

Analysis of Voltage Unbalance and Energy Loss in Residential Low Voltage Distribution Systems with Rooftop Photovoltaic Systems

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Abstract. This paper investigates effects of voltage unbalance and energy losses due to the connection of rooftop photovoltaic systems in a low voltage distribution system of a housing estate, which has light loads during daytime. The paper presents a case study of a real distribution power system of housing estate in Thailand. Voltage unbalance and energy losses were simulated by using system characteristic and load data from GIS database of PEA with the DIgSILENT Power Factory program. The key findings of our analysis are as follows. Firstly, the number of installable 1-phase rooftop PV systems varies directly with load density. Secondly, the number of installed 1-phase rooftop PV systems can be increased if the installation locations are closer to the transformer. For 3-phase rooftop PV systems, their installations do not have any effects on the voltage unbalance. Furthermore, system energy loss relates to the load density and PV system installation locations in the same way as the voltage unbalance. The key implication of our study is that the installation of 1-phase rooftop PV system should be granted based on a careful consideration of the installation location and the load density.

Keywords: Installation, load density, minimum distribution, system energy.

1 Introduction

Three-phase voltage unbalance occurs when phase or line voltages are different from the nominal balanced situation. The voltage unbalance at terminals causes high current unbalance in three phase wye systems. It may decrease efficiency and lifetime of 3-phase transformers, motors and other loads. Furthermore, energy losses of systems can be increased because unbalanced current will flow in neutral lines. Voltage unbalance is caused by large and/or unequal distribution of 1-phase generation and/or load. At present, 1-phase grid-connected rooftop photovoltaic (PV) systems are widely installed by residential customers because of encouraging policies in many countries.

A rooftop PV system is an alternative clean energy system installed on the rooftop of a residential or commercial building. In Thailand, rooftop PV systems on residential building

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normally are 1-phase systems and have a capacity of below 10 kWp, while those systems on commercial buildings are 3-phase systems and have a capacity of 10 kWp to 1 MWp [1]. A rooftop grid-connected PV system generates power to load of a building and to a distribution system during the day. In May 2019, the Thai government has a policy to encourage rooftop PV installation of 100 MWp by accepting to buy excessive power generated in the price of 1.68 Baht kWh⁻¹ for 10 yr [2].

According to [3], increase or decrease of voltage unbalance in a radial low voltage residential urban distribution system depends on sizing and locating of PV systems and load demand. Rooftop PV systems are installed at only 1-phase in a 3-phase and four-wires distribution system at light load condition leading to the impact of voltage unbalance [4, 5]. Because of the increase of rooftop PV systems, the maximum allowable number of grid-connected PVs in European and UK low voltage (LV) distribution networks was predicted based on voltage imbalance standard conditions [6].

This study investigated voltage unbalance and power loss issues due to the installation of rooftop PV systems in a LV distribution system of real housing estates. Thai housing estates normally have 50 households to 500 households built close together. Additionally, in Thailand, the number of rooftop PV systems within a single LV distribution system is regulated to be less than 15 % of distribution transformer rating [7]. The LV distribution systems in Thai housing estates are short-distance systems because houses are close to one another. Loads within these systems are light during daytime. This research used real circuits and all parameters from the Geographic Information System (GIS) database of Provincial Electricity Authority (PEA). The voltage unbalance and power loss were calculated by using the DIgSILENT Power Factory program.

2 Theory

2.1 Voltage unbalance

Rooftop PV systems are connected with three-phase LV distribution system presented in Figure 1. Most rooftop PV systems of lower than 10 kWp are 1-phase systems. A 1-phase rooftop PV residential system will be installed based on the phase of a load. The voltage unbalance may occur in a LV distribution system if the installation is not planned. Furthermore, a poor or illegal PV installation can make a LV distribution system having low power quality.

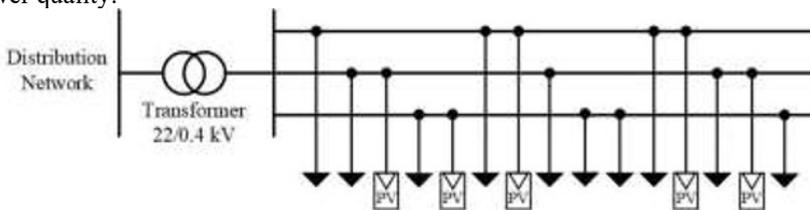


Fig. 1. Rooftop PV systems installed in a 3-phase LV distribution system.

