JST: Smart Systems and Devices
Volume 33, Issue 1, January 2023, 054-063

Study on Voltage Profile and Power Losses of Distributed Photovoltaics Systems Integrated into a Local Distribution Grid in Vietnam

***Nguyen Huy Tien*[1]*, Pham Manh Hai*[2]*, Nguyen Duc Tuyen*[1,3*]**
[1]*Hanoi University of Science and Technology, Ha Noi, Vietnam*
[2]*Electric Power University, Ha Noi, Vietnam*
[3]*Shibaura Institute of Technology, Tokyo, Japan*
[*]*Corresponding author email: tuyen.nguyenduc@hust.edu.vn*

Abstract

In recent years, the integration of renewable energy into power grid has gained prominence among researchers and scientists due to the growing energy demand and the depletion of fossil fuels. This paper would analyse the Huong Khe 35-kV medium voltage distribution network, in which 373E18.8 and 374E18.8 feeders are selected, to study the effects of the distributed Photovoltaics (PV) systems on the voltage quality and power losses on the grid such as overvoltage, reverse power, and increased power loss. The simulation results might solve the voltage quality and power loss problems. In addition, the results of different scenarios are examined. Using the Electrical Transient and Analysis Program (ETAP) software, we discussed how PV plants affected each scenario's voltage profile and power losses in the feeders. This study then provides solutions for those challenges using tap-changers of the substation from 37.5 kV to 36.5 kV and curtailment. Therefore, both the voltage quality and power loss problems have been solved.

Keywords: Distributed system, grid-connected PV systems, voltage profile

1. Introduction

Due to the depletion of traditional energy resources such as fossil fuels and energy demand significantly increasing, photovoltaic (PV) power has become essential in Vietnam's power systems over the last few years. Especially since 2019, distributed PV power in Vietnam has grown at a rapid pace. Fig. 1 shows the increase in installed PV power from 2010 to 2020. According to EVN, the total PV system capacity had reached 16,700 MW by 2020. Meanwhile, the fully installed renewable energy capacity reached 20,670 MW, accounting for 27% of the system installed capacity [1, 2].

PV power systems not only bring about economic but also electrical and environmental advantages. Distributed PV systems, for example, can reduce power losses by generating electricity directly for loads rather than relying on remote sources. Furthermore, PV systems can reduce CO_2 emissions from fossil power plants while meeting annual energy demand growth. However, when the installed PV system capacity has a significant penetration in the power structure, power quality issues (overvoltage, reverse power, incoordination of protective devices, harmonics, etc.) may arise for transmission or distribution grid after integration because the fluctuation of PV output power depends heavily on the weather [3-5]. All these combined put much pressure on the management, design, and operation of the flexible and reliable distribution grid for Power Companies.

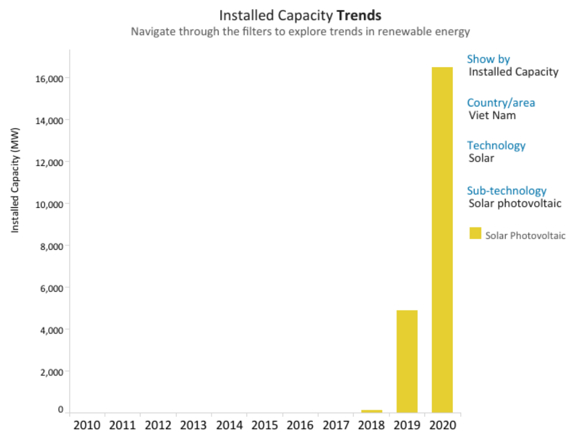

Fig. 1. Installed PV Systems capacity from 2010 to 2020 (*Source: IRENA*)

National grid codes strictly regulate voltage. The permitted operating voltage range on the low voltage grid is 10% of the rated voltage, according to European standard EN 50160. The 50-kV grid or lower in Canada must maintain a steady-state voltage in the range of 0.917 to 1.042 p.u [3]. According to Circular 30/2019/TT-BCT [4], Vietnam's permissible operating voltage range is +10% and -5% from 35 kV or less. When the voltage varies significantly, the transformer voltage tap changer and voltage regulators may be required to operate or regulate to keep the voltage

ISSN: 2734-9373
https://doi.org/10.51316/jst.163.ssad.2023.33.1.7
Received: July 11, 2022; accepted: September 8, 2022.

within the allowable range.

The distributed PV system can improve the voltage profile and power losses at low penetration levels [5, 6]. However, reserve power flow is at a high penetration level, leading to grid overvoltage. The issue arises primarily when PV capacity is at its peak in the low voltage network, whether it is a light load. As a result, an annual load and PV generation capacity map must be established, the relationship between distributed PV systems and power system security must be carefully examined, and the deployment of distributed PV systems must be optimized to achieve cost-effective integration [7]. Many researchers have been looking for ways to mitigate the drawbacks of incorporating distributed PV power into the grid. Reference [8] described numerous voltage regulation strategies for distribution networks with high PV penetration. The study [9] provided a comprehensive assessment of the impact of distributed systems on low-voltage (LV) distribution networks, highlighting commercially available and emerging methods for reducing voltage problems. Utility devices such as OLTCs, static VAR compensators (SVCs), other voltage regulators, and energy storage systems (ESS) require appropriate coordination. However, static compensators may cause over/under-compensation issues. Reference [10] investigated a distributed PV system on a distribution network and presented a charge and discharge control technique to avoid overvoltage concerns while still meeting peak load demand at night. As previously stated, the investment cost of BESS and new OLTC transformers is still prohibitively high in the medium/low voltage grid. References [11-12] presented a hybrid control of OLTCs and PV smart inverters. The method can significantly improve conservation voltage regulation and high PV penetration in a medium/low voltage network. Because of the higher current, modern inverters are less effective than OLTC for reactive power regulation. Besides, OLTC in existing transformers can make the grid more PV friendly. On the other hand, a PV inverter's reactive power capability is restricted by its immediate real power generation and perceived power rating [13]. As a result, when PV power production is large, reactive power control techniques alone cannot provide enough voltage regulation. Moreover, the distribution network has a high R/X ratio, which causes an active power curtailment that might result in improved voltage control. Consequently, curtailing real power is seen as a lucrative alternative in conjunction with reactive power regulation to prevent distribution overvoltage [14, 15].

