

Performance evaluation of PV penetration at different locations in a LV distribution network connected with an off-load tap changing transformer

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ABSTRACT

Solar photovoltaic (PV) power generation has shown a worldwide remarkable growth in recent years. In order to achieve the increasing energy demand, a large number of residential PV units are connected to the low voltage (LV) distribution networks. However, high integration of solar PV could cause negative impacts on distribution grids leading to violations of limits and standards. The voltage rise has been recognized as one of the major implications of increased PV integration, which could significantly restrict the capacity of the distribution network to support higher PV penetration levels. This study addresses the performance of the off-load tap changing transformer under high solar PV penetration and a detailed analysis has been carried out to examine the maximum allowable PV penetration at discrete tap positions of the transformer. The maximum PV penetration has been determined by ensuring that all nodal voltages adhere to grid voltage statutory limits. The simulation results demonstrate that the first two tap positions could be adopted to control the grid voltage under higher PV penetrations thus facilitating further PV influx into the existing network.

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1. INTRODUCTION

Solar PV systems have gained worldwide attention in generating greener energy. The cost reduction and technological advancement of solar modules and supporting policies by governments of many countries have aided the growth of solar PV to be one of the most promising renewable energy sources (RESs). According to IRENA (international renewable energy agency), the cumulative installed capacity of solar PV would reach to 8519 GW, emerging as the second prominent RES (after wind) by 2050 [1].

However, the extensive integration of solar PV poses new technical challenges for the operation and performance of conventional electricity distribution networks, which have been designed and operated as passive circuits, considering a unidirectional power flow feed. Earlier, it was justifiable to presume that the generation would balance the consumption under low PV penetration and hence eliminate the voltage drops and power losses. Nonetheless, these assumptions are no longer applicable with high PV penetrations as the technical issues will be increased if necessary precautions are not taken at an early stage.

Due to the high PV deployment in LV networks, reverse power flows could be seen when PV generation exceeds the load demand [2-4]. Consequently, a voltage rise along the distribution feeder could be

foreseen causing violations on utility planning limitations and standards. Several researchers have identified voltage violations as one of the most important limiting factors of increased PV integration [5-9]. Therefore, it is vital to introduce measures to mitigate these impacts and support high integration of solar PV into the existing LV grids.

According to the literature review, a fair range of studies have been carried out globally to examine feasible solutions that could be adopted to enhance PV uptake [10-20]. However, most of the studies are focused on advanced control approaches where a significant amount of infrastructure upgrades and maintenances are required to secure the efficiency. The use of LV on-load tap changing (OLTC) transformers has recently been studied by several researchers in order to enhance the voltage regulation and increase the network's PV hosting capacity [21-25]. Typically, the OLTC transformers are installed at medium voltage (MV) networks to regulate grid voltage, while LV networks are fitted with off-load tap changing transformers where the ratio between the primary and secondary voltages of the transformer could only be adjusted after disconnecting the load. Most of the OLTC control schemes suggested in literature have utilized complex optimization strategies that involve a substantial amount of communication infrastructure. Therefore, the distribution network operators (DNOs) are required to pursue massive capital investment to replace off-load tap changing transformers with OLTC transformers. Moreover, the number of tap operations could be significantly higher at different control schemes, which could lead to increased wear and tear of the OLTC [26].

In order to tackle the aforementioned limitations, it is important to develop pragmatic and cost effective mitigation techniques utilizing the available assets. Furthermore, it is recommended to evaluate the hosting capacity of the distribution network targeting to determine the potential technical issues and ensure smooth operation and optimum penetration level while reducing network reinforcements. This paper addresses the performance of the off-load tap changing transformer under high solar PV penetration. A detailed analysis was conducted to examine the maximum allowable PV capacity and power losses for discrete tap positions of the off-load tap changing transformer using a generic, Malaysian residential network.

2. RESEARCH METHOD

2.1. Problem identification

The adaptation of grid-connected solar PV has created new challenges to the existing distribution networks. Therefore, it is important to identify and understand these before they occur and develop methods to support high integration of solar PV into the grids. The potential impact of solar PV is illustrated in Figure 1 using a simplified LV distribution network. As shown in the figure, a voltage drop could be seen at the consumer point in the absence of solar PV, depending on the local demand and the impedance of the network. Similarly, a voltage rise could be seen when PV generation exceeds the local demand. This issue becomes aggravated when the voltage rises above the statutory limits particularly during middle of day with light load and peak generation.