Voltage unbalance can happen at any point throughout a 3-phase distribution system. The Percent Voltage Unbalance (PVU) is defined by the National Electrical Manufacturers Association (NEMA) as follows, in Equation (1) [8]:

$$PVU = (MAX(V_{AB}-V_{avg}, V_{BC}-V_{avg}, V_{CA}-V_{avg})/V_{avg}) * 100 \quad (1)$$

where V_{AB} is voltage between phase A and phase B (V),

V_{BC} is voltage between phase B and phase C (V),
 V_{CA} is voltage between phase C and phase A (V),
 V_{avg} is average phase voltage calculated by Equation (2):

$$V_{avg} = (V_{AB} + V_{BC} + V_{CA})/3 \quad (2)$$

In Thailand, the electricity authorities follow the IEC standard to ensure that the PVU is lower than 2 %.

2.2 Power loss in a feeder

Voltage unbalance causes imbalance current flows in a neutron line of a 3-phase 4-wire system leading to power loss in a neutral line. Therefore, power loss will increase in a distribution system. Power loss can be calculated by Equation (3) [9]:

$$P_{loss} = I_A^2 R_A + I_B^2 R_B + I_C^2 R_C + I_N^2 R_N \quad (3)$$

where I_A , I_B , I_C and I_N are currents in line as phase A, B, C and N, respectively.
 R_A , R_B , R_C and R_N are resistance values.

3 Method

This paper analyzes the impact of voltage unbalance and power loss causing by many rooftop PV systems installed in a LV distribution system of housing estate at which there is light load during daytime. Our research approach consists of several key steps:

- i). Study voltage unbalance and power loss in distribution systems.
- ii). Simulate 1-phase and 3-phase rooftop PV systems installed in LV distribution systems of housing estates by using real data from the GIS database and selecting the installation of rooftop PV systems in each phase at different load densities. The proportion of rooftop PV system penetration in a LV distribution system can be calculated by the ratio of installed PV power capacity and the transformer rated power.
- iii). Analyze and evaluate the impact of rooftop PV systems in LV distribution systems of housing estates on voltage unbalance and power loss issues.

4 Case study

4.1 Residential low voltage distribution system

This paper presents analysis results of the unbalance voltage and energy loss of a housing estate in Chonburi province, Thailand. The system has a rated LV distribution transformer of 250 kVA, 22/0.4 kV. The housing estates under this study consists of 92 households and a total system line length of approximately 1.449 km as shown in Figure 2. A transformer is located at S point.

The system circuit has two main lines, namely (i) the high load density of 82.67 % total system load in the long line of 1.182 km and (ii) the light load density of 17.33 % total system load in the short line of 0.176 km as shown in Table 1. Rooftop PV systems of 2.5kWp to 10 kWp were assumed to be installed for four case studies, namely the end of high load density and long line (X1) and (X5), the middle of high load density and long line (X2), the nearest transformer position (X3) and the end of light load density and short line (X4) and (X6). However, at the end of high load density and long line section, X1 has a

voltage unbalance more than X5. Therefore, X1 location was used to be a representative at the end of high load density and long line section. At the end of light load density and short line section, X4 has a voltage unbalanced more than X6. Thus, X4 location was selected to be a representative at the end of light load density and short line section.

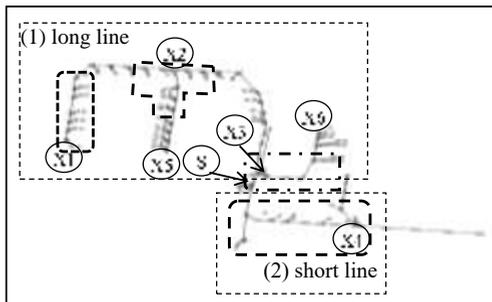


Fig. 2. The real residential distribution system circuit of a housing estate and installation locations of rooftop PV systems.

Table 1. Voltage unbalance at locations before installation of rooftop PV systems.

