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Voltage Profile and Power Loss Analysis of A Radial Distribution Network with Solar PV Integration

Soe Thiha Swe[1,*] and Su Leit Naing[2]
[1]*Sustainable Energy Transition, Faculty of Climate Change and Sustainability, Asian Institute of Technology, Pathum Thani, Thailand.*
[2]*Department of Electrical Power Engineering, Polytechnic University (Dawei), Dawei, Myanmar.*
**Corresponding author*: soethihaswe123@gmail.com, *ORCiD*: 0009-0004-4248-9788
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***Abstract* — Solar PV penetration on utility grid brings both benefits and technical challenges, particularly in radial feeders with long line lengths and distributed loads. This study investigates the impact of grid-connected solar photovoltaic (PV) integration on active power losses and voltage profiles in a radial distribution network in Kume, Myanmar, by using DigSILENT PowerFactory. Using realistic network and load data, load flow analysis is performed for a base case without PV and many PV integration scenarios. PV units are represented as distributed generation sources that inject active power at selected buses along the feeder. Simulation results indicate that buses located far from the substation experience significant voltage drops and higher technical losses. Voltage profiles approach 1.0 pu and overall feeder losses drop from approximately 0.5 MW to approximately 0.2 MW with solar PV integration at two and three buses. These results show that appropriate PV placement can significantly enhance distribution system performance without causing reverse power flow or overvoltage issues.**

Keywords— Solar PV integration, Voltage profile, Active power losses, Myanmar distribution system.

I. INTRODUCTION

Renewable energy has become practical and advantageous for both humans and the environment. The solar plant's sustainable and carbon-free electricity generation is highly useful. Thus, it can be seen that renewable energy is being integrated and replaced into conventional power system for various environmental and technical reasons. However, one of the most critical issues in solar PV integration is the selection of appropriate locations for PV injection into the utility grid.

The penetration of solar PV to utility grid has both advantages and disadvantages. On the benefit section, it can improve grid reliability, lessen power losses, and minimize voltage deviation when it is properly integrated into the distribution network. These benefits contribute to the development of a more sustainable and effective energy infrastructure in addition to guiding grid policy and planning [1]. On the drawback section, power mostly flows in only one direction in traditional grid from generation through transmission, distribution to consumers. Furthermore, if solar PV injection exceeds the accepted range, reverse power flow may occur in the distribution network, which can lead to protection issues, voltage regulation problems, and reduced system stability [2].

Over the past few years, Myanmar's power industry has faced numerous challenges, that have resulted in an obvious decrease in system performance. Since 2021, the availability of electricity has grown more limited, with several places reporting frequent and long outages. A rising imbalance between the supply and demand of electricity has resulted from a decrease in power generation capacity. Furthermore, the transmission network's operational stability has been negatively impacted by damage to the electrical infrastructure. Major cities like Yangon, Mandalay, and Nay Pyi Taw, as well as industrial zones around the nation, have therefore experienced ongoing power outages and increased operational demands [3]. The distribution system that supplies electricity in Myanmar is mostly radial and operates at medium-voltage levels, such as 11 kV. Long line lengths, aging systems, and insufficient reactive power adjustment are typical characteristics of distribution feeders. These features tend to result in voltage

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deviation and technical power losses, especially for buses that are far from the substation.

The impact of solar PV or distributed generation placement on voltage profile enhancement and loss reduction in distribution networks have been the focus of numerous research.

Edward Dodzi Amekah *et al.* has investigated the optimal placement of on-grid solar photovoltaic (SPV) systems in a distribution system with data from Ghana's Energy Self-Sufficiency for Health Facilities (EnerSHelF) project, where has a 90-kW solar plant. The authors analyze four SPV placement situations: high load nodes, voltage drop nodes, loss nodes, and a completely optimized scenario by employing dynamic programming and the Conditional New Adaptive Foraging Tree Squirrel Search Algorithm (CNAFTSSA) [4].