The actual case studies in Ha Tinh province are analyzed by examining the 373E18.8 and 374E18.8 feeders of the 35 kV Huong Khe distribution grid. One of the most critical technical constraints for connecting a large-scale PV system (approximately 13 MW) to the distribution grid is the voltage profile in the medium voltage grid studied in this paper. Furthermore, power losses are a significant technical implication that was investigated. ETAP software was used to simulate both scenarios, with and without PV systems. After analyzing the worst-case scenarios, we propose two solutions to overcome voltage profile issues. The first method to lower the operating voltage at the 100/35 kV substation from 37.5 kV to 36.5 kV from 6:00 to 18:00 during a day. This technique can enhance the voltage profile and stability margin and reduce power losses of the system slightly. Second, PV curtailment during peak hours of distributed PV power is proposed. Given that it only needs minimal adjustments to the PV's inverter control logic, the curtailment method avoidance appears to be quite attractive. Additionally, it is only turned on when necessary, decreasing the amount of output power losses significantly. Accordingly, the two main contributions of this study are: (i) the actual data are collected, and practical PV system are investigated by simulation. (ii) two solutions, which are change transformer operating voltage and PV output curtailment, to improve voltage profiles are proposed and validated by simulation.

The paper is organized as follows: Section 2 conducts a voltage profile of the PV systems integrated medium feeders. Section 3 provides the case study of the PVs systems under different scenarios. Section 4 proposes solutions to improve voltage quality and power losses. Section 5 concludes with a conclusion about the impact of PVs penetration on distributed network voltage and power losses and proposes a tuning tap changer at the substation to partially cut down on PVs generation.

2. Voltage Profile with a PV System

Consider a two-port network model with a PV plant connected to bus 2, shown in Fig. 2. The PV plant is connected to bus 2 and assumes the power factor is 1 and $P_{PV} < P_{Load}$. Conversely, when $P_{PV} > P_{Load}$, the PV system is regarded as the utility that transmits power back to the source (from bus 2 to bus 1). From Fig. 2, the voltage module of bus 2 is written as:

$$|U_2| = |U_1| - \left(\frac{PR + QX}{|U_1|}\right) \quad (1)$$

Then the voltage drop is determined:

$$\Delta U = \frac{(P - P_{PV})R + QX}{|U_1|} \quad (2)$$

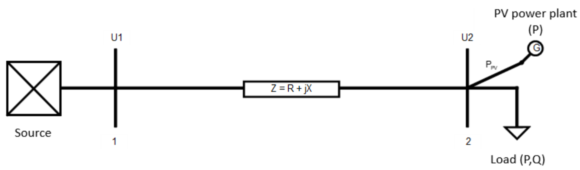

Fig. 2. Two-port network with a PV system

From (2), the voltage drop depends on operating voltage, the distributed power capacity, and the transmission line length. The traditional grid's end-line voltage is less than the bus voltage near the busbar. The longer the transmission line distance, the lower the voltage at the end-line bus. Nevertheless, in grid-integrated PV systems, the voltage drop also depends on the correlation between the load demand and the output power of the PV systems. Fig. 3 illustrates a voltage profile – transmission line length with the PV system. The following active and reactive power losses are calculated:

$$P_{loss} = \frac{(P-P_{PV})^2+Q^2}{|U_2|^2}R \quad (3)$$

$$Q_{loss} = \frac{(P-P_{PV})^2+Q^2}{|U_2|^2}X \quad (4)$$

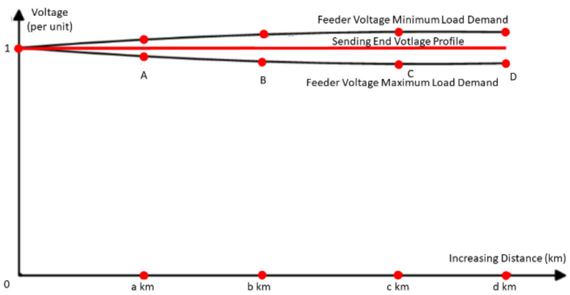

Fig. 3. Feeder voltage profile with PVs

The common voltage regulation methods will be affected when the PV systems are installed on the distribution grid. Voltage profiles are impacted due to the appearance of reverse power flow [16]. According to [17], the integration of PV systems can cause a voltage drop along the feeder and an increase in the bus voltage profiles of the end line. This is because of a reduction in the active power demand through bus 1 by the busbar. If the output power capacity of PV systems is not greater than the load demand, the power losses and the voltage profile are enhanced. Otherwise, reverse power appearance raises the power losses and voltage profile. Therefore, if the coordination is not correctly adjusted after PV is integrated, the controller of VRs, SCs, and OLTCs can bring on profile problems with the current operating mechanism [16].

3. Study on Effect of Distributed PV Systems Integrated Huong Khe Network

The Huong Khe distribution grid is a medium-voltage distribution network with a voltage level of 35/0.4 kV. Both feeders 373E18.8 and 374E18.8 of the Huong Khe grid were selected to analyze the influence of distributed solar power, as shown in Fig. 4. The distribution transformers 373E18.8 and 374E18.8 have total rated capacities of 8040 kVA and 6020 kVA, respectively. However, actual load demand only accounts for about 25% of the total rated capacity of each feeder's distributed transformers (Fig. 5). When simulating a solar power plant, this paper chose the Hanwha Q CELL brand of PV with a capacity of 230 W/panel due to the limitations of the library of ETAP software. Then, some PV panels are series-connected to form strings of PV modules whose DC voltage does not exceed 1000 VDC. Along with that, the number of strings will be set to close to the actual capacity of the solar power plants. At 373E18.8 feeder, the total PV capacity is up to 12795.6 kWp and is concentrated mainly at buses 54, 57, and 90 on the main branch. As for the 374E18.8 feeder, only 999 kWp is the total solar power capacity at bus 63 on the main branch.