Location		Voltage (pu)			PVU	Distance from S (m)	Load density ($W m^{-1}$) at midday		
		V_{AB}	V_{BC}	V_{CA}			A	B	C
The end of high load density and long line	X1	0.971 6	0.995 7	0.976 7	1.463	271.14	73.26	0.00	12.42
	X5	0.972 0	0.995 9	0.977 3	1.441	223.89	88.71	0.00	7.52
The middle of high load density and long line (X2)		0.974 2	0.995 9	0.979 4	1.295	146.82	57.84	0.00	11.46
The nearest transformer position (X3)		0.988 2	0.996 9	0.994 2	0.490	16.10	139.89	0.00	0.00
The end of light load and short line	X4	0.987 2	0.997 2	0.992 8	0.527	112.69	54.92	0.00	14.98
	X6	0.987 3	0.995 8	0.993 7	0.501	85.76	26.26	52.47	19.69
Transformer (S)		0.988 7	0.997 4	0.994 4	0.482	-	-	-	-
Total main feeder						856.40	47.66	5.26	7.87
Total main feeder and sub feeders						1449.00	28.17	3.11	4.65

4.2 Load profile

Daily load demand of residential low voltage distribution system for a housing estate illustrated in Figure 3 was used as an annual load profile to calculate unbalance voltage and

energy loss. The worst case of voltage unbalance appearing at midday having the total system load of 52.06 kW (20.82 % of rated transformer) was studied as shown in Table 1, at phase A of about 40.82 kW (78.4 %), phase B of about 4.5 kW (8.65 %) and phase C of about 6.74 kW (12.95 %) in 2016.

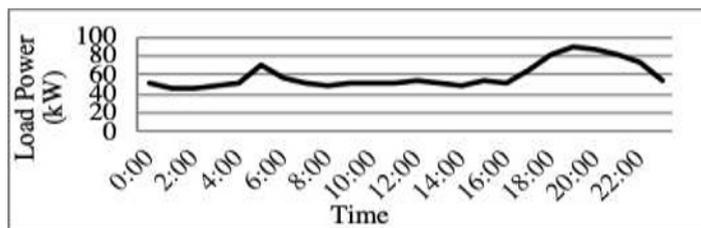


Fig. 3. Daily load of residential low voltage distribution system.

4.3 Rooftop PV system sizes

Single-crystalline silicon modules of 100 Wp were used with an efficiency of 14.5 % and a 25-yr guarantee. The optimum slope angle of 13° facing the South should be installed to get the annual maximum output energy for this housing estate. PV power was calculated from Photovoltaic Geographical Information System (PVGIS) by using data of solar radiation on an inclined surface, a PV array area and PV system efficiency. Hourly solar radiation was measured at Chonburi province in 2016. The sunshine duration was eight sunshine-h d⁻¹ and annual average solar energy was about 5.66 kWh m⁻² d⁻¹ [10]. Rooftop PV system sizes of 2.5kWp to 10 kWp were simulated in each location in Figure 2.

5 Results and discussion

This paper examines the unbalance voltage and energy loss of 1-phase and 3-phase rooftop PV system installation in the residential LV distribution system, for which results and discussions are as follows:

5.1 Voltage unbalance for installation of 1-phase rooftop PV systems

There are two main findings from the simulation results in Table 2 and Figure 4 to Figure 6.

First, A phase having the higher load density, the higher rooftop PV system installation can be and can reduce the PVU. The maximum number of rooftop PV systems can be installed at Phase A having the highest load demand. Moreover, the rooftop PV system installed at X1 in Phase A can decrease the PVU to 0.815 % (from 1.463 % without PV system installation). On the other hand, Phase B is connected with the lowest load density of 5.26 W m⁻¹ and then it can be allowed to install a lowest PV capacity of 2% transformer rating (about 5 kWp).

Second, the number of installed rooftop PV systems can be increased if the installation locations are closer to the transformer. The highest capacities of rooftop PV systems can be installed at the nearest transformer position (X3). Rooftop PV systems are able to be installed at the middle of long line (X2) and at the end short line (X4) more than at the end of long line (X1).

Based on our findings and the regulations by the electricity authorities in Thailand which state that (i) the Percent Voltage Unbalance (PVU) must be lower than 2 % (according to the IEC standard) and (ii) the number of PV grid-connected systems must be lower than 15 % transformer rating, the electricity authorities should take into account the

system installation location when issuing the permit for 1-phase rooftop PV systems. Specifically, for installation locations that are close to the transformer, the authorities can allow higher number of 1-phase rooftop PV systems whereas, for the installation locations that are far from the transformers, the authorities need to examine the total capacity of installed 1-phase rooftop PV systems in each phase before issuing the permission.

Furthermore, the scattering rooftop PV system installation of 5 % transformer rating was simulated at each location, namely X1, X2 and X4. Rooftop PV systems can be installed at Phase A (the highest load density) without the voltage unbalance impact. In the other hand, if they would be installed at Phase B or Phase C, the PVU would be higher than 2 % at X1 and X2.