Researchers: Saeed Alizadeh, Mehdi Mahdavian and Ehsan Ganji have analysed about the growing influence of distributed generation (DG), especially photovoltaic sources, on distribution networks as an outcome of emission reduction goals and renewable energy policies. The authors highlight to the fact that distribution system operators frequently have limited control over the size and location of the DG, which, if incorrectly planned, can result in higher losses and operational challenges. To solve this problem, the researchers utilized a meta-heuristic optimization approach using a genetically engineered Non-dominated Sorting Genetic Algorithm (NSGA-II) implemented in MATLAB. The results illustrate how photovoltaic DG can be located and sized optimally to achieve optimal voltage profiles, minimize system losses, and enhance the active-to-reactive power ratio in the distribution system [5].

The authors: Sam Ansari, Abdul-Kadir Hamid and Noor Ahmad Al Hindawi examines how grid-connected solar photovoltaic (PV) power plants should be placed optimally to maximize system performance under various technical and environmental constraints. The authors use machine learning-based clustering techniques, such as k-means, k-medoids, and fuzzy c-means, together with a proposed image-processing-based methodology, to obtain over constraints associated with irradiance fluctuation, geographical considerations, and system uncertainties. The results of the simulation suggest that choosing an appropriate location significantly improves the performance of PV systems, and the suggested approach is more effective than traditional clustering techniques [6].

This research paper investigates how solar PV placement impacts voltage profile and power loss reduction in a real medium-voltage radial distribution system in Myanmar based on the researched literature. Reverse power flow effects are disregarded, and the study's scope is limited to steady-state load flow analysis. The primary objective is to use actual network data to compare system performance under various PV placing conditions without applying optimization or artificial intelligence techniques.

II. METHODOLOGY

The method that was applied to assess how solar photovoltaic (PV) integration impacts voltage profiles and active power losses in a medium-voltage distribution network is described in this section. The study is carried out through distribution system modeling and steady-state load flow analysis using DigSILENT PowerFactory. For modeling, simulating, and analyzing electrical power systems, DIgSILENT PowerFactory is a professional power system analysis program. It provides tools for dynamic modeling, load flow analysis, short circuit calculation, and studies on the integration of renewable energy.

In this study, bus, line, and load elements from PowerFactory have been utilized to model the distribution network. The PV System element (ElmPvsys) was used to represent the solar photovoltaic generators, and the loads were shown as constant PQ loads. In order to assess bus voltages, power flows, and network losses under various PV integration scenarios, load flow simulations were performed.

Firstly, the characteristics of the study location and the selected distribution feeder are illustrated. After that, the distribution network and load models are created, followed by the modelling of grid-connected solar PV systems. Different simulation cases are denoted to investigate system performance under various PV integration scenarios, and key performance indices are applied to analyse voltage deviation and power loss reduction.

A. Location and Distribution Network Description

This study is conducted on a medium-voltage distribution feeder, which consists of 10 buses, located in Kume, a city in Myittha Township, Kyaukse District, Mandalay Region, Myanmar. Electricity in the research area is provided by using radial 11 kV distribution feeders connected to a primary substation. Kume is located around 69 km from Mandalay and 179.4 km from Nay Pyi Taw, and it represents a typical semi-urban distribution area supplied by Myanmar's medium-voltage network.

B. Distribution Network Modelling

Dig SILENT PowerFactory is applied to model the distribution network as a radial medium-voltage system operating at 11 kV. The model consists of several buses connected with distribution lines with specified electrical characteristics and lengths. The power network is represented by an external grid, buses, distribution lines, and loads in the model. While loads are modeled as constant power demands distributed across the network buses, line parameters such as resistance, reactance, and length are identified based on typical 11 kV distribution feeder characteristics. The single line diagram of this research network is provided in Fig. 1.