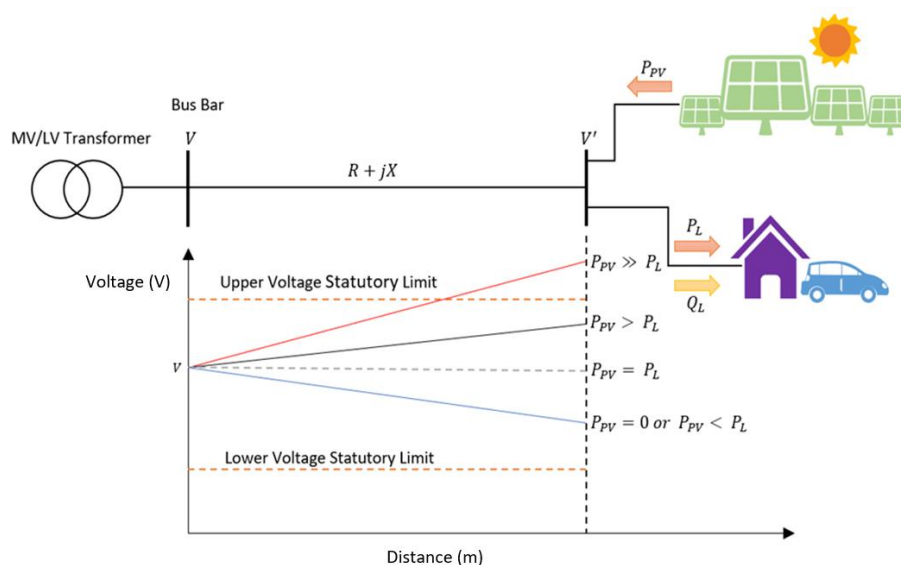


Figure 1. Impact of solar PV on LV distribution networks

2.2. Methodology

A comprehensive analysis was carried out to investigate the performance of the off-load tap changing transformer with the increased integration of PV systems.

2.2.1. Test network

The generic residential network shown in Figure 2 was considered as the test network for the study. The LV bus bar has three feeders, serving 31 customers via a three-phase connection. A peak load of 5kW with 0.9 power factor was connected to each customer point placed equidistantly at every 30m.



Figure 2. Test network

2.2.2. Integration of solar PV

It was assumed that the PV systems are only installed to the second (blue) feeder of the test network. Several PV location scenarios were considered as follows;

- a) PV clustered near the feeder starting point
- b) PV clustered near the feeder mid point
- c) PV clustered near the feeder end point
- d) PV evenly distributed throughout the feeder

2.2.3. Integration of solar PV

A typical 1MVA, 11kV/433V LV distribution transformer with an off-load tap changer capability range of $\pm 5\%$ (5 tap positions, 2.5% per step) was considered. The first three discrete tap positions (including the nominal tap – tap position 3), listed in Table 1 were reviewed under high PV penetration.

Table 1. First three discrete tap positions of the off-load tap changing transformer

Tap position	Primary voltage (V)	Secondary voltage (V)
1	11550	433
2	11275	433
3	11000	433

3. RESULTS AND DISCUSSION

3.1. Performance analysis

A detailed network model for a three-phase LV distribution system was developed in open distribution system simulator (OpenDSS) simulation platform. According to the Malaysian Electric utility, tenaga nasional berhad (TNB) standards and planning criteria for LV distribution networks,

- a) The statutory tolerance limits for voltage variation should be between +10% and -6%.
- b) The maximum allowable PV capacity connected to the LV feeder pillar is 180kW (to avoid exceeding of cable’s maximum current capacity).