Table 2. The percentage of rooftop PV system installation at the PVU of 2 %

Locations	Load (kW)			% Installation of rooftop PV systems		
	A	B	C	A	B	C
The end of high load density and long line (X1)	34.63	4.50	5.06	12.14 %	2.14 %	5.96 %
The middle of high load density and long line (X2)				18.63 %	4.49 %	11.45 %
The nearest transformer position (X3)				77.40 %	26.03 %	31.53 %
The end of light load and short line (X4)	6.19	0.00	1.69	24.03 %	13.17 %	17.83 %

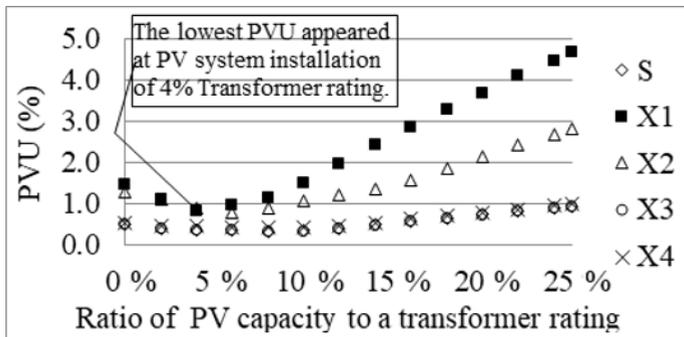


Fig. 4. The PVU for installation of 1-phase rooftop PV systems at X1 in Phase A.

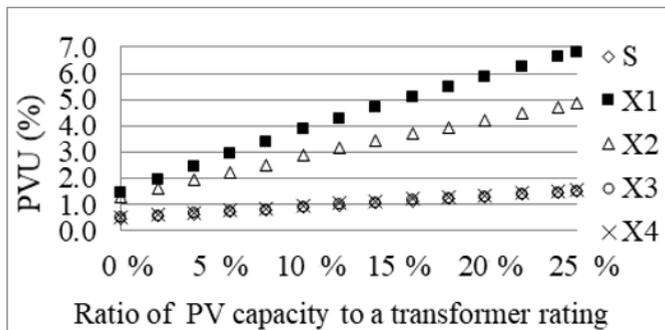


Fig. 5. The PVU for installation of 1-phase rooftop PV systems at X1 in Phase B.

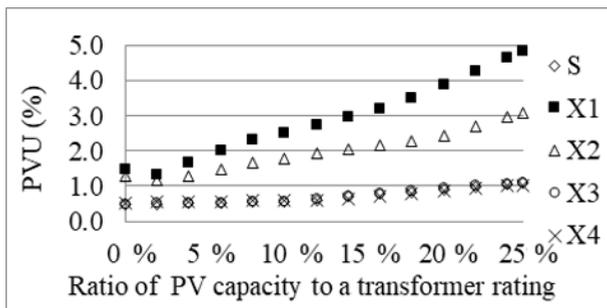


Fig. 6. The PVU for installation of 1-phase rooftop PV systems at X1 in Phase C.

5.2 Voltage unbalance for installation of 3-phase rooftop PV systems

The simulation results show that 3-phase rooftop PV systems can be installed at all locations in the feeder without the increase of voltage unbalance. Consequently, it is possible for the authorities to issue the permits for all cases as they do not have any effects on the voltage unbalance including the overvoltage.

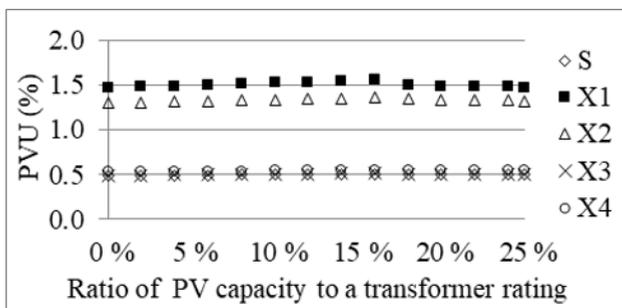


Fig. 7. Voltage unbalance due to 3-phase rooftop PV systems installation at each location.