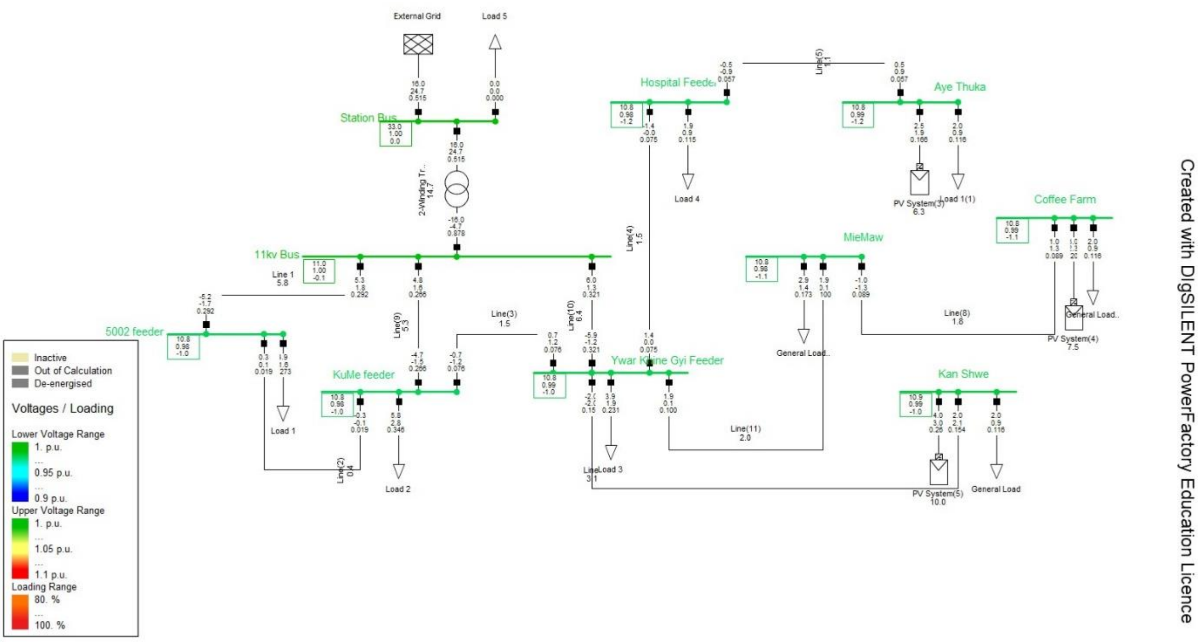

Fig. 1. Single-line diagram of the studied 11 kV distribution network modeled in DIgSILENT PowerFactory.

C. Load Flow Analysis Method

To analyze bus voltage magnitudes, line power flows, and active power losses under various operating conditions, a steady-state load flow study is performed. Despite the fact that distribution systems usually have high R/X ratios and are radial, the Newton-Raphson method is applied in power system analysis due to its excellent convergence properties and reliable implementation in DigSILENT PowerFactory for balanced medium-voltage networks. [7].

The iteration limit is raised to ensure convergence under various loading and PV integration scenarios [8]. Thus, this study sets an outer loop limit of 20 iterations and a maximum of 50 Newton-Raphson iterations. For high- and medium-voltage buses, the maximum allowable load flow error is 1 kVA, and for low-voltage buses, it is 0.01 kVA. The model equation tolerance is set at 0.1%. To improve numerical stability during the iterative solution process, automatic step size adaptation has been used.

To establish reference operating conditions, a base-case load flow without solar photovoltaic (PV) integration is first carried out. The impact on voltage profiles and system losses will be assessed through contrasting subsequent simulations with PV integration to this base case.

D. Load Modelling

The distribution network for the research's electrical loads is expressed as constant power (PQ) loads. The distribution system in Myanmar is assumed to have standard residential and commercial load characteristics with a power factor of 0.9 lagging in this research.

In DIgSILENT PowerFactory, the distribution lines in the feeder under study are represented as three-phase overhead cables. Resistance and reactance measurements per kilometer are used to define the line parameters. For the 11 kV distribution network operating at 50 Hz, the line resistance and reactance are adjusted to 0.01 Ω/km and 0.02 Ω/km, respectively, in this study. The length of lines between buses and load data for each bus is provided in Table I.

Table I. Length of lines and load data.

