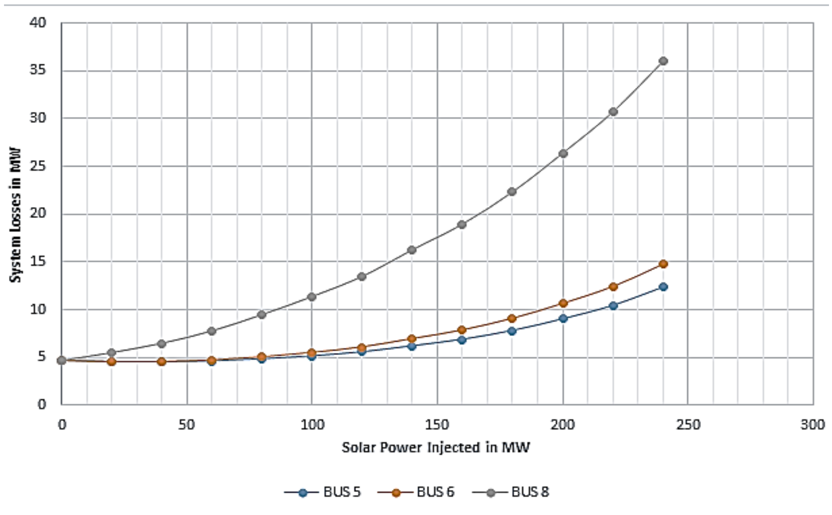

Figure 6. Plot of system losses in MW v/s solar penetration levels for injection at various bus locations

In the case of the process loss graph, a similar trend was observed in terms of reactive power i.e. MVAR. It is possible to identify optimum penetration level with regard to system losses from the system loss profile and it is also possible to identify the best penetration position from this analysis.

4.3. Effect on Transmission Line Power Flow

The real and reactive power loading of all network transmission lines is observed and plotted for all levels of penetration as shown in Figure 5.

The variability in transmission lines charging as shown in Figure 7 was mixed with few lines experiencing power increases and few lines experiencing power decreases.

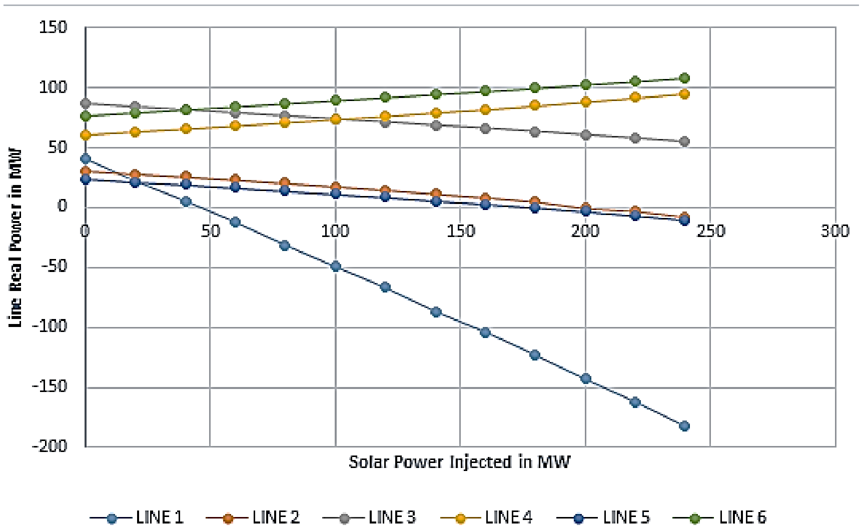

Figure 7. Plot of real power in transmission lines at various solar PV penetration levels

Few of the lines even had signs of power flow changes that caused the power reversal beyond a point.

Line 1 loading shifts were extreme of all. Therefore, considering the effect of solar penetration on the parameters of transmission line charging when designing the network is very significant. Improved PV penetration may bring fluctuations in stable state bus voltage levels and can sometimes be very critical and may even contribute to the grid's voltage stability.

Also, it might bring about severe changes into other parameters like steady-state real power and reactive power loading of transmission lines and other equipment in the system and also affect the system losses as shown in Figure 5. It is, therefore, necessary to carry out such a study that will enable engineers to design the system with high penetration rates of solar PV power and identify critical levels of PV penetration for a given network.

4.3. Transient Stability Analysis

Transient stability is described as the power system's ability to maintain synchronism during major perturbations. These disruptions could be a fault in a bus, loss of a large load, a fault in a transmission line or its disconnection, loss of generation, or failure of equipment.