5.3 Energy Loss

Voltage unbalances will generate extra power loss and decrease system efficiency because of increasing current flows in the neutral line of a LV distribution system. Many 1-phase rooftop PV systems installed in the residential LV distribution system can affect the voltage unbalance as the result and discussion in 5.1. Considering the results of system energy loss (E_{loss}) in all cases of 1-phase PV systems, it was found that the system energy loss relates to the load density and PV system installation location in the same way as the voltage unbalance. The total system energy losses were investigated during day time at 7 am to 6 pm, as shown in Figure 8 and Table 3. In this case of system without rooftop PV systems installed, the system energy loss is approximately 10.25 kWh. If rooftop PV systems are installed at Phase B and C, the energy loss will be increased. Alternatively, rooftop PV systems can be installed at X1 in Phase A and the energy loss can be decreased when PV capacities will be less than 12 % transformer rating as shown in Figure 9.

Although, the installation of 3-phase PV systems will not affect the voltage unbalance, the installation at the end of light load and short line (X4) of above 15 % transformer rating can increase the system energy loss to 11.63 kWh. Nevertheless, if 3-phase PV systems are installed diffusely, they can be installed about 20 % transformer rating and energy loss can be reduced.

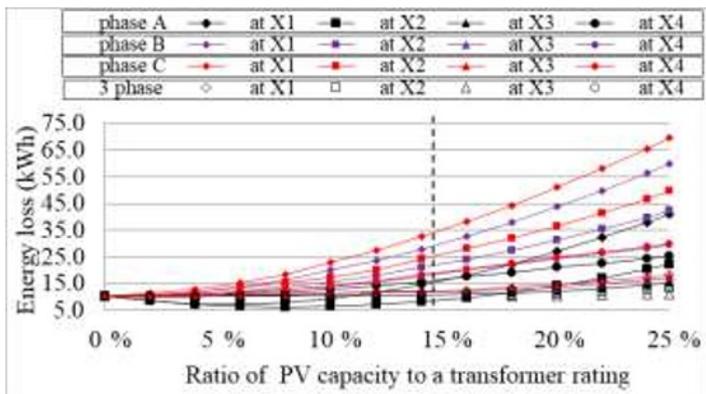


Fig. 8. Total energy loss of 1-phase and 3-phase rooftop PV system installation.

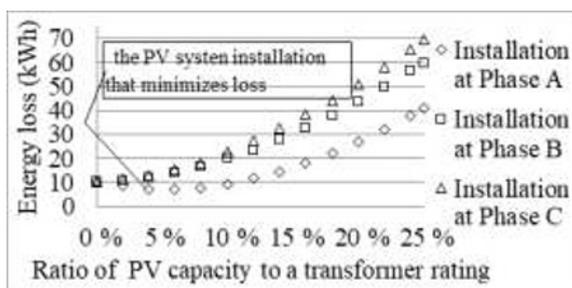


Fig. 9. Total energy loss of 1-phase rooftop PV system installation at X1.

Table 3. The percentage of rooftop PV system installation and the system energy loss.

Installation Location	Phase	Minimum E_{loss}		%PV installation ($E_{loss} > E_{loss}$ without PV systems)	E_{loss} of 15 % installation (kWh)
		%PV installation	E_{loss} (kWh)		
The end of high load density and long line (X1)	A	6	7.18	12	16.22
	B	0	10.25	1	30.11
	C	0	10.25	1	35.30
	ABC	6	9.36	12	11.59
The middle of high load density and long line (X2)	A	8	6.22	18	8.97
	B	0	10.25	1	22.59
	C	0	10.25	1	26.21
	ABC	8	9.07	18	9.65
The nearest transformer position (X3)	A	4	10.25	6	10.82
	B	2	10.25	4	12.01
	C	0	10.25	1	12.29
	ABC	8	10.16	18	10.20
The end of light load and short line (X4)	A	2	9.91	6	16.60
	B	0	10.25	1	18.94
	C	0	10.25	1	19.37
	ABC	4	10.23	6	11.63
X1, X2, X4 (equally of each location)	A	10	6.26	20	7.70
	B	0	10.25	1	19.18
	C	0	10.25	1	22.12
	ABC	10	9.06	20	9.48

6 Conclusions

There are two main findings from the simulation results. Firstly, a phase having the higher load density, the higher rooftop PV system installation can be. Secondly, the number of installed rooftop PV systems can be increased if the installation locations are closer to the transformer. For the installation of 3-phase rooftop PV systems, it is possible for the authorities to issue the permits for all cases as they do not have any effects on the voltage unbalance. The total system energy losses were investigated during daytime at 7 am to 6 pm. The results show that system energy loss relates to the load density and PV system installation location in the same as the voltage unbalance. Consequently, the installation of 1-phase rooftop PV system should be granted based on the result of examining the installation location and the load density.

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