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NUMERICAL AND EXPERIMENTAL INVESTIGATION OF HIGH PENETRATION COEFFICIENT PHOTOVOLTAIC POWER PLANTS IN THE PRESENCE OF AVR

[1]Joodaki, A., [1]Shojaei, A.A.*, [1]Lotfi, H., [1]Pourhosein, H., [2]Yazdi, M.H.

[1] Department of Electrical Engineering, Neyshabur Branch, Islamic Azad University, Neyshabur, Iran.

[2] Department of Mechanical Engineering, Neyshabur Branch, Islamic Azad University, Neyshabur, Iran.

* Corresponding Author: A.shojaei@iau-neyshabur.ac.ir TEL: (+98)-426-21901

Abstract: One of the main concerns in distributed generation is the existing weak electrical grid infrastructure, especially in old and undeveloped areas. In this paper, a 5 MW photovoltaic power plant with high penetration coefficient which is connected to a long 95 km feeder is simulated and experimentally studied in order to investigate the effect of using automatic voltage regulator (AVRs) on grid voltage fluctuations. Results show that voltage fluctuation about ±15% is experienced when the plant is connected to the feeder in full capacity in the presence of AVR, in a cloudy day, when sharp changes in production can be observed. As an alternative solution, the plant grid connection is halved into the existing host feeder and another adjacent feeder of the same length and load distribution. In this case, very high penetration coefficient of the plant implies only a slight change in voltage fluctuation, i.e. 0-5%, in point of common coopling (PCC) point, in spite of decreasing the penetration coefficient to half. Therefore, it is found that AVR cannot appropriately overcome the voltage fluctuation problem, due to its inherent working characteristics which is not instantaneously adaptable with generated power changes.

Keywords: Photovoltaic; Penetration Coefficient; AVR; Voltage Profiles.

1. Introduction

Appropriate and optimum positioning of the site, based on the land cost, power losses, and grid restrictions is crucial in designing photovoltaic power plants. Different configurations can be introduced for the plant grid connection. Each country has certain definitions and grid-connection regulations for small-scale power generators. For instance, distributed generators (DGs) with nominal capacity below 7 MW are allowed to be connected to the medium-voltage (MV) local grid, i.e., 20 kV grid, in Iran. DGs can be connected to MV grids either through a medium-voltage bus bar using dedicated power transmission line, or though the nearest location to the substation in the case of lower capacities (Khalid & Dwivedi, 2011). In this work, penetration coefficient is introduced as a constraint on the renewable DG capacity and grid connection. Penetration coefficient is defined as the ratio of the DG maximum capacity to the maximum load connected to the feeder. This constraint is due to power quality issues that can occur for local loads connected to the host feeder. Stochastic behaviour of renewable DGs such as wind and photovoltaic generators, i.e., stochastic energy production due to radiation intensity, environmental conditions, wind gust, etc., accounts for restriction on penetration coefficient of DGs. These transient ambient conditions can cause adverse effects on power quality and especially grid voltage profile.

The harmful effects of grid connection of photovoltaic (PV) power plants with high penetration coefficient on voltage profile and power quality have been investigated in many researches (Lotfi et al, 2015; Al-Sumaiti et al., 2019; Schinke & Erlich, 2018; Kenneth & Folly, 2014; Saidi, 2020). Schinke and Erlich investigated the negative effects of high penetration coefficients on voltage profile and grid frequency (Schinke & Erlich, 2018). This issue was more comprehensively studied in (Barker & Mello, 2000; Radwan et al, 2020; Wagner, 2008; Fernández et al., 2019; Feilat et al., 2018). The results showed that high penetration coefficient inherently implied sudden sharp changes in power production rate, in the cases like cloud edge effect (Inzunza et al., 2020). In this condition, weak performance of compensators, settings of protective equipment and the time required for network reconfiguration can be harmful.

The harmful effects of grid connection of PV power plants with high penetration coefficient on voltage profile and power quality have been investigated in many researches (Lotfi et al., 2015; Al Sumaiti et al., 2019; Schinke & Erlich, 2018; Kenneth & Folly, 2014; Saidi, 2020). Schinke and Erlich investigated the negative effects of high penetration coefficients on voltage profile and grid frequency (Schinke & Erlich, 2018). This issue was more comprehensively studied in (Wagner, 2008; Fernández et al., 2019; Feilat et al., 2018). The results showed that high penetration coefficient inherently implied sudden sharp changes in power production rate, in the cases like cloud edge effect (Inzunza et al., 2020). In this condition, weak performance of compensators, settings of protective equipment and the time required for network reconfiguration can be harmful.