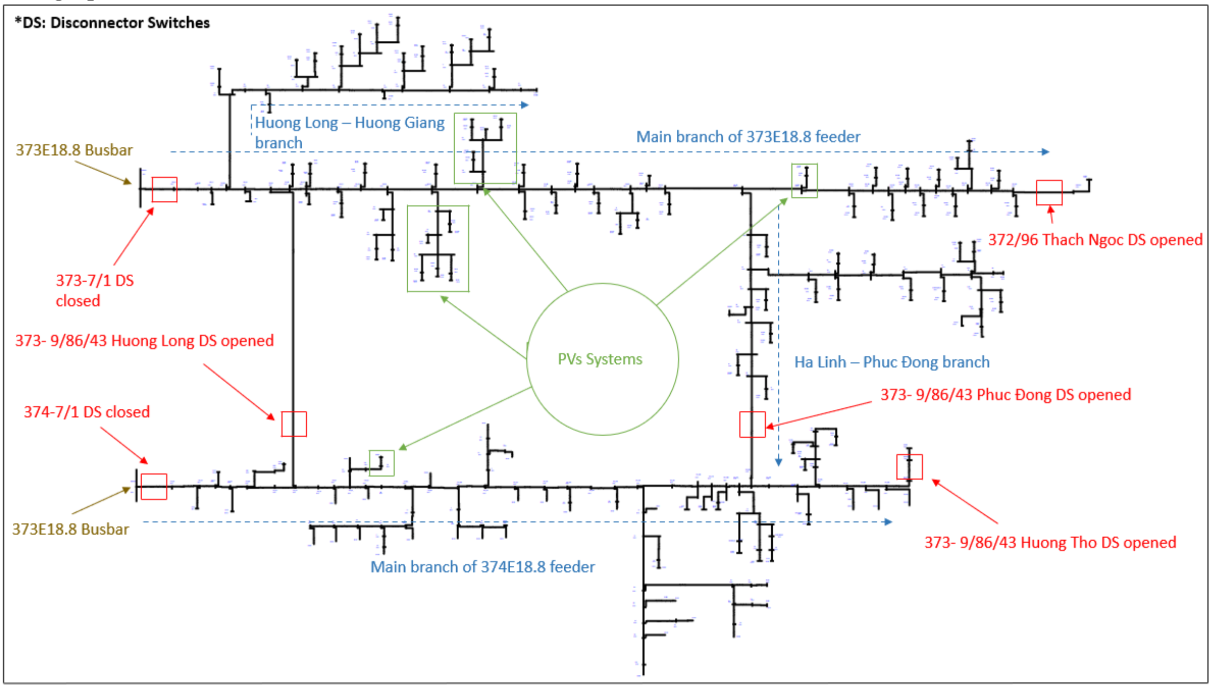

Fig. 4. Single line diagram of 373E18.8 and 374E18.8 feeders in ETAP software

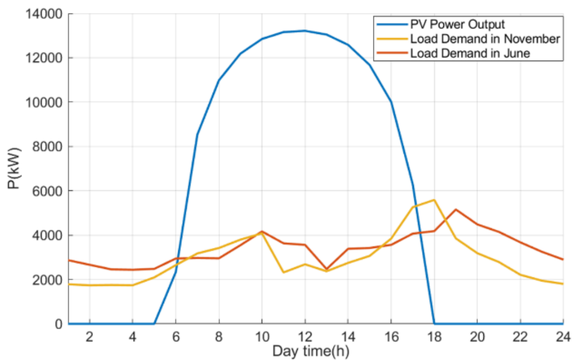

Fig. 5. Typical daily load capacity curve in June, November and generating capacity of solar power

According to Fig. 5, when PV output power peaks at noon, the winter load curve is typically lower than in the summer. As a result, the winter scene is the worst-case scenario. The voltage is extremely high, exceeding the Vietnamese grid code [4]. This paper is primarily concerned with the winter scenario.

3.1. 373E18.8 Feeder

3.1.1. Voltage profile

According to [4], in normal operation without PV sources, the voltage profiles of the two feeders do not violate the Vietnamese grid codes.

Summer scenario

The voltage rises from 1.07U_{nom} when there is no solar power to more than 1,095U_{nom} when solar power is integrated into the grid, as shown in Fig. 6. These buses are mainly concentrated at the end of the line, starting from bus 86 to bus 105 on the main branch, and buses along the Ha Linh-Phuc Dong branch (Fig. 8). Based on [4], although the voltage profile does not exceed the allowable level of 1.1U_{nom}, it must be noted that this only shows a typical day of June. There will be times when a worse scenario occurs. Moreover, with a slight change, it is possible to exceed the allowable operating voltage at any time. Fig. 7 depicts the voltage profile at the branch of Huong Long and Huong Giang. Because this feeder is closer to the source, the voltage is always guaranteed to be within the allowable operating voltage range.

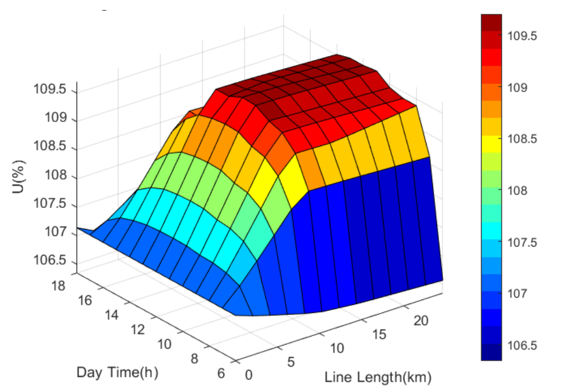

Fig. 6. Voltage profile on main branch of 373E18.8 feeder when PV systems are integrated in summer

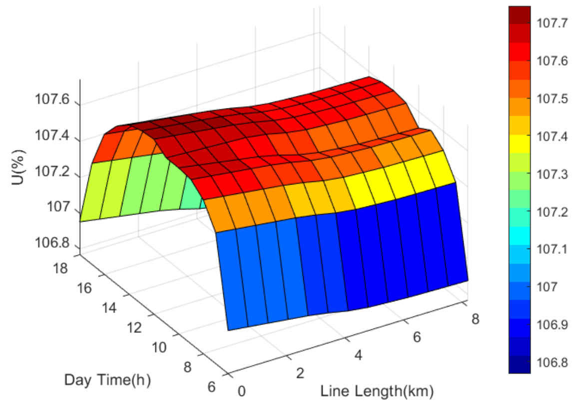

Fig. 7. Voltage profile on Huong Long – Huong Giang branch of 373E18.8 feeder when PV systems are integrated in summer

