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Technical Impacts of Solar Photovoltaic Systems Integration into Malaysian Medium Voltage Reference Networks

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Abstract

Decentralized renewable energy resources have been identified as one of the promising ways to sustain the future energy demands. However, most of the energy produced by renewable energy resources, particularly the Photovoltaic (PV) system is intermittent in nature and often fluctuates. In this regard, this paper utilizes Malaysian Reference Networks model, with the aim to analyse the effects of solar PV integration with medium voltage (MV) network under various solar variability conditions. For validation, network losses and voltage profiles had been evaluated on various PV variability profiles using DIgSILENT power factory software. The impact of solar generation variability on transformer On-Load Tap Changer (OLTC) had been investigated through the utilization of five types of solar variability day in Malaysia; compiled as one-minute resolution. In addition, urban, sub-urban, and rural MV networks had been considered in this study. The results presented in this paper show that proper allocation of PV plants can help to reduce network losses and improve voltage profiles. Rural network incurred the highest number of tap changes in OLTC to control the voltage level, compared to urban and sub-urban networks.

Keywords: Photovoltaic, Reference Network, On-Load-Tap-Changer, Network Losses, Voltage Profile Improvement.

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1. Introduction

In facing the escalating demand for energy in the future, the world also witnesses the depletion of energy resources at the same time. Consequently, there is a worldwide search for other energy sources such as solar power [1]. Distributed Solar Photovoltaic (PV) has emerged as among the preferred

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alternative forms of energy resources in Malaysia [2], substantiated by the enactment of Renewable Energy Act 2011, which promotes investment in the Renewable Energy (RE) sector via the Feed-in Tariff (FiT) incentive scheme. The aforementioned system acknowledges great responses, especially for grid-connected PV systems [3].

The increasing PV penetration level in medium voltage distribution networks has necessitated the needs of examination on both the positive and negative impacts of the distributed PV integration. The PV systems do assist in minimizing power losses, enhancing voltage profiles and on-peak demand, minimizing system upgrades, as well as boosting the efficiency and stability of the power scheme [4]. Conversely, the distributed generation (DG) will increase the complexity of the system by introducing bi-directional power flow, and may cause fluctuations in the system voltages due to their variable and unpredictable nature [5].

There are claims that the DG injection in the distribution system possesses the capability of enhancing the power system distribution achievements, in terms of diminishing the power losses and enhancing the voltage profile. Previous work in [6] had emphasized on the introduction of new method to generate power in the distribution network, with further improvement of the distribution system's voltage profile,in addition to the reduction of electric system losses through the installation of DG in the distribution scheme. There are findings that show DG possess a huge favourable impact on enhancing the voltage profile and diminishing the entire electric power losses encompassing the whole distribution network. Bawan et al. [7] discovered that utilizing DGs can lead to reduction of power losses and improvement of voltage profile according to the position of the DG, and the size of injection. The research was conducted through the utilization of ETAP 6.0 application program and the Manokwari electricity distribution system as case study. From the outcomes, they found reduction in power loss from $240.15kW$ to $99.39kW$ at specific sites, due to the effect of the power injection of DG. Furthermore, the utilization of DG was discovered to be more economical. Power loss reduction by solar photovoltaic (PV) integration as DG was observed by [8] using MATLAB simulation with IEEE 13 bus unbalanced system. Similar results were observed from IEEE 34 bus test system by [9]. Sahito et al.[10] demonstrated DGs impacts on voltage profile improvement of radial distribution feeder in HESCO.