Desert and remote areas, villages and cities are often far away from each other. The long distances between these powers consumers implies that the length of the MV feeders in deserts is longer than standard, especially in developing countries. On the other hand, due to lower costs of the land and also minimum effect of shadings, deserts are usually known as very susceptible locations for constructing photovoltaic power plants. However, constructing the long energy transmission lines is very expensive, time-consuming and with many legal complications. Hence, power plant owners tend to inject the generated energy into the nearest available feeder. In this regard, the penetration coefficient of solar power plants plays an important and challenging role as a constraint in designing such DGs.

Development of distributed PV power plants is a complicated twofold problem, implied by irradiation as a free source of energy and on the contrary, the high cost of long grid line construction and their drawback on grid power quality. Considering power quality as a critical design parameter in simulations is of great importance in grid studies. Many researches have been dedicated to investigate and simulate PV power plants effects to prevent undesirable and uncontrollable effects on grid. Maximum allowable penetration coefficient of PV power plant was studied in (Lotfi et al., 2015; Al-Sumaiti et al., 2019; Schinke & Erlich, 2018; Kenneth & Folly, 2014; Saidi, 2020).

There are many inherent problems in power quality and voltage profile of long radial distribution grids in distributed areas. Compensating and enhancing power quality in such grids are recently of great interest among researches (Barker & Mello, 2000; Radwan et al, 2020). To solve power quality problems, compensating devices, which generally have lower installation and commissioning costs than constructing transmission lines, are considered more than other methods. For example, Automatic Voltage Regulator (AVR) is a typical wise alternative for transmission line construction. Radwan et.al. studied the effects of using AVR as a compensator in a long radial gird in Egypt (Radwan et al., 2020).

2. Expressing the Problem

Distributed locations of PV plants usually get the grid owners and operators into trouble for continuous adjustment of voltages along the whole grid. Hence, the load points at the beginning of the feeder always experience over-voltage and transient voltage during the day. Besides, voltage profile may also be more affected in load points near the Point of Common Coupling (PCC) than at other points of the network during daylight hours.

The PV power plant under investigation in this paper had a high penetration coefficient of around 200%, due to the long distance between the site location and the feeders, as well as the power substations. The capacity of the photovoltaic power plant is 5 MW, which was initially connected to a 95 km long feeder. The power plant is located 50 km from the beginning of the feeder. An AVR was employed between the power plant and the beginning of the feeder and at a distance of 10 km from the power plant in order to solve the problem of power quality, especially voltage fluctuation. Feeder loads, especially loads near the power plant connection point, were affected by voltage fluctuations caused by DG power production changes. As a solution, a new 8 km power transmission line was constructed into which half of the power plant capacity was connected. These two feeders were identical both in loading and length. In this case, by reducing the penetration coefficient of the power plant by 50% and connecting half of its capacity to the second feeder, the penetration coefficient of both new sections on the respective feeders is equal to 100%. Due to the high penetration coefficient of both 2.5 MW sections in the new solution, voltage fluctuations due to their stochastic production reduce the power quality at the connection of loads connected to feeders too.

Voltages at feeder endpoint, plant PCC point and power generated by the DG was recorded by data loggers with a resolution of 5 minutes over an 18-month period. The first scenario, i.e. full capacity grid connection to the host feeder, takes the earliest 12 months. All the prescribed case were also simulated and analysed by DIgSILENT.

3. Methodology

Governments and grid managers use manual scientific calculation methods and advanced supercomputers (heuristic algorithms, artificial neuron network (ANN), etc.) to predict the load, optimal load flow, and economic dispatch.

Calculating governing correlations and advanced grid modelling (such as heuristic algorithms, ANN, etc.), energy policy makers and grid owners predict load distribution, optimize load flow and economic dispatch (Al Talaq & Belhaj, 2020; Hoke et al., 2012; Hlalele et al., 2020; Hossain et al. 2018; Al-Shetwi et al., 2020; Barus & Dalimi, 2019). Against typical DGs with predictable production, the stochastic nature of PV power plants accounts for the several recent researches on prediction and modelling of this unpredictable behaviour (Nguyen et al., 2014; Biswas et al., 2017).