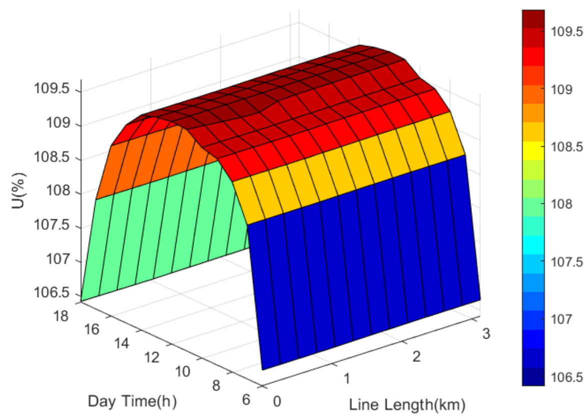

Fig. 8. Voltage profile on Ha Linh – Phuc Dong branch of 373E18.8 feeder when PV systems are integrated in summer

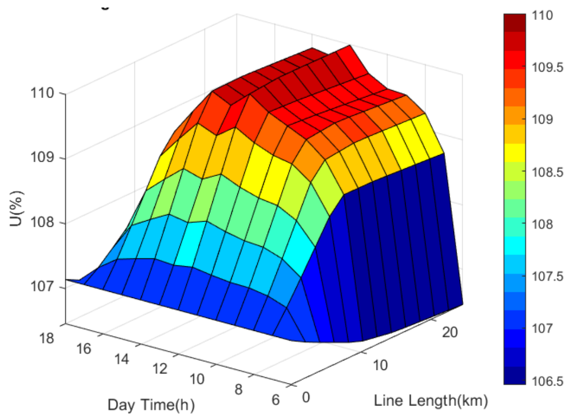

Fig. 9. Voltage profile on main branch of 373E18.8 feeder when PV systems are integrated in winter

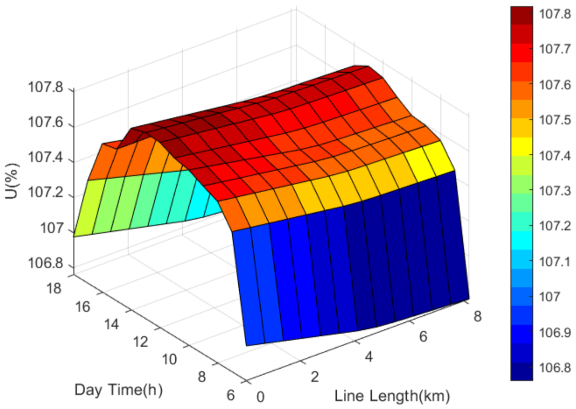

Fig. 10. Voltage profile on Huong Long – Huong Giang branch of 373E18.8 feeder when PV systems are integrated in winter

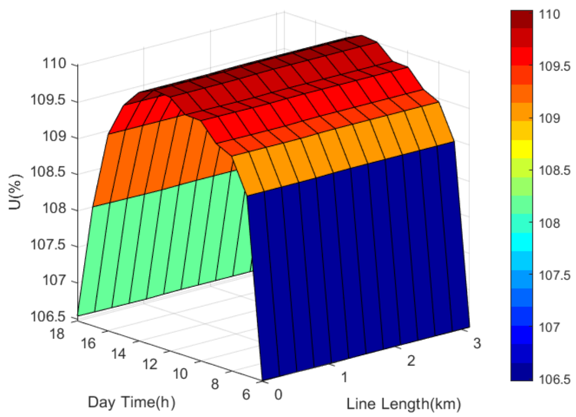

Fig. 11. Voltage profile on Ha Linh – Phuc Dong branch of 373E18.8 feeder when PV systems are integrated in winter

Winter scenario

According to the simulation results, most of the bus voltage is overvoltage. The voltage profiles in Fig. 9 and Fig. 11 show how voltage rises during the day and when PV plants operate at full capacity. Compared with the normal case results, the integration of solar PV causes a voltage surge for the selected buses. At 13:00, the voltage is up to 1.10014U_{nom} at the end of the line. This voltage profile violates the Vietnamese grid code as in [4]. This paper only looks at how things work on a typical day. On a day that load demand is lower at noon, the voltage profile will increase highly. This is the worst-case scenario.

3.1.2. Power losses

Line losses are proportional to the current flowing through the line. As a result, losses can be kept to a bare minimum when the power supplied by the PVs equals the power absorbed by the load. Any further increase in PV penetration can result in reverse currents and total losses. When PVs are unavailable (between 18:00 and 5:00), grid power loss with and without PVs is the same. Therefore, we only consider power outages from 6:00 to 18:00. Because each load bus has a different working mode, a different maximum capacity usage time, and changes continuously, we do not calculate the exact loss when calculating power losses. T_{max} is approximated as the same for all buses. Thus, reducing active power loss is a goal that must be accomplished in order to achieve the goal of reducing power loss (including transformer and line losses).

When looking at the percentage of losses in Table 1, integrating solar power into the grid can reduce the percentage of losses, here from 4.43% to 3.57%. The power flow is transferred to the load and back to the source due to generating capacity of PVs greater than the load's total capacity. In a traditional grid, power flows only from source to load. The ratio of active power loss to transmitted active power is relatively small.

Table 1. Power loss ratio with and without solar power at full load at 12:00 at 373E18.8

	Total generating power (MW)	Total power loss (MW)	Percentage loss (%)
Without PVs	8.373	0.371	4.43
With PVs	12.305	0.439	3.57

However, Table 2 shows that after incorporating solar power, the power loss increases dramatically, from 371 + j443.7 (kW + jkVAr) to 438.3 + 790.8 (kW + jkVAr). This is because the generated solar power capacity is greater than the load's consumption capacity, causing excess power to be injected back into the source. Furthermore, the power losses are affected by the location of the PV plants installation. Solar power clusters are mostly found on feeder 373E18.8 in the centre of the main branch.

Table 2. Power losses at full load with and without solar power at 373E18.8 feeder at 12:00.