The major problems of voltage regulation in distribution system are of great significance, specifically the variable and intermittent nature of the distributed generation [11,12]. Conventionally, in order to solve voltage problems on the distribution system, transformer On-Load Tap Changer (OLTC) is usually implemented for the maintenance of voltage on the secondary side of power transformers; however, not going over the regulatory restrictions. The set voltage at the transformer's secondary side is customarily maintained by the autonomous tap control of OLTC, according to a calibrated local busbar voltage [13]. Since it is a norm for the OLTCs to be configured on the assumption of a decrease in the voltage along the feeder, an increase in the voltage due to reverse power flow during times of low demand and high solar power feed-in may result in overvoltages []. Furthermore, a high PV penetration on a distribution system, and high frequency solar ramping resulting from fast-moving clouds may lead to surplustap operations [15]. Nevertheless, there is absence of decisive outcomes on how the PV variability affects the transformer's OLTC. In that perspective, investigation on the tap changer operation of voltage regulator devices like OLTC, specifically at the time when high PV penetration level is required.

The current study focused on the effect of distributed PV generation on the voltage profile and network losses of Malaysian MV reference networks. The objective of this study paper is to quantify the transformer's tap changing operations due to the impact of solar intermittency on MV reference networks. The voltage profiles and network losses were determined by load flow calculations using DIgSILENT power factory software, utilizing a four-year compilation of solar irradiance data with one-minute time resolution situated in Melaka, Malaysia. The outcome of this work is anticipated to inform distribution network operators and power utilities on the potential technical impacts of integrating solar PV systems at the Malaysian medium voltage networks.

2. Methodology

(a) Modeling of Reference Networks (RNs)

Various methodologies have been developed by researchers to model large scale distribution networks [16-18]. In this work, Malaysian MV reference networks have been considered. Three reference networks, i.e. urban, sub-urban, and rural networks with three voltage levels transformations of $132/33/11kV$ were modelled utilizing the generic characterization and parameters of RN as reported in [19,20]. DIgSILENT power factory was used to generate the models. One-minute time interval of load flow simulations were performed on RNs models. The reference network for$132/33/11kV$ voltage transformation is indicated in the line diagram in Figure 1, which consists of two stages of voltage transformation that are $132/33kV$ and $33/11kV$ primary substations.