Cloud edge effect, which may occur frequently in spring or autumn, can increase the production rate of a solar generator from 10% to 100% in about 30 to 120 seconds. It can result into sharp increase in voltage at PCC point and local loads, in high penetration coefficient cases. Two applicable methods are proposed for damping such negative effects, as follows. Firstly, grid owners shall prevent connection of PV plants with high penetration coefficient to grid, according to their own regulations. Maximum allowable penetration coefficient is generally around 40-50 % (Hoke et al., 2012; Hlalele et al., 2020). Secondly, owners and developers of PV plants above 3 MW should employ optimized location, as near as possible to local substation, which consequently can yield noticeable reduction in grid connection costs (Javaid & Islam, 2020; Vermeulen et al., 2016).

As mentioned above, lack of standard feeder can impose serious problems to grid owners and operators and also plant owners. This deficiency is more usual in developing countries, where renewable DGs growth is fast and unbalanced with regard to available infrastructures.

Alquthami et.al investigated the voltage profile problem in Saudi Arabia (Alquthami et al., 2020; Nusair & Alhmoud, 2020). Some similar cases have also been investigated in references (Alshahrani et al., 2019; Movahedi et al., 2019; Geng et al., 2019; Alam et al., 2020; Hamdeen et al., 2018; Kopicka et al., 2014; Abdelaziz et al., 2011; Remon et al., 2017; Seguin et al., 2016; Mather et al., 2011; Mather et al., 2012).

AVR with programmable controller is one of the compensators that can switch with regard to the load and correct the voltage profile. The number of up and down taps, sensitivity, i.e. percentage of voltage deviation, operation delay time (to extend the life of tap changer) and its capacity should be calculated and taken into account. Longevity of the tap changer is actually recognized as an operational constraint. Its rapid and repeated operation will cause transient faults in the grid and reduce the lifespan of tap changer and increase maintenance costs. Therefore, in this solution, the design and location of the AVR are also critical.

In the current simulation, the solar power plant and feeder are modelled in two stages. First, the total capacity of the power plant, equivalent to 5 MW, is injected into the first host feeder. Then, to reduce the penetration coefficient, half of the power plant capacity is injected into the second feeder. At each stage, the simulation results are compared with experimental records. Simulation results were used to derive the inverters production and local load consumption distribution profiles. Two feeders are approximately 95 km and 80 km long. The nominal load of each feeder is about 2.5 MVA. The loads include residential, agricultural, official, lighting, and industrial consumers. These loads are located in urban and rural areas. The feeders, load points, PV plant, and AVR are simulated in DIgSILENT software.

4. Results and Discussion

4.1. Scenario 1 – Full Capacity on the Host Feeder

This paper is based on the existing conditions of two feeders and PV power plants connected to them. Two feeders are approximate 95 km and 80 km long. The nominal load of each feeder is about 2.5 MVA. The loads include household, agricultural, official, lighting, and less industrial consumers. These loads are located in urban and rural areas.

In the first scenario, full capacity, i.e. 5 MW, is connected to the host feeder with a length of 95 km and connecting loads of about 2.5 MVA, as illustrated with green line in **Figure 1**.

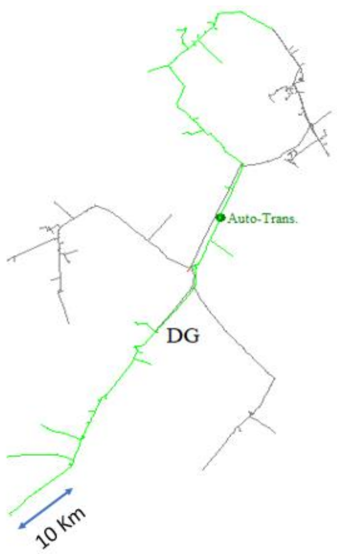


Figure 1. 95 km long green feeder where the PCC point of the PV plant and the place of the autotransformer are marked

A 5.2 MVA AVR was installed at 35 km at the beginning of the feeder, as shown in **Figure 1**. It had 9 taps including 6 negative and 2 positive taps, which could adjust the voltage in the range of 18 to 21 kV. The additional voltage per tap was 2.5%. Hence, the voltage-neutral tap was 20kV, and each step was adjusted to 2.5% of per unit (PU). The operation time, i.e.

Delay time of the AVR was set to 40 seconds in the controller. The applied settings are presented in **Table 1**.

