Voltage Regulation in Excessive Penetration of Solar Rooftop Distribution System Using Battery Energy Storage System

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ABSTRACT

This paper presents the methodology and solutions for mitigating voltage variation under steady conditions caused by differing levels of PV penetration in low-voltage (LV) rural networks. The LV rural area of the Provincial Electricity Authority (PEA) North-East area 3 District of Thailand is used as a case study with load profiles from Geographic Information System (GIS) software. Moreover, rooftop PV power generation is calculated using recorded data on irradiation in Nakhon Ratchasima Province. DIgSILENT Power Factory software is used to simulate and analyze the quality of the proposed method by focusing on the voltage level at the end of the line or dead-end (DE) of the LV network. The results show overvoltage at the DE under the high rooftop PV penetration. The battery energy storage system (BESS) is applied to mitigate the problem of low quality. Meanwhile, the system is operated by examining load demand and rooftop PV power generation to define the state of charging and discharging conditions. The proposed method can be integrated into the algorithm of a rooftop PV system and BESS local control in the home energy management system (HEMS). The results show that the proposed method can reduce the voltage variation problem existing in the PEA standard while improving the voltage level at all DEs.

Keywords: Battery Energy Storage System, Low-Voltage Network, Overvoltage, Rooftop PV System, Voltage Drop

1. INTRODUCTION

In the last decade, distributed energy resources (DERs) have been widespread in the electricity networks of many countries due to the energy crisis and global warming. [1–7]. Among several types of DERs, the photovoltaic (PV) system is the most popular and increasingly installed in many countries [8] due to its ease of application

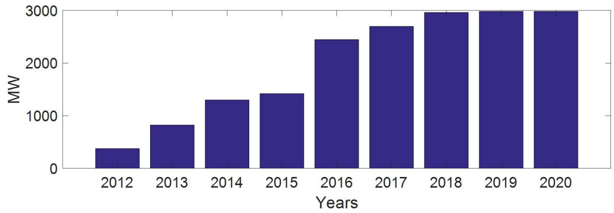

Fig. 1: *The increasing use of PV systems in Thailand [12].*

[9] and the fact that solar radiation can never run out. The use of integrated photovoltaics (BIPV) at the residential level small PV systems, or rooftop PV systems, is the starting point for the smart grid (SG) era. The preference for rooftop photovoltaic (PV) systems has continued to increase in recent years due to their simple installation, independence from the grid, and economic benefits. However, the adverse effects of high peak-PV output rather than load demand on distribution networks are disturbing. In particular, excessive PV penetration is the main cause of voltage stability problems, over-voltage, frequent voltage fluctuations, and disrupted protection systems.

The capacity of PV systems was monitored in Thailand from 2012–2020, and the results revealed that the cumulative use of PV systems equated to 2982.62 MW [10]. The trend of PV systems use in Thailand is shown in Fig. 1. In 2020, the Energy Regulatory Commission (ERC) of the Ministry of Energy of Thailand promoted the use of rooftop PV systems by offering to purchase electricity from prosumers connected to the Provincial Electricity Authority (PEA) networks at the rate of 2.20 baht per unit (kWh). Since 2016, according to the grid connection code, the PEA has prohibited the total capacity of rooftop PV systems from exceeding 15% of the distribution transformer rates in the LV network. This rule of thumb in Thailand permits distributed PV systems with peak power to reach up to 15% of the peak load on a feeder. Nonetheless, for single-phase feeders, differences in the capacity of rooftop PV systems between phases of 5 kW_{peak} are not permitted [11]. This necessary grid code rule is a useful way to allow many distributed PV systems to be installed in response to concerns about power quality issues.

Many rooftop PV systems for self-consumption do not operate within the grid connection code rules. However, in 2036, the growth of rooftop PV systems is expected to

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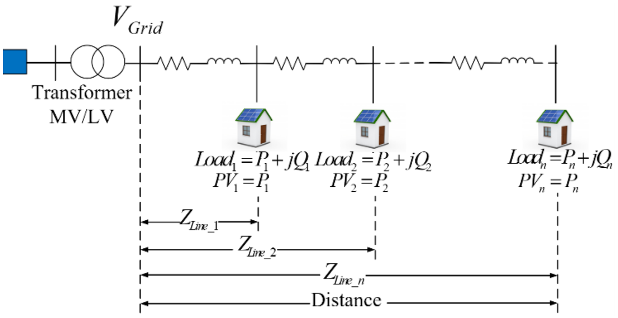


Fig. 2: The simplified radial network.