In this paper, PV penetration was defined as the ratio between total connected PV capacity and the maximum allowable PV capacity to the LV feeder pillar (1).

$$PV\ penetration = \frac{Total\ connected\ PV\ capacity}{Maximum\ allowable\ PV\ capacity} \times 100\% \tag{1}$$

The performance of the off-load tap changing transformer was analyzed under several cases as presented in Table 2. For all 12 cases, the maximum allowable PV penetration without any statutory limit violations was examined under no-load (worst case scenario) and peak load conditions. Moreover, power flow simulations were performed for each discrete tap position under peak consumer load and zero PV generation to examine possible under-voltage issues. The input voltage applied to the primary winding of the transformer was retained at 11kV for all power flow simulations.

Table 2. Cases considered for the performance analysis

Case	Tap position	PV location
1	1	PV clustered near the feeder starting point
2		PV clustered near the feeder mid-point
3		PV clustered near the feeder endpoint
4		PV evenly distributed throughout the feeder
5	2	PV clustered near the feeder starting point
6		PV clustered near the feeder mid-point
7		PV clustered near the feeder endpoint
8		PV evenly distributed throughout the feeder
9	3	PV clustered near the feeder starting point
10		PV clustered near the feeder mid-point
11		PV clustered near the feeder endpoint
12		PV evenly distributed throughout the feeder

3.2. Results

Power flow simulations were performed for all PV location scenarios under different tap positions (1, 2 and 3). The maximum PV penetration for each case was determined by ensuring all nodal voltages are within the required statutory limits. The simulation results obtained for the no-load and peak load conditions are summarized and presented in Table 3 and Figure 3.

Table 3. Maximum PV penetration for different PV location scenarios and tap positions

Tap position	Maximum PV penetration (%)							
	PV clustered near the feeder starting point		PV clustered near the feeder mid-point		PV clustered near the feeder endpoint		PV evenly distributed throughout the feeder	
	No-load	Peak load	No-load	Peak load	No-load	Peak load	No-load	Peak load
1	100	100	100	100	65.5	100	100	100
2	100	100	80.5	100	41.7	84.4	77.8	100
3	100	100	59	94.4	16.1	58.3	31.2	100

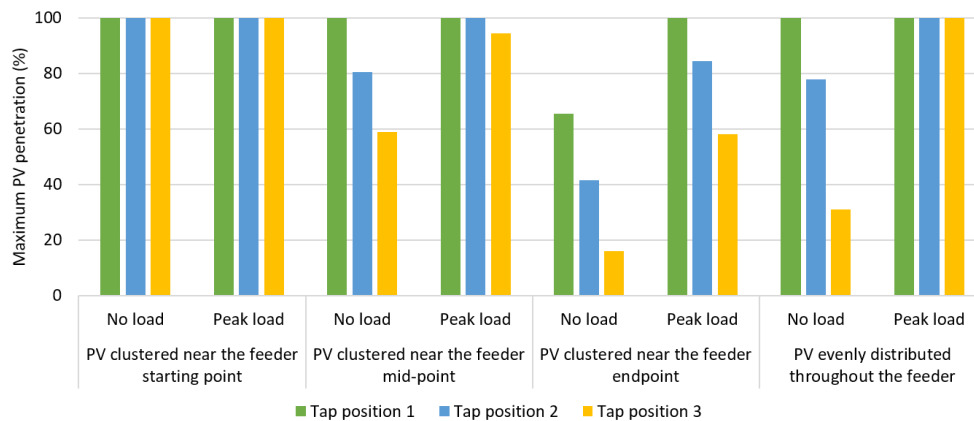


Figure 3. Maximum PV penetration for different PV location scenarios and tap positions

By examining the results obtained for all 12 cases, it could be seen that the discrete tap position of the off-load tap changing transformer has an impact on the maximum PV penetration. As it is evident in Figure 3, the maximum allowable PV integration increases for transformer tap positions 1 and 2 compared to the nominal tap position 3 for all PV location scenarios under no-load and peak load conditions. However, for many location combinations, the maximum PV penetration under the peak load condition reaches 100%.

The nodal voltage variation of feeder 2 of the test network (PV connected feeder) with different tap positions under peak load and zero PV generation is depicted in Figure 4. As illustrated in the figure, the nodal voltages lie between the allowable statutory limits preventing under-voltage violations.