The purpose of the transient analysis, discussed in this section, is to examine whether such large system disturbances affect the system differently with high levels of PV penetration.

Simulations were made considering various cases of disturbances under different levels of solar PV penetration, such as bus fault, loss of a large load and the loss of a transmission line.

The effect of penetration of solar PV on the crucial clearing period is also being studied.

Solar PV factory, as defined in the previous section, was incorporated into bus 5 of the IEEE 9-bus System. Even used for transient analysis was the same framework that was used for steady-state research. ETAP module "Transient Stability Analysis" was used for simulation and analysis.

A bus failure was considered at bus-7, as it experiences the highest short circuit current due to its fault in the 3-phase bus.

At first, the simulation was done without any solar PV for the system.

Fault clearance time has been gradually decreased until the system is dysfunctional. Critical clearing time is considered the maximum allowable period within which the fault has to be cleared. If the fault is not resolved within the system's critical clearing period, the system integrity will be severely impacted. The critical clearing time is continually diminishing as the penetration of the solar PV increases. And the system is unstable for any clearing time, for penetration beyond 20 %.

Next, the effect on the transient behaviour of the system was studied due to a bus fault that occurs in it at various levels of solar PV penetration.

The oscillations after the base case disturbance with 0 % solar PV penetration are smooth and converging to a stable value.

The amplitude of oscillations is a little more for the case of 10 % solar penetration and is a little irregular. Yet it converged, and the system remained stable.

A similar trend for the case was observed with a penetration of 20 %, but with little higher amplitude.

The device was becoming unstable above 20 % penetration. A similar trend in the relative rotor angle of generator G3 was observed.

The oscillations for the case of penetration of 10 % were with higher amplitude and were becoming abnormal. The dips in voltage are fairly high. But, after a while, it got stabilized. Whereas the oscillations and voltage dips were very severe for the 30 % penetration case and were not stabilizing.

Therefore, as the level penetration increases the system becomes unstable and after some percentage of penetration goes out of synchronism.

The biggest load in the network, load A linked to bus 5, was abruptly disconnected and results are tested for different levels of penetration.

The base case oscillations were uniform and converge and settle to a new value.

The oscillations for the case of penetration of 10 percent and 20 % are also less in amplitude but are little irregular compared to the base case.

Yet that converges to a finite one. The system is unstable above 20 % penetration. The oscillations for the case of penetration of 30 % are severe from the base case and completely irregular.

As the PV penetration level increases, the system became unstable for a transient disturbance.

During the transients in the device with high PV penetration, bus voltage magnitudes and relative rotor angle and therefore synchronism is the most adversely affected system parameters.

For most of the disturbances, systems with high PV penetration rates are observed to achieve greater voltage dips.

Therefore, given the transient performance of the system with high PV penetration rates, it is very important to maintain the system's stability and integrity following faults.

Improved PV penetration may bring fluctuations in stable state bus voltage levels and can sometimes be very critical and may even contribute to the grid's voltage stability. It could also lead to severe changes in other parameters such as steady-state real power and reactive energy loading in the network of transmission lines and other equipment and also affect system losses.

It is, therefore, necessary to carry out such a study that will enable engineers to design the system with high penetration rates of solar PV power and identify critical levels of PV penetration for a given network.

5. Conclusion

The solar energy industry is rapidly rising. Iran's policies and regulatory framework promote renewable energy, particularly solar photovoltaics, like never before.

Therefore, the penetration of solar photovoltaics into the Iran grid will increase and large-scale plants will arise.

The disadvantages of high-penetration solar photovoltaics have been established in the power system.

The conventional power plant analysis helped identify the generation side controls that are currently lacking from the new solar photovoltaic plants to maintain grid stability. The need and importance of evaluating the effect of high-penetration photovoltaics on the grid was therefore clearly understood in the beginning.

The increased penetration of solar PV into the grid without any specific controls has been shown to influence the steady stable performance of the grid. With the location and the level of penetration, the steady-state voltages are adversely affected. Several Steady State disturbance cases have been dealt and the impact of increased penetration on the Steady State stability of the grid after those disturbances have been analysed.

In all cases, the bus voltage magnitudes, the system loss, and transmission line power flow are the most adversely affected system parameters during the Steady State in the system with high penetration of PV.

Therefore, the upcoming large solar plants need adequate control mechanisms to resolve these issues and mitigate the stability issues arising from increased solar PV penetration.

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Biography

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