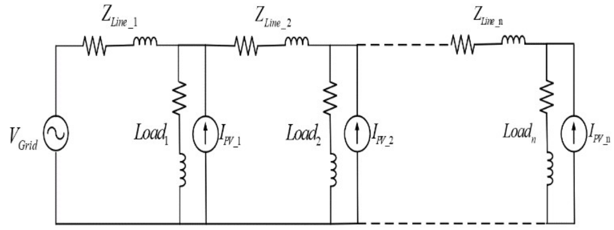


Fig. 3: The equivalent circuit of the simplified radial network.

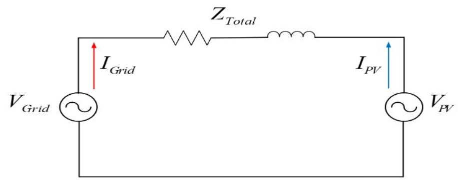


Fig. 4: The simplified circuit of the radial network from source transformation theory.

be about 300 MW_{peak}. Therefore, if several rooftop PV systems are connected to the PEA LV networks, then the grid effect would be as follows [13–17]:

- Violation of voltage profile;
- Unbalanced voltage level between phases;
- Amplified, erased, or reduced background harmonics;
- Energy losses;
- Reverse or bi-directional power flow;
- Fricker;
- Exceedance of transformer and cable rating.

Due to the severe effects of the high increase in rooftop PV systems on LV networks, many studies have focused on the problem of overvoltage [18] which is an important power quality issue [19]. The quality of supply directly affects customers. This work focuses on the impact of voltage variations at the dead-end (DE) of the LV network from the self-consumption of rooftop PV systems and their mitigation.

When many customers install rooftop PV systems to reduce billing charges or self-consumption, they inject electricity into the LV network so that the power generated is greater than demand. The PEA controls a one-way meter for measuring power consumption to prevent the meter from reversing direction when the rooftop PV generates more energy than the customer load. This study assumes that a uniform random number of customers are interested in installing rooftop PV. Thus, the highest random number from the results is selected. Moreover, when overvoltage occurs, BESS is operated to improve the voltage level at the HEMS and reduce the variation in the voltage level at all DEs. This work uses DIgSILENT Power Factory software to simulate the load flow results with the random number of houses interested in rooftop PV installation. In addition, PVsyst software is used to design the optimal capacity of BESS.

This paper is organized as follows: Section 2 describes the impact on voltage level, Section 3 explains the studied methodology and data, Section 4 describes the simulation and results, and Section 5 presents the conclusion.

2. IMPACTS ON VOLTAGE QUALITY

According to [7], the impacts of overvoltage at the point of common coupling (PCC) and DE are important issues. In Thailand, the installation of rooftop PV systems are regulated according to the 2008 grid connection code. This regulation requires that the total peak power generating capacity of the rooftop PV system should not exceed 25% of the distribution transformer rate, while the system for a single-phase must not exceed 10 kW_{peak} per house. In the case of three-phase connection, the PEA requires the total capacity of rooftop PV systems installation not to exceed 80% of the distribution transformer rates.

Due to an increase in applications, more problems are arising in the electrical system and traditional methods alone are insufficient for resolving them. Moreover, the overvoltage problem also depends on the following:

- The weakness of the network structure;
- The location of the installed rooftop PV systems;
- The ratio of the electricity consumption to the electricity produced by the rooftop PV systems;
- The prevalence of rooftop PV systems.

The overvoltage issue can be explained by the simplified radial network in Fig. 2. Using the current source as the equivalent of a PV system, the equivalent circuit of the simplified radial network is shown in Fig. 3. The PV systems are clustered by source transformation theory as shown in Fig. 4.

According to Kirchhoff's Laws, the voltage of rooftop PV systems can be given as

$$V_{Grid} = \left[\left(I_{Grid} - I_{PV}\right) \times Z_{Total}\right] + V_{PV} \quad (1)$$

$$V_{PV} = V_{Grid} - \left[\left(I_{Grid} - I_{PV}\right) \times Z_{Total}\right] \quad (2)$$

where V_{Grid} is a grid voltage, V_{PV} is a voltage of the rooftop PV system, I_{Grid} is a grid current, I_{PV} is a current of the rooftop PV system, and Z_{Total} is the summation of cable impedances and loads.