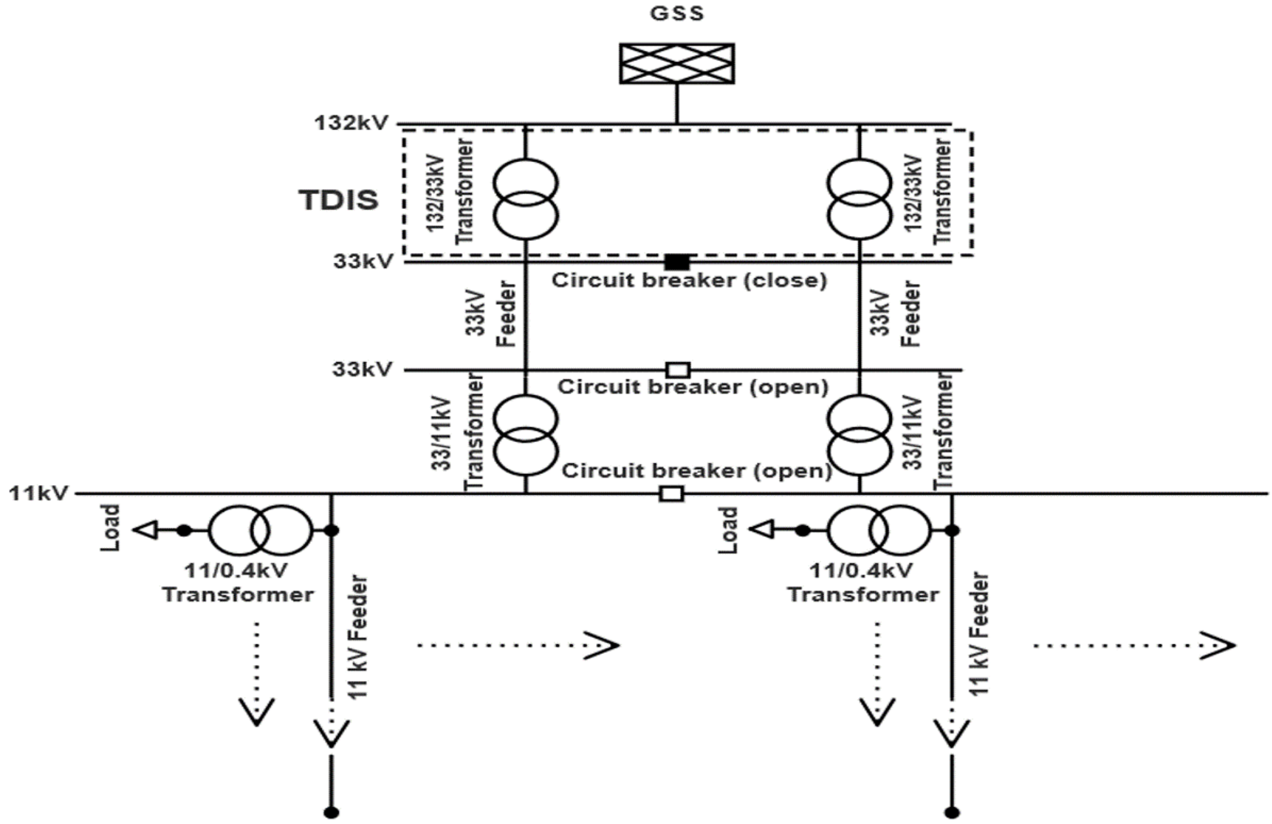

Figure 1: Single line diagram for medium voltage Reference Network (RN) with 33kV and 11kV feeders.

1) Urban RN with 33 & 11kV feeders

The second column in Table 1 shows the parameters for urban network development. Five $11kV$ feeders were linked to each of the $33/11kV$ transformers. Each $11kV$ feeder was linked to each of the five $11/0.4kV$ transformers. Additionally, two transformers of $33/11kV$ and $11/0.4kV$ capacities were configured to $30MVA$ and $1MVA$, accordingly. The entire load for the low voltage transformer was $728kW$ each, with an assumed power factor of 0.90 lagging. The average distance was $600m$ between each $11/0.4kV$ distribution transformer; where each $11kV$ feeder possesses the average total length of $3km$.

2) Sub-Urban RN with 33 & 11kV feeders

The parameters for the sub-urban network are indicated in the third column in Table1. Each $33/11kV$ transformer was linked to four 11kV outgoing feeders. Additionally, 8 units of $11/0.4kV$ transformers were set up in each $11kV$ feeders. The distance of the 33kV line from $132/33kV$ transformer to the $33/11kV$ transformer was $9.4km$ long. The entire length of $11kV$ feeder was $9.6km$, while the length between $11/0.4kV$ transformers was $1.2km$ individually. The $33/11kV$ and $11/0.4kV$ transformer capacities were $30MVA$ and $1MVA$, respectively. The Low Voltage (LV) transformer showed maximum energy need of $322.5kW$.

3) Rural RN with 33 & 11kV feeders

Rural network parameters are illustrated in the fourth column in Table 1. The maximum demand was $163.2kW$ for individual $11/0.4kV$ transformer for Rural. The distance of the $33kV$ line from $30MVA$ rated $33/11kV$ transformer was $18km$, which is a more extensive length in comparison to urban and sub-urban. A $11kV$ feeder having $31.5km$ length was connected with 15 units of $11/0.4kV$ transformers. The length between each $0.5MVA$ rated $11/0.4kV$ transformer was $2.1km$.

Table 1: Parameters of urban, sub-urban, and rural RNs with 33 and 11 kV feeders

Parameter	Urban	Sub-Urban	Rural
132/33kV transformer capacity, MVA	45	45	45
No. of 11kV feeders per 33/11kV transformer	5	4	3
No. of 11kV transformer per 11kV feeder	5	8	15
Length 33kV line, km/each	5	9.4	18
33/11kV transformer capacity, MVA	30	30	30
11kV feeder length per feeder, km/each	3	9.6	31.5
11/0.4kV transformer capacity, MVA	1	1	0.5
Distance between TX 11/0.4kV, km/each	0.6	1.2	2.1
11/0.4kV transformer maximum demand, kW	728	322.5	163.2