Power loss	Without PVs		With PVs	
	P (kW)	Q (kVAr)	P (kW)	Q (kVAr)
Main branch	274	311.8	338.8	654.1
Huong Long - Huong Giang branch	48,7	66.7	48.8	66.0
Ha Linh – Phuc Dong branch	48.3	65.2	51.7	70.8
Summary	371	443.7	439.3	790.8

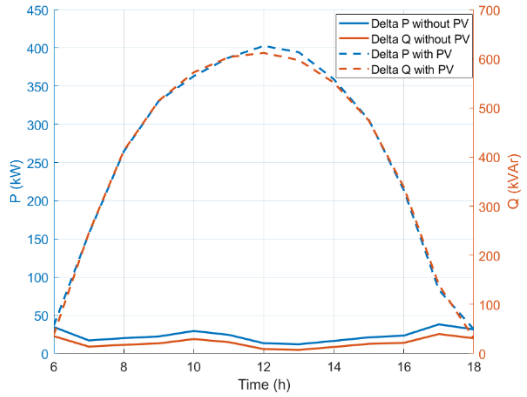

Fig. 12. Comparison of 373E18.8 feeder capacity losses with and without PV systems in November

Fig. 12 illustrates that integrating solar power into the grid results in significant losses. The increase in active power loss is that the solar power source's capacity is much greater than the total power consumed by the load, resulting in excess power being pushed back into the grid. Furthermore, when integrating solar power, the reactive power loss is primarily in the PVs' transformers.

3.2. 374E18.8 Feeder

On feeder 374E18.8, there is only one Quynh Nga solar power plant with a capacity of 999 kWp and an installed transformer capacity of 6020 kW.

3.2.1. Voltage Profile

Summer scenario

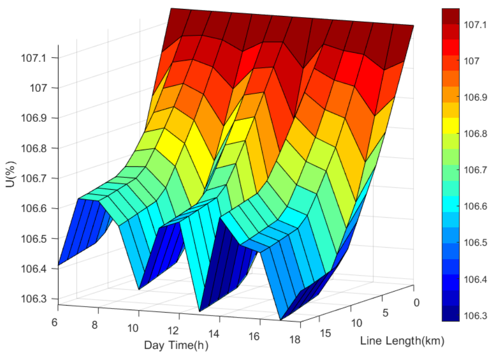

Fig. 13. Voltage profile on main branch of 374E18.8 feeder when PV systems are integrated in summer.

At feeder 374E18.8, the solar power generating capacity on this feeder is less than 1 MW, and the Phuong Hoa solar power plant installation location is relatively close to the source. As a result, power returned to the source is quite limited and has little effect on the overall voltage profile of the feeder.

Winter scenario

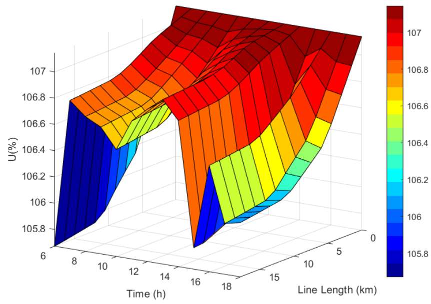

Fig. 14. Voltage profile on main branch of 374E18.8 feeder when PV systems are integrated in winter.

The before-in voltage profile after integrating distributed solar power in the winter scenario is depicted in Fig. 14. After integrating PVs, the voltage profile increased slightly but not significantly; this does not violate the Vietnamese grid code.

3.2.2. Power Losses

Table 3 shows the results of the simulation. Table 3 compares power loss at full load before and after installing solar PV. The power loss is reduced from 314.8 + j344 (kW + jkVAr) to 288.5 + 332.8 (kW + jkVAr) after incorporating solar power. In this case, as opposed to feeder 373E18.8, the generated solar power capacity is less than the load consumption capacity. The generation capacity of a solar power source reduces the power flow from the source to the load.

Similar to Table 4, the percentage of capacity loss in the feeder 374E18.8 scenario is reduced from 5.21% to 4.81%. Furthermore, the active power loss ratio in both cases is less than 10% of the transmitted active power.

Table 3. Power losses at full load with and without solar power at 374E18.8 feeder at 12:00.

Power loss	Without PVs		With PVs	
	P (kW)	Q (kVAr)	P (kW)	Q (kVAr)
Main branch	264.6	260.7	25.1	37.1
Huong Binh branch	25.3	37.4	24.8	35.6
Hoa Hai branch	24.9	35.8	238.7	250.1
Summary	314.8	334	288.5	332.8

Table 4. Power loss ratio with and without solar power at full load at 12:00 at 374E18.8

	Total generating power (MW)	Total power loss (MW)	Percentage loss (%)
Without PVs	6.048	0.315	5.21
With PVs	6.014	0.289	4.81

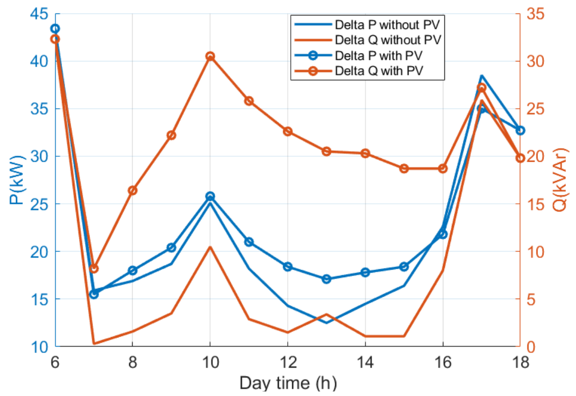

Fig. 15. Comparison of 374E18.8 feeder capacity loses with and without PV systems in November

The daily load curve shows that when the grid is in no-load mode at noon, the PVs' generating power is at peak power mode in the noon time frame when the grid is under-loaded. As a result, the generating capacity of solar power is injected back into the grid, which leads to an increase in power loss. As shown in Fig. 15, at 17:00, the solar PV generating capacity is less than the power consumption of the load, which reduces the power flow from the source to the loads and thus reduces power loss.

4. Solution

Based on the observations from the voltage profile, with increasing penetration of PVs, there is an increase in voltage bias in the buses of the 373E18.8 and 374E18.8 feeders. The paper presents a method to improve the voltage quality of the 373E18.8 feeder in winter. The reason is that this scenario is worse than the summer scenario, as we have already covered the cause. Moreover, 373E18.8 has a much higher entry rate than 374E18.8.