According to Eq. (2), the various voltage levels of this simplified network can be classified into three conditions;

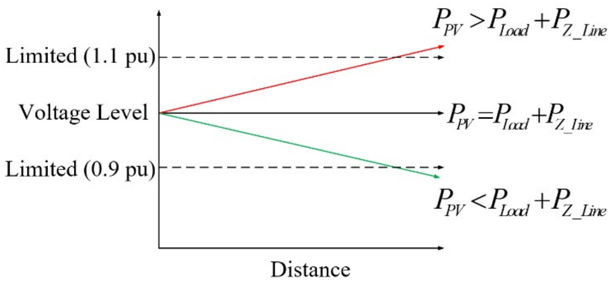


Fig. 5: Correlation between the distance and grid voltage level of three behavioral cases.

- Case 1: $V_{PV} > V_{Grid}$ when $I_{PV} > I_{Grid}$,
- Case 2: $V_{PV} = V_{Grid}$ when $I_{PV} = I_{Grid}$, and
- Case 3: $V_{PV} < V_{Grid}$ when $I_{PV} < I_{Grid}$.

The 3-case behaviours of various grid-voltage levels with the different distance from the load to the grid network is shown in Fig. 5. The decrease of grid voltage level at the end of the line or dead-end (DE) in the LV network depends on the increasing distance from the load to grid network location for Case 3. At DE, Case 1 and Case 2 are unacceptable under the grid voltage restriction.

3. THE PROPOSED METHODOLOGY AND TEST SYSTEM CHARACTERISTICS

3.1 Methodology

In order to prevent overvoltage problems in the PV system, the net energy demand of the consumer should be considered. In this paper, the rural imbalance or multiple-phase network under the responsibility of the PEA North-East region 3, Nakhon Ratchasima Province is used as a case study. The customer loads connected to each phase are defined by considering the structure of this network. Phase A-N is randomly classified by the network structure. Phase B-N and C-N are based on the random loads associated with AB-N and ABC-N. The residential loads are classified into power consumption of less than 150 kWh/month, and over 150 kWh/month. This is due to the random electricity demand of each customer. Thus, rooftop PV generation is allowed at the rates of 3 kW_{peak} and 5 kW_{peak} for residential loads consuming less than 150 kWh/month and over 150 kWh/month, respectively. Customers acting as both electricity producers and consumers who become "prosumers" were obtained by uniform random numbers: "1" = installed a rooftop PV system or "0" = not installed a rooftop PV system. Power flow was then executed using DIgSILENT Power Factory software. If the network did not have any impact, then the random customers who installed a rooftop PV system were examined again.

When the results indicate that the overvoltage exceeds the standard, five solutions can mitigate this problem by considering the end user [20, 21]:

- Installation of battery energy storage system (BESS);
- Inverter voltage control;

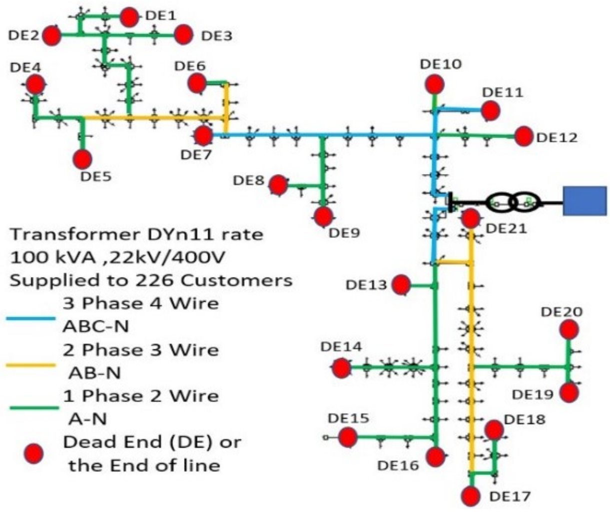


Fig. 6: Defined location of the test network system.

- Active power curtailment;
- Reactive power compensation;
- Respond to demand.

In this work, the BESS is proposed to mitigate voltage violation by generating the compensated power and self-consumption for the PV or hybrid system [22]. This solution is also an efficient way of increasing the performance of the PV system.