From Bus	To Bus	Length (km)	R (Ω/km)	X (Ω/km)	Load (P) (MW)
Station	5002	20	0.01	0.02	0.002
	KuMe	23	0.01	0.02	
	YwarKhine Gyi	17	0.01	0.02	
5002	KuMe	15	0.01	0.02	5
KuMe	YwarKhine Gyi	12	0.01	0.02	6
YwarKhin eGyi	Hospital	15	0.01	0.02	4
	MieMaw	7	0.01	0.02	
	KanShwe	5	0.01	0.02	
Hospital	AyeThuka	10	0.01	0.02	2
MieMaw	Coffee Farm	3	0.01	0.02	3
KanShwe	-	-	-	-	2
AyeThuka	-	-	-	-	2
Coffee Farm	-	-	-	-	2

E. Solar Photovoltaic (PV) Modelling

The solar photovoltaic (PV) systems in this study are represented as distributed generation units connected to the grid that supply active power to the radial distribution network. The solar power (PV) plants are modelled as constant power (PQ) sources which are connected at the selected three buses that is commonly accepted simplification for steady-state power flow studies of the distribution networks with inverter-based PV systems [9].

To determine the impact of distributed PV integration on voltage profile and active power losses, a PV penetration level of 50% of the total feeder load is taken into consideration. In a radial distribution feeder, this level represents a moderate to high penetration scenario that allows the assessment of technical performance enhancements while preventing significant reverse power flow and power quality violations [10].

In order to account for practical inverter controls that may provide limited reactive power support for voltage regulation, each PV unit is assumed to operate at a specific power factor. To achieve consistency while comparing the effects of PV placement, uniform modeling assumptions have been used across scenarios. Such PQ or constant power factor representations are frequently used in inverter-based distributed power generation models for steady-state evaluation of performance in distribution systems.

To analyze the optimal placement of solar PV integration into grid, some different scenarios are considered in this research. Initially, the reference voltage and loss conditions are established by analyzing a base case (case 0) without PV integration. PV systems are subsequently integrated at selected buses along the feeder according to load distribution and network configuration. PV units are placed at buses with higher load demands and located far from the substation, where power losses and voltage drops are more obvious. To ensure a fair comparison, every simulation case is examined under the same load conditions. The solar PV integration scenarios are mentioned in Table II.

Table II. Solar PV integration scenarios.

Case	PV Bus	PV Capacity (MW)
Case 0	-	-
Case 1	Coffee Farm	3
Case 2	Coffee Farm, Kan Shwe	3 + 4 = 7
Case 3	Coffee Farm, Kan Shwe, Aye Thuka	3 + 4 + 2.5 = 9.5

III. RESULTS AND DISCUSSION

The simulation results from the distribution network's load flow analysis under different solar PV integration scenarios will be presented in this section.

A. Base Case Analysis (Without PV)

The distribution network's operation without any solar PV integration can be seen in the Base Case. As shown in Fig. 2, Bus voltage magnitudes range from roughly 0.955 pu to 1.0 pu, according to load flow analysis, indicating that the system operates within the well-recognized voltage limits of 0.95–1.05 pu for distribution networks. The total active power loss for the Base Case is around 0.5 MW.

Even though the voltage profile follows regulatory requirements, buses located away from the substation have significant voltage drops. These voltage variations and high active power losses are apparent the technical challenges related with long radial distribution feeders providing dispersed loads.

B. Impact of Solar PV Integration on Voltage Profile

The comparison of bus voltage magnitudes under various simulation scenarios can be seen in Fig. 2 to illustrate how solar PV integration influences the distribution network's voltage profile.

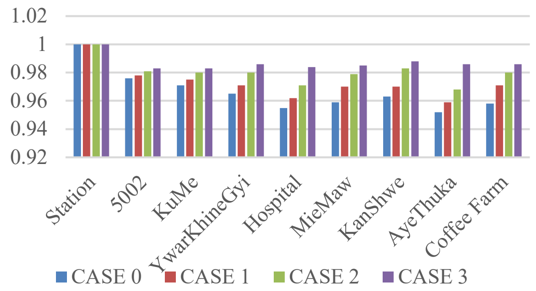

Fig. 2. Voltage profile for different cases.

Bus voltages gradually drop along the feeder in the base case (case 0), with buses farther away from the substation, like Hospital, Aye Thuka, and Coffee Farm, showing the lowest voltages. All voltages remain within the 0.95–1.05 pu acceptable operating range, however the minimum voltage values are near the lower limit, indicating an inadequate voltage margin under normal operating conditions.