4.1. Lowing the Operating Voltage at Peak Hours of the Solar Power System

When the penetration of PVs is large enough, the current regulator voltage setpoints cannot minimize the voltage bias [18]. Therefore, the voltage setpoint of the 110/35 kV substation regulator on the source side must be lowered to maintain voltage levels within limits.

The transformer on the source side is a voltage regulator under a 110/35 kV load. Based on the parameters available in the library of ETAP software, each step of adjustment voltage is 0.625% U_{nom} and the voltage adjustment range is 31.5 kV to 38.5 kV. Fig. 25 shows the voltage tap changes of the regulator over 24 hours to minimize voltage violations. The 11th step means that the voltage is being operated with an amplitude of 37.5 kV. As for the 9th voltage division, the grid is operated at a voltage of 36.5 kV, in which step 0 represents the voltage level of 35 kV.

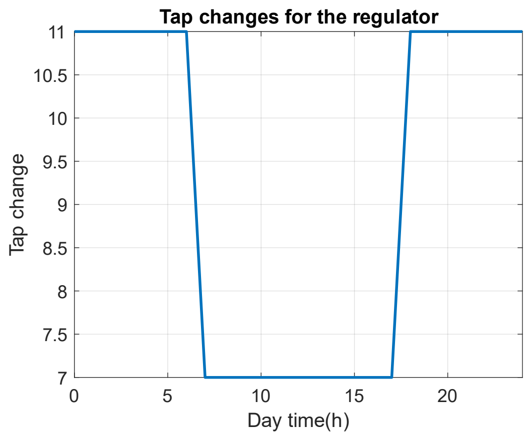

Fig. 16. Using tap changer solution to improve voltage quality

We may have a solution to ultimately lower the voltage tap to a fixed 36.5 kV (instead of 37.5 kV) as before distributed power penetration. However, in the time frames without PVs, the voltage is relatively low at the end of the line. To ensure future load growth and reduce power loss, adjusting the tap of the 110/35 kV transformer as we suggested is recommended.

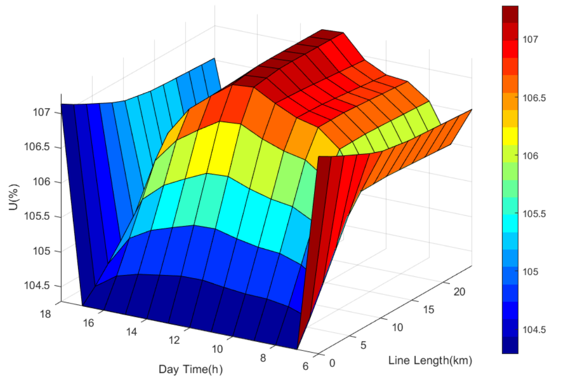

Fig. 17. Voltage profile at main branch after using proposed tap changer

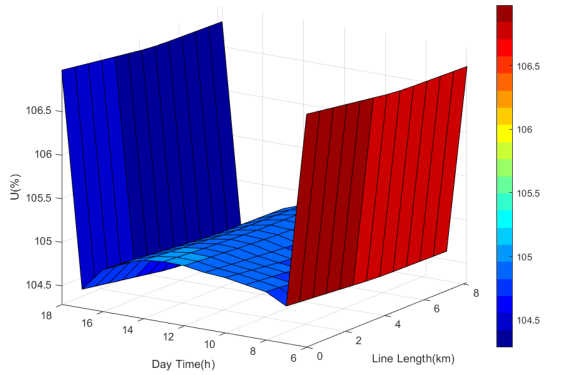

Fig. 18 Voltage profile at Huong Long -Huong Giang branch after using proposed tap changer

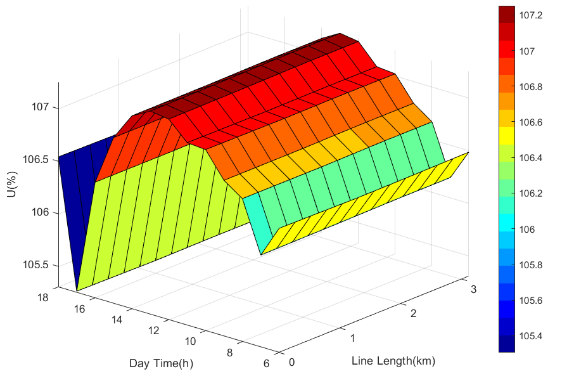

Fig. 19. Voltage profile at Ha Linh - Phuc Dong branch after using proposed tap changer

Lowering the voltage setpoint leads to a decrease in base case voltage levels at the source over 24 hours, with voltage improvements during peak solar power periods from 7:00 to 17:00, which can be observed in Fig. 17, Fig. 18, and Fig. 19.

Fig. 20 shows that the difference in power loss before and after using the proposed tap change does not differ significantly. In 24 hours, only 11.3 + j20.9 (kW + jkVAr) was reduced. During the time frame from 7:00 to 17:00, the tap is constant at 36.5kV. Power losses are reduced only outside of that time frame.

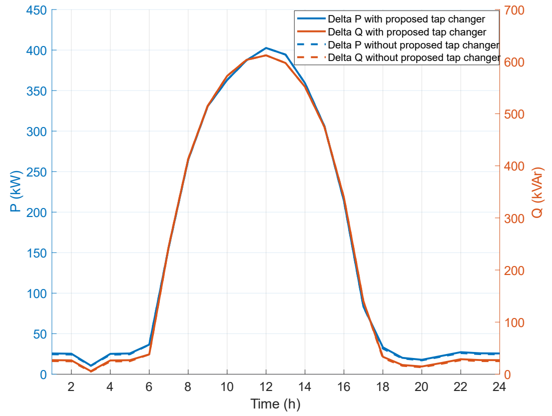

Fig. 20. Power losses comparison before and after using the proposed tap changer

4.2. Reducing the Generating Capacity during Peak Hours of the Solar Power System

When PV production is extremely near to load demand, the voltage loss is minimal. Therefore, we proposed 50% and 70% PV output curtailment methods to verify the optimal technique.