3.2 Studied Network

The radial LV network under study is located in a rural area under the responsibility of the PEA Bua Yai district, Nakhon Ratchasima province, PEA North-East Region 3. The presence of an unbalanced network is identified using the historically random method. The network consists of a distribution transformer at the rate of 100 kVA, 22 kV stepping down to 400/230 V for supplying 226 households via two feeders. The main cable is provided by the Geographic Information System (GIS) software from the PEA. As shown in Fig. 6, the DE1-DE12 and DE13-DE21 are defined on the left and right sides of the distribution transformer, respectively.

3.3 Power Generation in a Rooftop PV System

The power generation characteristics of a rooftop PV system were computed by comparing the solar radiation with the load rate, defined as 1000 W/m^2. The load rate of a rooftop PV system was defined by the rate of new rooftop PV system installations by the PEA, namely 3 kW_{peak} and 5 kW_{peak}. The prevalence of solar radiation in Nakhon Ratchasima Province is high in comparison to other areas in Thailand. On a clear day, a rooftop PV system generates power at the rate of 3 kW_{peak} and 5 kW_{peak} equating to energy levels of 22.245 kWh/day and 37.0606 kWh/day, respectively. The power generation of the rooftop PV is set to a unity power factor. The pattern of power generated by a PV system is shown in Fig. 7.

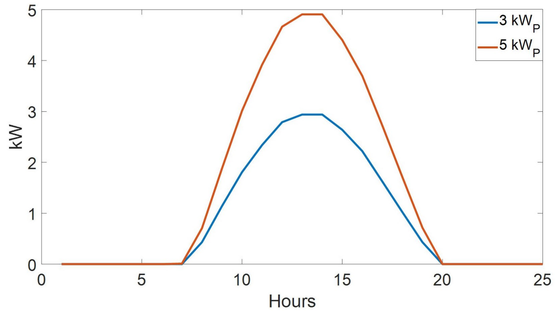


Fig. 7: *Generated power patterns of a rooftop PV systems.*

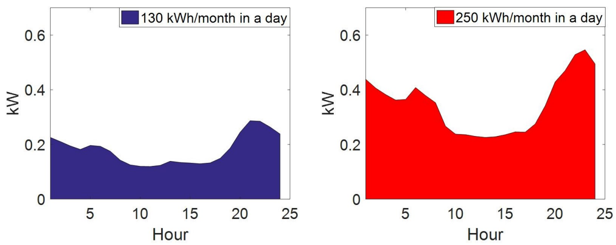


Fig. 8: *The load patterns of customer power consumption.*

Table 1: *The BESS designed from PVsyst software.*

Load (kWh/Month)	BESS (kWh)	Global Capacity (Ah)	Charging Time (Hours)
130	3.7	180	5.7
250	7.4	180	2.5

Note: • Global capacity in Ah units is the rate provided in the global market
• Charging time during full sun conditions
• Discharge under maximum load

Table 2: *Users' data for simulation.*

Item	Phase A-N	Phase B-N	Phase C-N	Total
Load connected	156	49	21	226
Load <150 kWh connected	76	24	9	109
Load >250 kWh connected	80	25	12	117
PV system rated at 3 kWh_{peak}	41	13	6	60
PV system rated at 5 kWh_{peak}	46	15	7	68
BESS rated at 3.7 kWh	41	13	6	60
BESS rated at 7.4 kWh	46	15	7	68

3.4 Load Patterns

The residential load data provided by the PEA is divided into two types: 1) small customers with energy consumption of less than 150 kWh/month—defined here as 130 kWh/month. 2) Large customers with energy consumption of more than 150 kWh/month—defined here as 250 kWh/month. In this study, it is assumed that the power factor of the load is 0.95. The load patterns are shown in Fig. 8. It should be noted that the daily load consumption for small customers is 4.276 kWh/day and 8.2184 kWh/day for large customers.

3.5 Characteristics of a BESS

A lithium-ion battery is used for this investigation since it is light, more durable, charges or discharges at a faster rate, and is more efficient than a lead-acid battery [22]. The daily load consumption data is used in PVsyst software for simulating the rate of BESS in this network. Additionally, the strategy for the state of charge (SOC) is a state-of-the-art peak shaving mode which is a BESS controlled at the household level or by HEMS operation. The static operation mode of BESS and a unity power factor are assumed in this work. The BESS under the conditions of SOC and state of discharge (SOD) are described as

$$P_{BESS} = P_{Load} - P_{PV} \tag{3}$$

where P_{BESS} is the power rate of BESS, P_{Load} is the power of load, and P_{PV} is the power generation of rooftop PV system.