The total power loss of the test network for different tap positions under peak load and zero PV generation is tabulated in Table 4. According to the simulation results, the total power loss of the network has shown an increment in tap positions 1 and 2 compared to the nominal tap of the transformer. Nevertheless, feeding consumer loads from local PV systems decrease the grid current and reduce the overall power loss of the network. In addition, it was clearly observed that the maximum PV penetration significantly varies with the PV location. The allowable PV penetration without any violation of statutory limits has a negative correlation with the distance between the transformer and the PV integration point as shown in Figure 5.

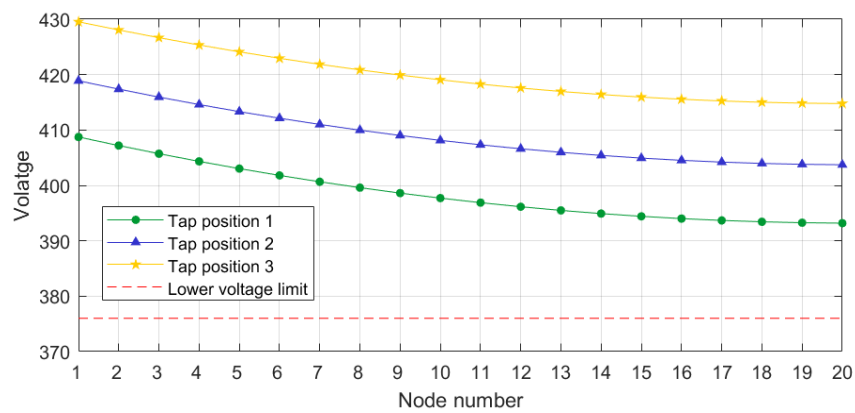


Figure 4. Nodal voltages of feeder 2 with different tap positions under peak load and zero PV condition

Table 4. Total power loss of the network

Tap position	Total network power loss (kW)	Incremental loss compared to the nominal tap position (%)
1	4.0	11.1
2	3.8	5.5
3	3.6	-

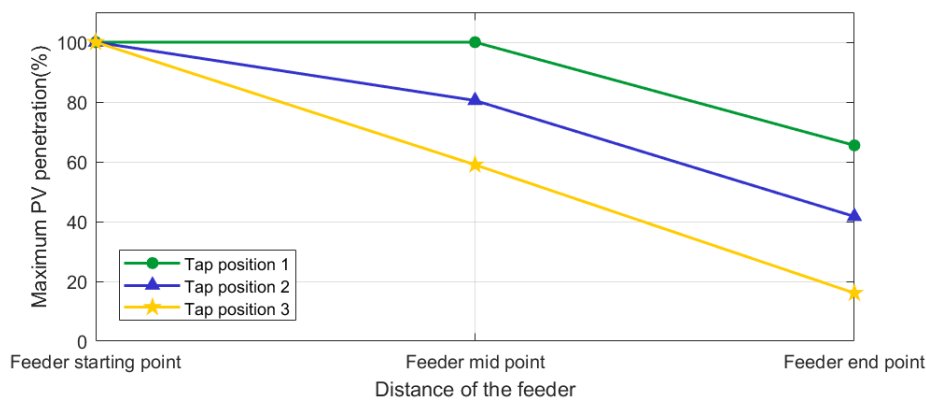


Figure 5. Variation of the maximum PV penetration with the distance between the transformer and the PV integration point

4. CONCLUSION

The growth of grid-connected PV systems causes voltage violations and substantially limits the capability of distribution networks to accommodate higher PV penetration levels. In this paper, the performance of the off-load tap changing transformer was addressed under high solar PV penetration to examine the maximum allowable PV penetration at the first three discrete tap positions. The simulation results demonstrate that the maximum allowable PV penetration increases for the transformer tap positions 1 and 2 compared to the nominal tap position 3 and generally declines as the distance between the source node (transformer) and the PV integration point rises. Even though the nominal tap position is considered to be the optimal tap position in normal operation, the first two tap positions could be adopted to regulate the grid voltage with a higher level of PV while allowing further PV integration into the existing network. Therefore, the adjustment of the tap position of the LV off-load tap changing transformer could be introduced as a cost-effective solution for overvoltage problems associated with high PV penetration.

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