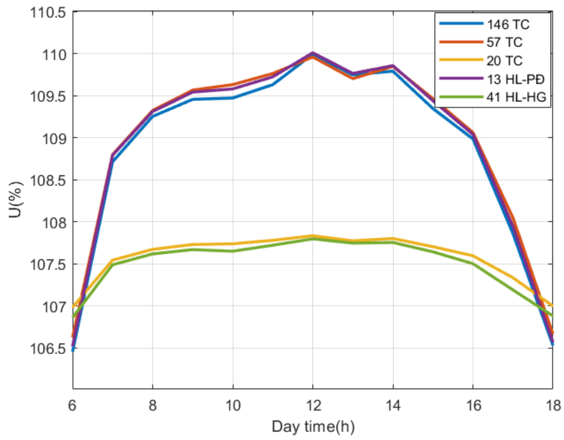

Fig. 21. Voltage profile at some typical feeder 373E18.8 buses with 100% PV generating capacity

In this solution, we will consider the power grid when connecting 100% of the generating capacity of solar power to the Huong Khe grid. Fig. 21 shows voltage profiles at some typical buses on 373E18.8. The objective of this scenario is to compare the voltage norms before and after the reduction of solar power capacity.

50% PV generation curtailment

Fig. 5 shows that the generating capacity of the PVs is 3–4 times larger than the load consumed, especially between 8:00 and 16:00. Intending to cut PV system generation capacity by 50%, we tested and recommended cutting between 8:00 and 16:00. during the day. The total generating capacity of the PV system after 50% reduction of total power is 6400 kW.

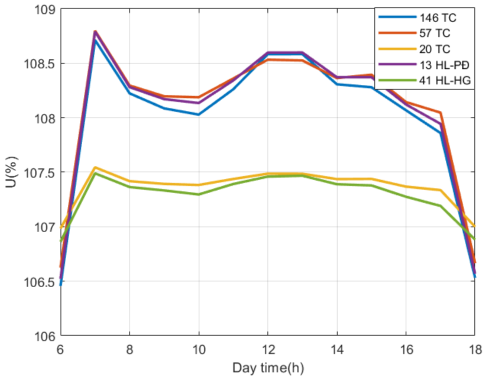

Fig. 22. Voltage profile of a typical bus on 373E18.8 feeder when PV generating power is reduced by 70%

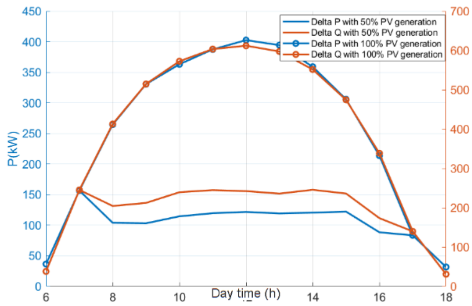

Fig. 23. Comparison of power losses before and after reducing PV generating power by 50%

Fig. 22 and 24 shows the voltage profile of some typical buses on feeder 373 when reducing PV's generating capacity by 50%. It can be seen that the voltages at buses 146 and 57 on the main branch and bus 13 on the Ha Linh - Phuc Dong branch have been significantly improved during peak hours of PV generations. The peak voltage at noon is near 1.1U_{dm}, which has been brought to an approximate voltage range of 1.08U_{nom} to 1,085U_{nom}. Then we will have a reserve voltage oscillation distance of nearly 0.2U_{nom} to increase voltage stability in case the capacity of the load fluctuates.

Fig. 23 depicts the hourly power loss obtained after simulating ETAP software. Compared to the loss, 1321.2 + 2488.1 (kW + kVAr) is the power loss roughly halved to. Without the previous solar power cut, the voltage is 3329.5 + j5152 (kW + jkVAr).

70% PV generation curtailment

During the peak hours of PVs, the voltage profiles of buses 146 and 57 on the main branch, and bus 13 on the Ha Linh - Phuc Dong branch, are significantly improved. The voltage oscillation margin with this power cut is better than the PVs' 50 percent power cut solution.

After simulating the assumption of 70% reduction of PVs' generating power, we obtain the total power loss is 690.8 + 1375.5 (kW + kVAr) from 6:00 to 18:00. PV capacity that is much less than 100% grid-connected is 3329.5 + j5152 (kW + jkVAr).

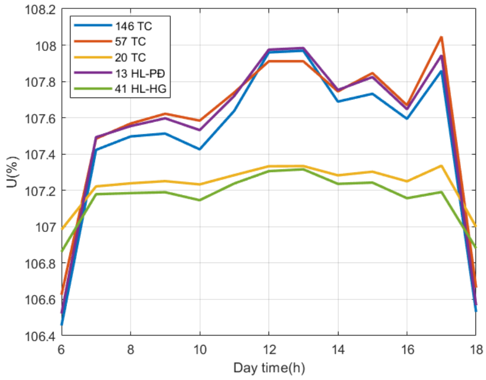

Fig. 24. Voltage profile of a typical bus on 373E18.8 feeder when PV generating power is reduced by 70%

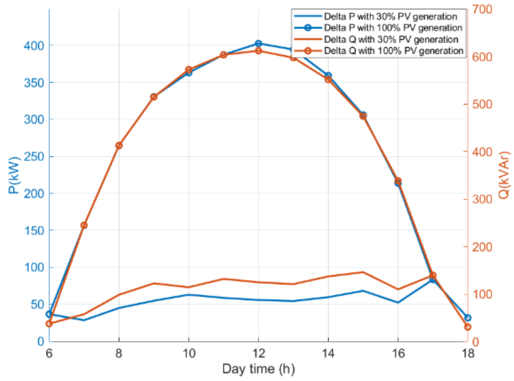

Fig. 25. Comparison of power losses before and after reducing PV generating power by 70%

With the solution of reducing the generating capacity of a solar power plant, we can see that this solution achieves both the goals of improving voltage quality and reducing power loss. This is much better than the solution of lowering the operating voltage at peak hours, which only enhances voltage quality. However, cutting capacity by such a large amount will cause difficulties for investors in solar power plants. Investors suffer economic losses when the installed capacity of PVs is very high but only partially connected to the power grid.