As in Eq. (3), P_{BESS} is a positive sign in the SOD and a negative sign under SOC.

$$SOC_{Min} < SOC_{(t)} < SOC_{Max} \tag{4}$$

Table 1 shows the BESS sizing obtained by PVsys software for two types of users.

4. SIMULATION RESULTS AND DISCUSSION

The simulation is based on household solar rooftop penetration. Therefore, a uniform distributed installation is investigated. This work aims to analyze the impact of rooftop PV systems with high penetration distributed in the test network. Therefore, the maximum number of random numbers is selected for the study. The load connection information of the test system is shown in Table 2. The case studies of the grid network are classified into three scenarios: no PV connected to the grid; PV connected to the grid; and integrated BESS with a PV system.

The PV system and BESS in DIgSILENT software are the static models used in this study. The combination of these models in the test network is created by first selecting the bus for connection, then the phase for connecting and coupling the load model at the same bus, as shown in Fig. 9.

4.1 Case of No Rooftop PV Systems Being Installed

The PEA voltage standard level is defined as being in the range of 0.9–1.1 pu. According to the simulation results, the voltage levels on the steady-state of DE1–DE21 were within the standard range defined at ±10% of V_{rms} as illustrated in Figs. 10 and 11. It should be noted that a longer distance between the load location and the grid affects the DE drop in the LV network due to the

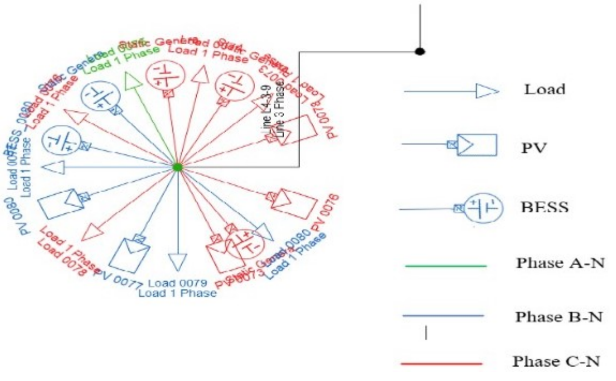
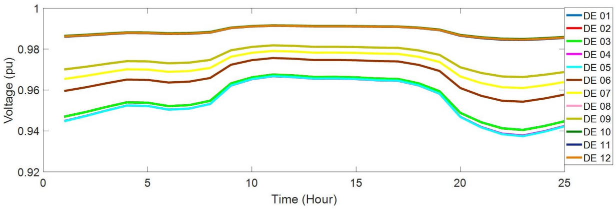
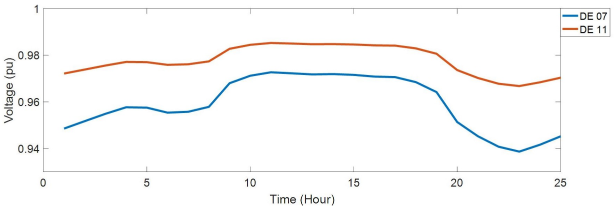


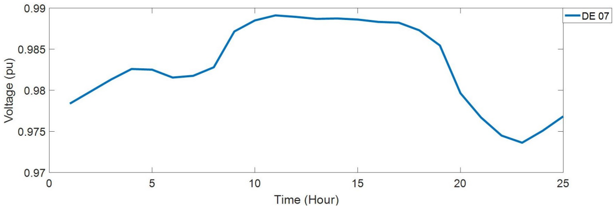
Fig. 9: *Example of a combination load, PV system, and BESS at bus.*



(a) Phase A-N



(b) Phase B-N



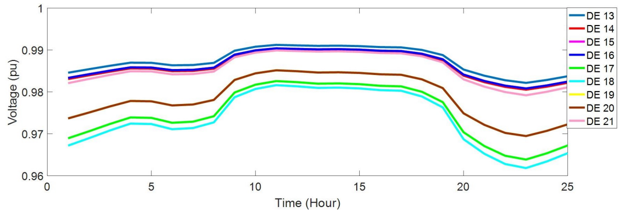
(c) Phase C-N

Fig. 10: *The behaviors of voltage levels DE1–DE12.*

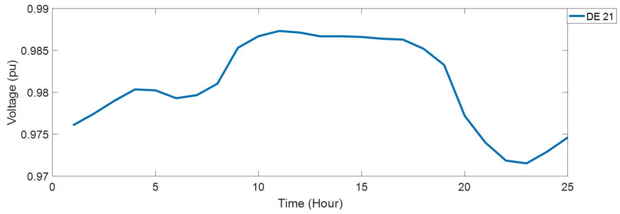
many loads connected along the feeder and higher line impedance.