There is a noticeable improvement in the voltage profile throughout the network with solar PV penetration. Voltage magnitudes at downstream buses slightly rise in Case 1, when PV is integrated at specific buses, lowering the overall voltage loss along the feeder. In Case 2, where more PV integration enhances voltage levels, especially at buses with higher load demands and longer electrical distances from the substation, more improvement is achieved.

The voltage profile is significantly enhanced in Case 3, thanks to solar PV integration at three buses, with the majority of buses operating around 1.0 pu. All bus voltages remain within acceptable limits, and no overvoltage conditions occur in any of the cases. These findings indicate that by supplying active power locally and minimizing feeder voltage drops, distributed solar PV integration efficiently improves voltage regulation in radial distribution networks.

C. Impact of Solar PV Integration on Power Losses

Active power losses are also substantially decreased as a result of solar PV integration. The overall feeder loss in the Base Case is approximately 0.5 MW. System losses have fallen to about 0.3 MW when solar PV is integrated at two buses. The losses further drop to around 0.2 MW when PV is placed at three busses.

The main reason of the observed loss reduction is the decrease in line current brought on by local power generation close to load centers. Feeder losses are proportional to the square of current, thus even moderate current reductions decrease a significant amount of cost. This illustrates how distributed PV integration can enhance radial distribution systems' efficiency.

D. Discussion

The results demonstrate that PV integration provides measurable technical benefits, even though the distribution system for analysis operates within acceptable voltage limits without solar PV. As the number of PV-connected buses increases, improvements in the voltage profile and reductions in active power losses have been observed.

In addition, no voltage violation or reverse power flow problems are found under the PV penetration levels taken into consideration, suggesting that the selected PV locations and capacities are technically appropriate for the current network. These results imply that distribution system performance can be improved by well-planned solar PV integration without losing system stability.

IV. CONCLUSION

This study analyzed the technical effects of solar photovoltaic (PV) placement on a radial distribution network in Kume, Myanmar, with an emphasis on minimizing active power loss and improving voltage profiles. Several PV integration scenarios and a Base Case without PV have been investigated for load flow under actual operational conditions.

The results reveal that while the current distribution system performs in the base case within the acceptable voltage range of 0.95–1.05 pu, buses that are far from the substation encounter noticeable voltage drops and comparatively significant technical losses. A significant reduction in active power losses and a progressive improvement in voltage profiles across the feeder are the result of the integration of solar PV at particular buses. The minimum bus voltage improves close to 1.0 pu as PV penetration increases from two to three buses, and overall feeder losses fall from approximately 0.5 MW to 0.2 MW.

Furthermore, considering the PV penetration levels analysed in this study, no overvoltage or reverse power flow problems were found, suggesting that the chosen PV locations and capacities are technically suitable for the network under investigation. These results demonstrate that distributed solar PV integration can improve radial distribution systems' operational performance and efficiency without losing system stability. The findings provide beneficial data for distribution network planning in Myanmar and other electricity systems dealing with growing demand and infrastructural limitations.

In order to enhance voltage regulation and lessen technical losses, it is recommended that future distribution network planning in Myanmar takes into account the strategic integration of solar PV at downstream buses with higher load demand. By adding reactive power control, dynamic load and solar profiles, and optimization algorithms to identify the ideal PV size and placement under various operating conditions, future research may expand on this work.

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AUTHOR CONTRIBUTIONS

Soe Thiha Swe: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing–Original Draft Preparation;
Su Leit Naing: Conceptualization, Formal Analysis, Investigation, Methodology, Validation, Visualization, Supervision, Writing–Review & Editing;

CONFLICT OF INTERESTS

The author declares no conflict of interest.

ETHICS STATEMENTS

Our publication ethics follow The Committee of Publication Ethics (COPE) guideline. https://publicationethics.org/

DATA AVAILABILITY STATEMENT

Due to institutional restrictions, the data utilized in this study were not made publicly available; instead, they were obtained from an engineer employed in the relevant department. However, the corresponding author may make the data available upon reasonable request and with the data provider's permission.

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