Table 1. AVR settings

Type	**Three Phase Autotransformer**
Real Power	5.2 MW
Nominal Frequency	50 Hz
Number of Tap	9
Additional Voltage per Tap	2.5%
Neutral Position	0
Maximum position	2
Minimum position	-6
Rated Voltage high voltage (HV)-Side	20 kV
Rated Voltage LV-Side	20 kV
Delay Time	40s

All 20 inverters are paralleled by the low voltage (LV) bus bar of step-up transformers. Any transformer is 1250 kVA (Dyn5) that is grounded in the centre of the star at the LV side as shown in **Figure 2**. The settings of step-up transformers are shown in **Table 2**.

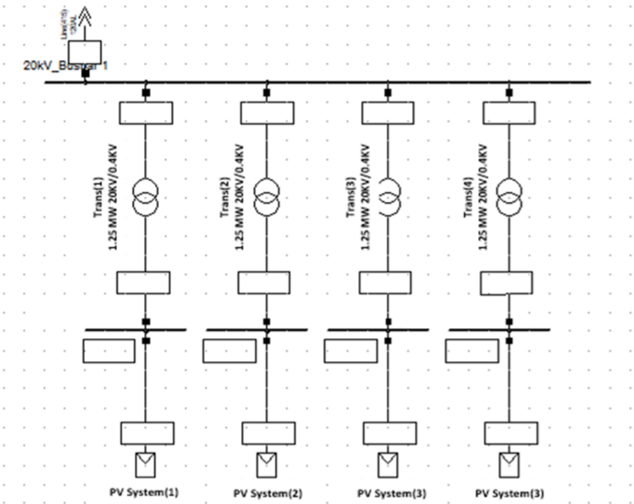


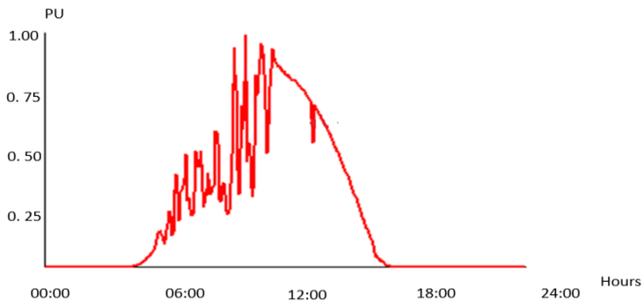
Figure 2. Schematic of placement and connection of inverters, transformers and PCC points in the PV plant

Table 2. Transformer setting

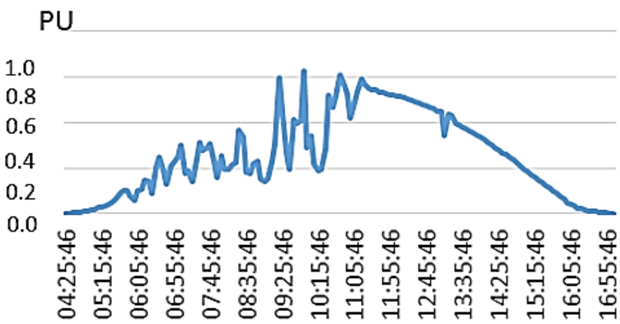
Type	**Three Phase Transformer**
Real Power	1.25 MW
Nominal Frequency	50 Hz
Rated Voltage HV-Side	20Kv

Rated Voltage LV-Side	0.4Kv
Vector Group	High Voltage – Delta (HV-D) and Low Voltage-Wye (LV-YN)
Phase Shift	5*30deg

For better and more precisely investigating transient phenomena, like cloud edge effect, the experimental data collected from the DG monitoring system were used to set production profile of the inverters during a cloudy day. To increase the accuracy of quasi-dynamic simulation, data acquisition resolution is 5 minutes. For example, the inverter production on April 20, 2020 as a cloudy day, is applied to time characteristic and the production curve and real production for an inverter during the day is presented in **Figure 3**.