Normally, the voltage level of each DE remains within the standard boundary. The voltage profiles of each DE in the LV network have similar shapes. Nevertheless, the voltage levels of each DE are different due to the total demand of the loads in each DE and the distance to the installed rooftop PV system. The length of the cable affects the impedance, therefore, the voltage level of some DEs such as DE1 which is farthest away, exhibits a greater drop than those nearer the distribution transformer.

Moreover, it can be assumed from the load demand simulated in the test LV network, that the voltage levels of each DE are close to those of a real network. Since residential loads are shown in the data, the voltage level at noon is higher than at night, inverting the load demand in time series. As can be observed from Figs. 10(b), 10(c), and 11(b), the shapes of the voltage level of phases B-N and C-N are similar to phase A-N.



(a) Phase A-N



(b) Phase B-N

Fig. 11: *The behaviors of voltage levels DE13–DE21.*

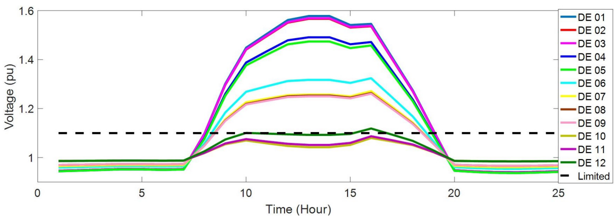
4.2 Case of Rooftop PV Systems Connected to the Grid

To meet the electricity needs of both domestic and commercial buildings, PV installation is simpler and more attractive than other renewable energy sources. However, the negative effects of increased PV system penetration on the distribution system are disturbing. The percentage of excessive penetration of rooftop PV systems connected to the LV network is calculated using Eq. (5). The number of customers who installed rooftop PV systems is considered in the test network.

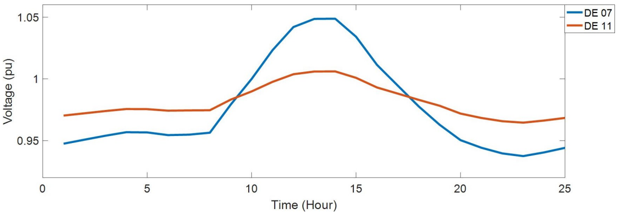
$$\text{Penetration} = \frac{\text{Capacity of rooftop PVs}}{\text{Distribution transformer rates}} \times 100\% \tag{5}$$

In this case study, the capacity of rooftop PV systems is assumed to be the sum of all rooftop PV system capacity in this LV network with a distribution transformer rate of 100 kVA. Rooftop PV system penetration in this network is calculated to be 547.3% or 520 kW_{peak}. The reason for using the maximum amount of random data is to analyze and investigate the impact of rooftop PV systems in accordance with the Thai government's policy of promoting their use. Moreover, Thai people are currently interested in installing rooftop PV systems in order to reduce their electricity costs. The voltage level profiles of DE1–DE12 and DE13–DE21 with the installation of rooftop PV are shown in Figs. 12 and 13, respectively.

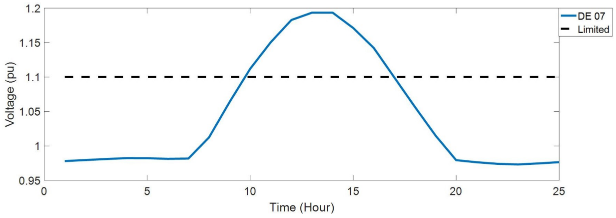
When the rooftop PV systems distributing high penetration are connected to the test LV network, the highest voltage level at the most distant bus is consistent with the theory previously mentioned above. The total current of PV systems is more than that obtained from the