5. Conclusion

This paper first gives an overview of the voltage profile when integrating distributed PV power into the grid. In the next section, with actual data from NPC Ha Tinh, ETAP software simulated two feeders, 373E18.8 and 374E18.8, of Huong Khe DS (distributed system). The results were used to evaluate voltage quality and power losses in 2 cases: before and after PVs integration. It shows that in feeder 373E18.8, due to the penetration of PV being much larger than the total load demand, there are severe violations on the grid, such as over-voltage, substantial reverse power flow, and a sharp increase in total power losses. On the other hand, feeder 374E18.8 has small-scale PV penetration and is often less than the load demand, so voltage quality and power losses are improved.

After studying both cases, we devised two solutions to improve both problems. First, we proposed lowering the operating voltage at the intermediate transformer station from 37.5 kV to 36.5 kV from 6:00 to 18:00. With this solution, the voltage profile is significantly improved, but the power losses are barely changed. Therefore, the second proposal to cut off distributed PV generations is given. We consider the curtailment of the total output capacity of PVs and have achieved significant improvements in voltage quality and power losses with the Ha Tinh case study. Nonetheless, with the second solutions, PV investors will suffer a significant loss in terms of profit. In any distributed power system, it is recommended to apply a careful calculation to connect each PV plant to the grid, such as a detailed hosting capacity strategy and to effectively divide curtailment among PV units and throughout different periods.

In this study, the voltage profile is enhanced successfully and validated by simulation by using two solutions. Both methods should be applied flexibly to the various distributed power system.

References

[1] Ministry of Industry and Trade of Vietnam, Proposed national power planning development from 2021-2030, with a vision to 2045, 2021.

[2] Annual Report 2021, EVN, 2021.

[3] R. Tonkoski, D. Turcotte, T. H. M. El-Fouly, Impact of high PV penetration on voltage profiles in residential neighborhoods, IEEE Trans. Sustain. Energy, vol. 3, no. 3, pp. 518–527, 2012, https://doi.org/10.1109/TSTE.2012.2191425.

[4] Circuler 30/2019/TT-BCT, Electricity Regulatory Authority of Vietnam (ERAV)

[5] O. Gandhi, W. Zhang, C. D. Rodriguez-Gallegos, D. Srinivasan, T. Reindl, Continuous optimization of reactive power from PV and EV in distribution system, IEEE PES Innov. Smart Grid Technol. Conf. Eur., pp. 281–287, 2016, https://doi.org/10.1109/ISGT-Asia.2016.7796399.

[6] M. Zeraati, M. E. H. Golshan, J. M. Guerrero, Voltage quality improvement in low voltage distribution networks using reactive power capability of single-phase PV inverters, IEEE Trans. Smart Grid, vol. 10, no. 5, pp. 5057–5065, 2018, https://doi.org/10.1109/TSG.2018.2874381.

[7] T. Aziz, N. Ketjoy, PV penetration limits in low voltage networks and voltage variations, IEEE Access, vol. 5, pp. 16784–16792, 2017, https://doi.org/10.1109/ACCESS.2017.2747086.

[8] O. Gandhi, D. S. Kumar, C. D. Rodríguez-Gallegos, D. Srinivasan, Review of power system impacts at high PV penetration Part I: Factors limiting PV penetration, Sol. Energy, vol. 210, no. July, pp. 181–201, 2020, https://doi.org/10.1016/j.solener.2020.06.097.

[9] D. Sampath Kumar, O. Gandhi, C. D. Rodríguez-Gallegos, D. Srinivasan, Review of power system impacts at high PV penetration Part II: Potential solutions and the way forward, Sol. Energy, vol. 210, no. February, pp. 202–221, 2020, https://doi.org/10.1016/j.solener.2020.08.047.

[10] H. Sugihara, K. Yokoyama, O. Saeki, K. Tsuji, L. Member, Economic and efficient voltage management using customer-owned energy storage systems in a distribution network with high penetration of photovoltaic systems, IEEE Trans. Power Syst., vol. 785, pp. 1–10, 2012, https://doi.org/10.1109/TPWRS.2012.2196529.

[11] T. Aziz, N. Ketjoy, Enhancing PV penetration in LV networks using reactive power control and on load tap changer with existing transformers, IEEE Access, vol. 6, pp. 2683–2691, 2017, https://doi.org/10.1109/ACCESS.2017.2784840.

[12] T. T. Ku, C. H. Lin, C. S. Chen, C. T. Hsu, Coordination of transformer on-load tap changer and PV smart inverters for voltage control of distribution feeders, IEEE Trans. Ind. Appl., vol. 55, no. 1, pp. 256–264, 2019, https://doi.org/10.1109/TIA.2018.2870578.

[13] S. Lakshmi, S. Ganguly, Coordinated operational optimization approach for PV inverters and BESSs to minimize the energy loss of distribution networks, IEEE Syst. J., vol. 16, no. 1, pp. 1228–1238, 2022, https://doi.org/10.1109/JSYST.2020.3041787.

[14] S. Ghosh, S. Rahman, and M. Pipattanasomporn, Local distribution voltage control by reactive power injection from PV inverters enhanced with active power curtailment, IEEE Power Energy Soc. Gen. Meet., vol. 2014-October, no. October, 2014, https://doi.org/10.1109/PESGM.2014.6939358.

[15] S. Ghosh, S. Rahman, M. Pipattanasomporn, Distribution voltage regulation through active power curtailment with PV inverters and solar generation forecasts, IEEE Trans. Sustain. Energy, vol. 8, no. 1, pp. 13–22, 2017, https://doi.org/10.1109/TSTE.2016.2577559.

[16] S. Mohagheghi, Impact of rooftop photovoltaics on the distribution system, J. Renew. Energy, vol. 2020, 2020, https://doi.org/10.1155/2020/4831434.

[17] E. Mulenga, Impacts of integrating solar PV power to an existing grid, Department of energy and environment , Chalmers university of technology , gothenburg, Sweden 2015.
[Online]. Available: 218826.pdf (chalmers.se)

[18] S. K. Solanki, V. Ramachandran, S. Member, and J. Solanki, Steady state analysis of high penetration PV on utility distribution feeder, PES T&D 2012, pp. 1–6, 2012, https://doi.org/10.1109/TDC.2012.6281716.