(a)

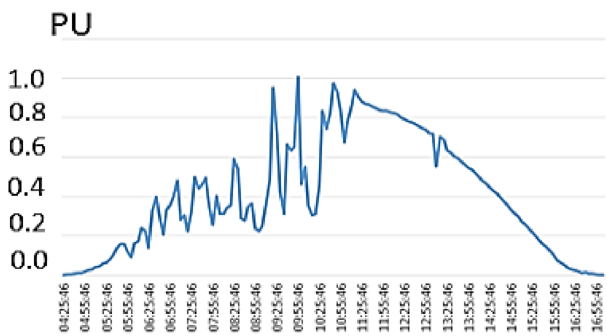


(b)

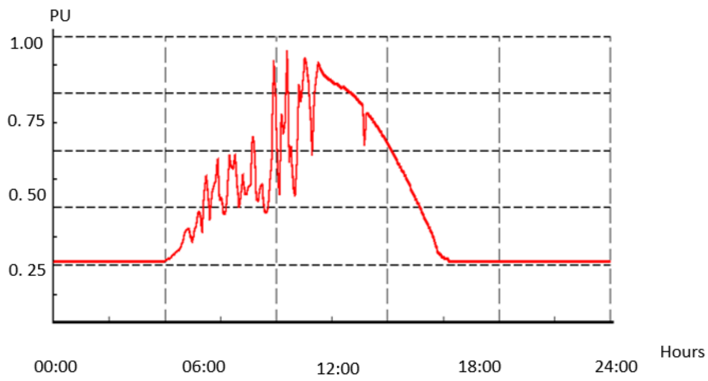
Figure 3. (a) Time Characteristic and (b) the experimental production curve for a PV inverter during a cloudy day

As seen in **Figure 3**, the fluctuation in the inverter production curve caused by cloud edge effect is noticeable. Since all the inverters are parallel, the energy injected by DG to the grid raised sharply from 0.8 MW to 5.1 MW at 9:45 AM just in a few seconds, that consequently resulted into remarkable grid voltage fluctuations. These fluctuations are recognized to be very dangerous and critical in the mid-day when the plant power output is maximum, e.g., 4.3 MW in the current work. Experiments shows that power injected to the grid can sharply rise from 0.5 MW (or lower) to above 4 MW in 30 to 120 seconds (Figure 4). The AVR is employed to compensate these voltage fluctuations. It should be noted that a delay time is adjusted in order to reduce the maintenance costs.

Using the information collected from the substation, the load of feeders has been used for simulation and analysis of AVR operation for 18. The load curves in a holiday and a working day are shown in **Figures 4** and **5**, respectively. The required time characteristic is set with a resolution of 5 min, like the inverters production records. Since the feeder is located in a desert area with residential and agricultural consumers, the holiday load curve is identical to the working days. As shown in **Figure 4**, many fluctuations in energy production are observed which can cause voltage fluctuation at PCC and load points. Any power production fluctuation could create the same noise in the voltage profile. The solar DG production curve for a selected cloudy day in the terms of the percentage during and the real production curve this day is shown in **Figure 4**.



(a)



(b)

Figure 4. The solar DG production curve for (a) selected cloudy day according to the simulation and (b) experimental data

According to the results obtained in the case that all 5 MW is injected into the feeder 95 km, the voltage curve at PCC, which is located near many local loads, is not suitable during the day. As shown in **Figure 5**, for a load point at the end of the feeder the voltage profile is not suitable. In the hours of the day, the voltage is out of the standard values and has high fluctuations. Grid owner has a limit to increase the voltage at the beginning of the feeder due to its risks for loads near the substation. Unfortunately, due to this restriction, at 7:30 PM, the voltage dropped to 0.85 PU and at other times during the day when DG is off, the voltage does not have a standard value based on power quality. The voltage profile curve for the PCC point is displayed in **Figure 6**.