(a) Phase A-N

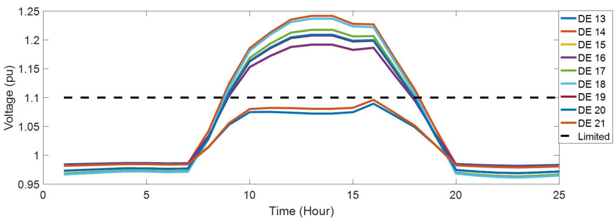


(b) Phase B-N

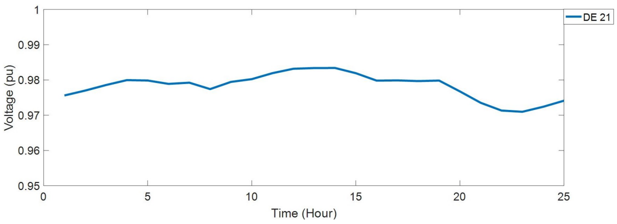


(c) Phase C-N

Fig. 12: *Voltage profiles of DE1–DE12 in the presence of high penetration for rooftop PV systems.*



(a) Phase A-N



(b) Phase B-N

Fig. 13: *Voltage profiles of DE13–DE21 in the presence of the high penetration for rooftop PV systems.*

grid due to reverse power flow. These characteristics of the voltage correspond to the behavior of sunlight. The voltage levels of rooftop PV systems located in the vicinity of the distribution transformer (DE10, DE11, DE20, and DE21 for phase A-N and DE7, DE11, and DE21 for phase B-N) are within the acceptable standard, as illustrated in Figs. 12(a), 12(b), and 13(b). The other DEs and phases are beyond the standard limit. This situation leads to damage to appliances or electronic devices.

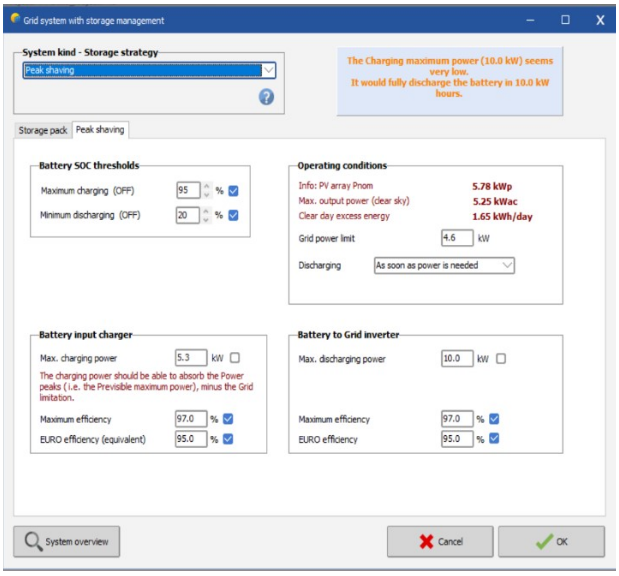


Fig. 14: *The BESS design (SOC, SOD).*

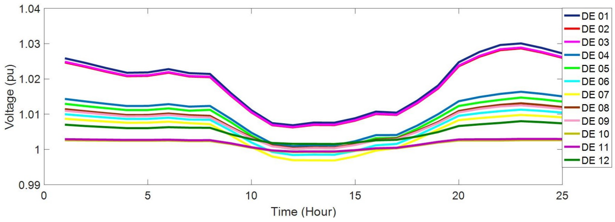
4.3 Integrating BESS into Rooftop PV Systems

This study selects the installation BESS to mitigate the overvoltage problem because a hybrid system (rooftop PV system integrated with BESS) can supply power all day and all night. The BESS overcomes the disadvantage of the PV system which can only supply the load during the daytime. The rooftop PV system rate of 3 kW_{peak} and 5 kW_{peak} can be increased with the integration of BESS to 3.7 kWh and 7.4 kWh, respectively. The SOC and SOD are as previously described. The BESS design in this study is shown in Fig. 14. The results of the voltage levels of each DE are shown in Figs. 15 and 16.

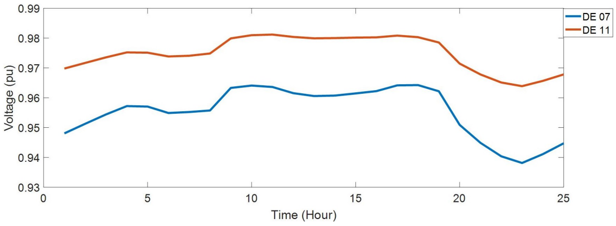
It should be noted that when the rooftop PV system is integrated with the BESS, the voltage levels of all nodes are within the standard range as illustrated in Figs. 15 and 16. For phase A-N in Figs. 13(a) and 14(a), the ideal characteristics of voltage profiles for DEs should be similar to the base case. Since the PV system and BESS absorb the reactive power, the cable lines cause a voltage drop when high power is generated in the PV system.

For phase B-N in Figs. 15(b) and 16(b), the voltage levels of DE7, DE11, and DE21 are close to the base case, but DE7 is farther away than DE11 and DE21. Therefore, the curve of the voltage profile of DE7 drops slightly at noon. In phase C-N, DE7 connects with the rooftop PV system slightly. Therefore, the voltage profile of DE7 is still similar to that of the installed PV system but smaller in scale.

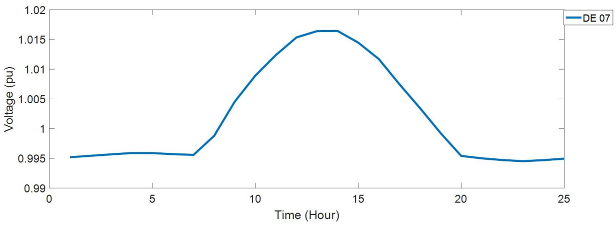
The improvement in voltage level through the installation of BESS mitigates overvoltage at the test network when several rooftop PV systems are connected to the grid during the period of maximum power generation, as shown in Table 3.



(a) Phase A-N

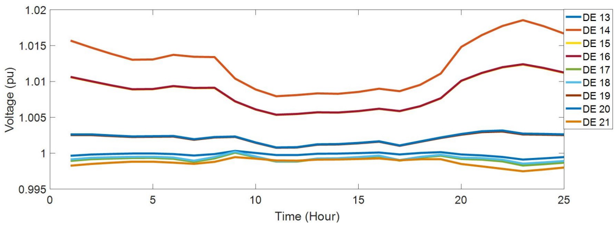


(b) Phase B-N

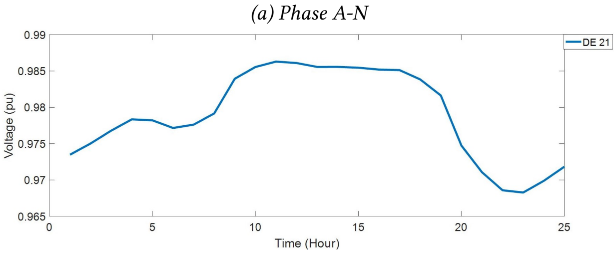


(c) Phase C-N

***Fig. 15**: Voltage profiles of DE1–DE12 with BESS integrated into the rooftop PV system.*



(a) Phase A-N



(b) Phase B-N

***Fig. 16**: Voltage profiles of DE13–DE21 with BESS integrated into the rooftop PV system.*

5. CONCLUSION

This paper investigates the effects of installing rooftop PV systems in multiple-phase networks. The excessive penetration of rooftop PV systems causes an overvoltage problem at the DEs when many rooftop PV systems are connected to the grid. The BESS can solve this problem, but the network must support the reactive power because the PV system and BESS absorb reactive power when operating at the unity power factor. Moreover, Eqs. (1) and (2) can explain the factor of overvoltage at DEs.

***Table 3**: Improvement level with the installation of BESS.*

DE	Phase A-N	Phase B-N	Phase C-N	Improvement Voltage Level (%)
1	✓	–	–	36.15
2	✓	–	–	35.73
3	✓	–	–	35.82
4	✓	–	–	32.86
5	✓	–	–	32.13
6	✓	–	–	24.20
7	✓	✓	✓	20.71, 8.41, 14.84
8	✓	–	–	20.16
9	✓	–	–	19.96
10	✓	–	–	4.13
11	✓	✓	–	4.97, 2.60
12	✓	–	–	8.33
13	✓	–	–	6.76
14	✓	–	–	18.79
15	✓	–	–	15.59
16	✓	–	–	15.62
17	✓	–	–	17.94
18	✓	–	–	19.21
19	✓	–	–	17.10
20	✓	–	–	17.19
21	✓	✓	–	7.55, −0.22

APPENDIX

The improvement voltage level is given by

$$\% = \left[1 - \left(\frac{V_{PV\_Install\_BESS}}{V_{PV}}\right)\right] \times 100\% \qquad (6)$$

where $V_{PV\_Install\_BESS}$ is the voltage at any bus when rooftop PV system integrated BESS and V_{PV} is the voltage level at any bus when a rooftop PV system is installed.

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