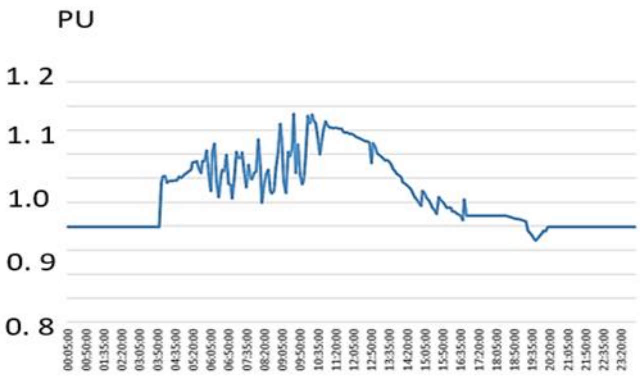
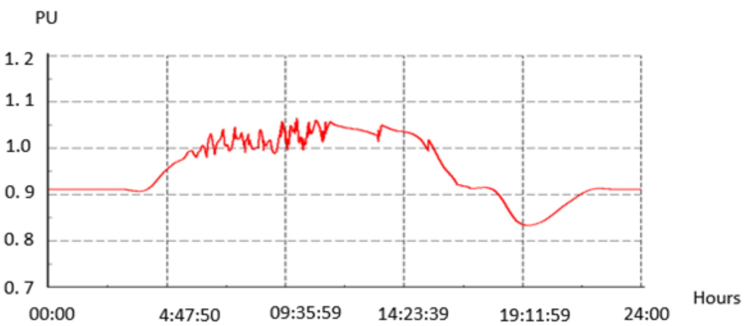
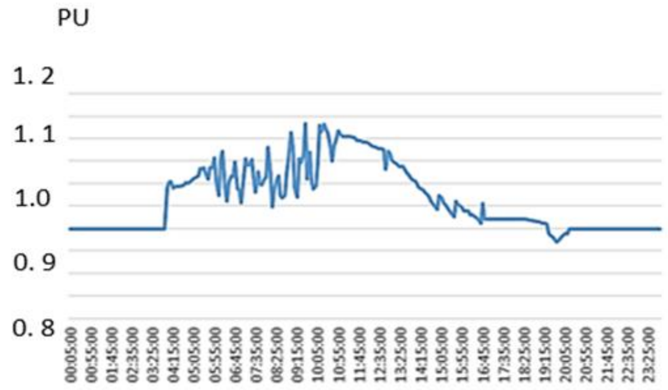


Figure 5. Voltage curves at the end of the feeder similar to holidays and normal days according to the simulation results and experimental data



(a)



(b)

Figure 6. The voltage profile curve for the PCC point according to the (a) simulation results and (b) experimental data

As seen, the AVR couldn’t compensate the voltage profile in transient phenomena such as the cloud edge effect. Note that the voltage profile is the same for holidays and normal days. The PV penetration in this scenario is around 200% and AVR cannot compensate and regulate the voltage.

4.2. Second Scenario

In the second scenario, to reduce the penetration coefficient of the power plant on the host feeder, it has been tried that half of the power plant production injects into other feeders. This feeder has the same specifications. **Figure 7** shows a schematic of the two feeders (blue feeders), PCC point, loads, and AVR.

Figure 7. Two long blue feeders where the PCC point of the PV plant and the place of the autotransformer are marked

The design of PV, such as the connection between inverters, trances, and PCC points of the two parts of the power plant can also be seen in **Figure 8**. **Figure 9** indicates the voltage profile curve at the new PCC point when half of the production of the 5 MW power plant is injected into the other feeder. Voltage profile at the PCC point of the first feeder is displayed in **Figure 10**.

The simulation results are similar to the experimental data collected from the PCC. Due to the high penetration coefficient of the power plant in the two feeders and despite the relatively different load distribution in the two feeders, the voltage fluctuations of the power plant at the two connection points are similar.

It should be added that in the second scenario and in the experimental information, instead of the information on April 20, used the information on another similar cloud day. Because on April 20, the entire capacity of the 5 MW power plant was connected to the first feeder. For this reason, another cloudy day has been selected for comparison after connecting half of the power plant capacity to the second feeder. It has been tried as much as possible that the two cloud days are similar in terms of the number of cloud edge effects and voltage fluctuations. **Figures 11** and **12** show the voltage profiles in PCC for the first feeder and the second feeder.

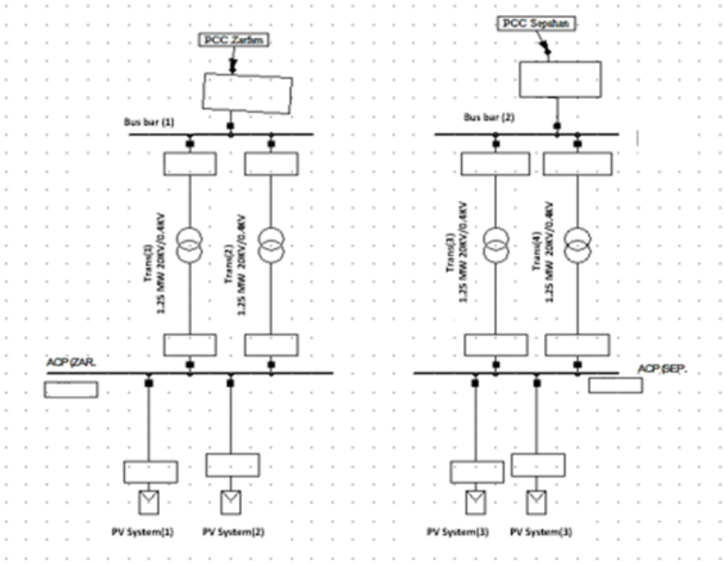
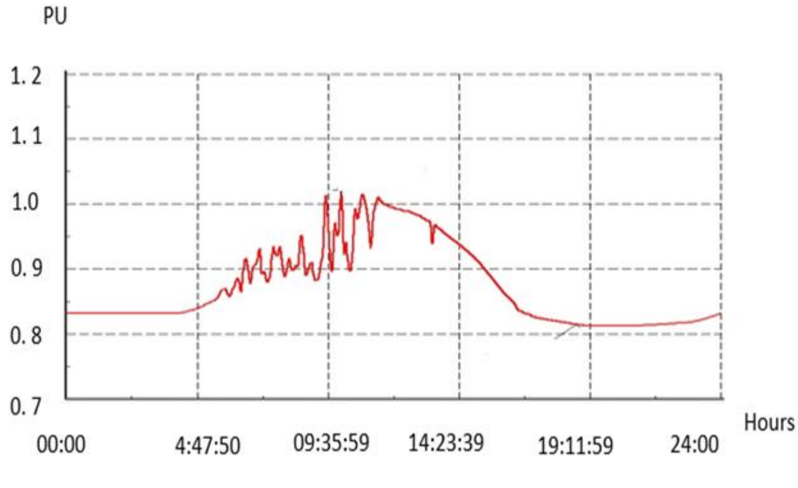
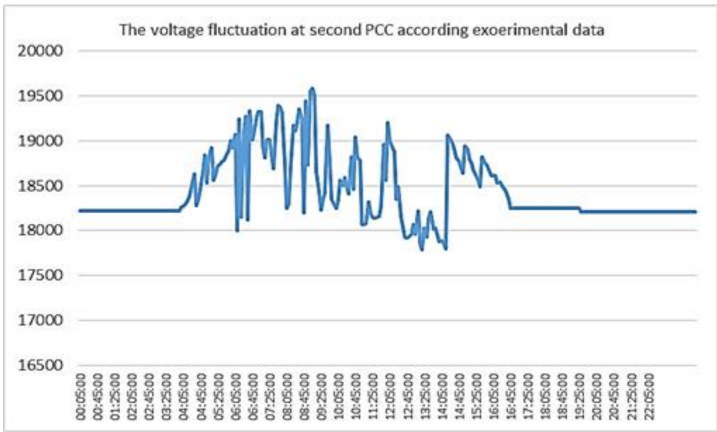


Figure 8. Schematic of placement and connection of inverters, transformers and PCC points in the PV plant



(a)



(b)

Figure 9. The voltage fluctuation at the new PCC according to the (a) simulation results and (b) experimental data

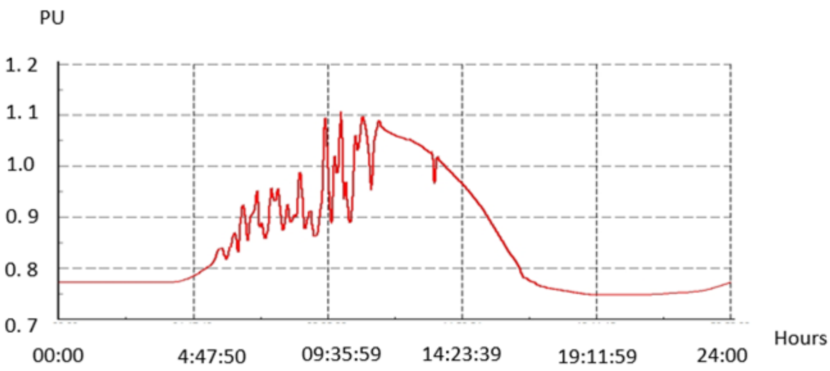


Figure 10. The voltage at the PCC point (the first part of the PV plant) to the primary feeder

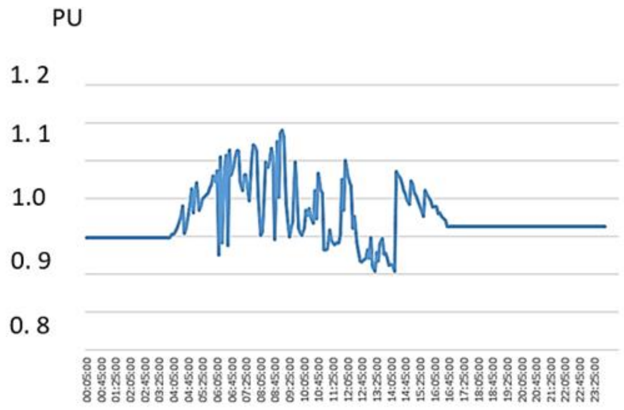


Figure 11. The voltage fluctuation at the first PCC (The experimental data)

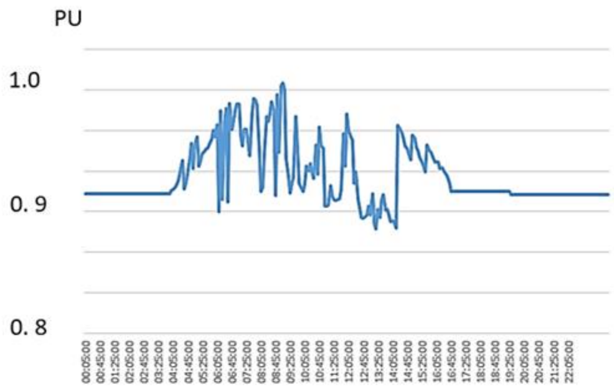


Figure 12. The voltage fluctuation at the second PCC (The experimental data)

There is the same situation for load points located at the end of these feeders. As shown in **Figure 13**, despite the improvements made compared to the first scenario, there are many voltage fluctuations and this issue naturally will have some negative effects on the power quality. However, reducing the DG penetration coefficient led to a noticeable and of course insufficient voltage profile improvement. In this scenario, similar to the first scenario, the voltage profiles at the PCC points and endpoint of feeders as critical points in two vacation and normal days by using quasi dynamic simulation investigated. The simulation results show us that on both days due to high PV penetration, autotransformer cannot solve the problem. Also, note that due to the high penetration coefficient of the PV plant in the second scenario, the number of load changes in two holiday and working days has not had a significant effect on the voltage profile.

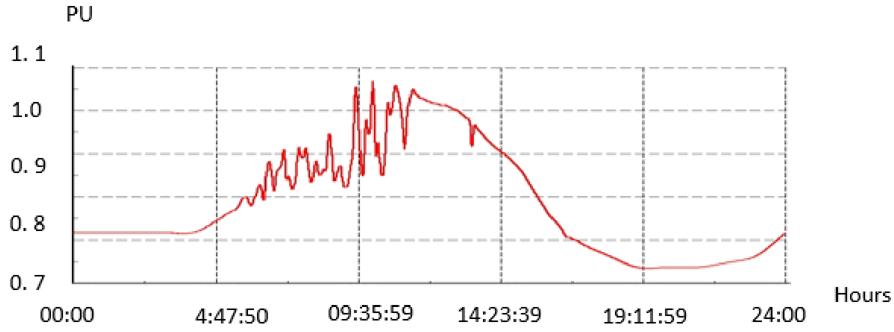


Figure 13. Voltage at the endpoint of two feeders

5. Conclusion

The ability of the AVR to compensate for voltage fluctuations generated by a very high penetration PV plant was investigated. In the first stage, the generator penetration coefficient was 200%, which was reduced to 100% by constructing a power transmission line. Most of the voltage fluctuations are due to rapid changes in power plant output. Therefore, by analysing the data collected on a cloudy day in each scenario and simulation, an attempt was made to investigate the ability of the AVR for compensating voltage fluctuations. Due to the rapid changes in generator output power, the AVR was not able to solve the problem and voltage fluctuations of about 0.1 PU to 0.15 PU were frequently observed at the junction of loads connected to the feeder. Due to the length of the feeder and the inability of the grid operator to regulate the voltage of the feeder, compensating the negative effects of the high penetration factor of the PV plant has become a more complex problem that could not be solved by the AVR.

According to the experimental and simulation results, serious sharp voltage changes are measured when the cloud edge effect phenomenon on cloudy days occurs. When the penetration coefficient is much higher than the standard range, using AVR as a compensator is not successful, especially in transient conditions such as the cloud edge effect. In such cases, it is recommended to construct a private power line or decrease the PV plant penetration coefficient under 50%.

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