(b) PV Variability

A compilation of four-year (2014, 2015, 2016, and 2017) solar PV output data was conducted by the Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka. The variability of the profiles was categorized through the utilization of the clearness index (KT) and daily variability index (VI) into five solar irradiance day types which were: clear sky, overcast, mild variability, moderate variability, and high variability. The equations used to calculate the KT and VI were Equation (1) and Equation (2), respectively. Selection of representative profile of individual solar day types was conducted in the current research for the analysis of their associated impact on the network losses, voltage profiles, and tap changes operation. Table 2 shows the number of days for each PV variability type. It also shows that half of the total number of days in a year are of high variability. Notably significant is that due to the tropical weather in Malaysia; the huge cloud coverage contributes to an approximation of 53% of the total number of days in a year (annual days) with high variability, and 31% with moderate variability. The clouds movement contributed in a significant way to the comparatively high solar variability in tropical countries like Malaysia. However, it is interesting to note that cloudless clear sky only comprises 1% of the total number of annual days.

$$K_T = \frac{I_t}{I_t^{EX}} \tag{1}$$

Where, I_t = Ground level irradiance, I_t^{EX} = The irradiance extraterrestrial, K_T = Clearness index

$$VI = \frac{\sum_{k=2}^{n} \sqrt{(GHI_k - GHI_{k-1})^2 + \Delta t^2}}{\sum_{k=2}^{n} \sqrt{(CSI_k - CSI_{k-1})^2 + \Delta t^2}} \tag{2}$$

Where,GHI_k = Vector of length n of global horizontal irradiance, CSI_k = Vector calculated of clear sky irradiance, = Time interval in minutes, VI = Variability index

Table 2: Number of days for each PV variability type

PV variability	No. of days (2014)	No. of days (2015)	No. of days (2016)	No. of days (2017)	No. of days (Average)
Clear sky	6	4	4	5	5
Overcast	10	9	10	14	11
Mild variability	53	39	45	31	42
Moderate variability	110	119	100	127	114
High variability	186	194	206	188	193
Total	365	365	365	365	365

(c) Modeling of PV System

The photovoltaic system utilizes PV cell as the essential device, in which the combination and grouping of the number of cells are for the formation of PV panels or modules, and for the formation of extensive photovoltaic arrays. The PV module output characteristic is dependent upon the solar insulation and the cell temperature. The PV system outputs were obtained based on a one-minute resolution radiation data measured at The Research Laboratory of Solar PV Systems and Smart Grid at Universiti Teknikal Malaysia Melaka (UTeM). A model PV system was designed by using 'ElmPVsys' function in DIgSILENT simulation software. The employed PV system with unity power factor is categorised as a grid-tied inverter type.

(d) Network Losses

Energy losses in distribution networks are largely due to technical losses resulting from current resistance (I2R), eddy currents, and hysteresis. There are numerous factors that can cause varying power losses in network systems, for example transmission and distribution lines, transformers, capacitors, and insulators. Fair PV system integration on the network has a latent role to reduce network losses (NL). This is because the PV system near to the local load produces power supply, and the balance power will flow back to the branches. However, high penetration of PV integration will result in the increase of network losses and reverse power flow; hence the reason why the effect of network losses by PV system integration is the main focus in this research. The network losses (NL) assessment was carried out using Equation (3), while the network losses reduction was calculated by using Equation (4). Total losses were then calculated to examine the effect of five varying solar PV variability profiles on network losses, as shown in Equation (5). It is important that the total capacity of PV system generation linked to a MV distribution network is to be restricted according to the demand of local distribution network. The recommended maximal allowable capacity of solar PV system integration is85%of daytime trough load, as suggested by the local power utility [21, 22]; notably 1.286MW, 0.857MW, and 0.759MW for Malaysian urban, sub-urban, and rural reference networks, respectively. Furthermore, in this study, the PV systems were fixed near to the 11kV bus bar, middle of the 11kV feeder, and end of the 11kV feeder to investigate their impacts on the MV distribution network, as shown in Figure 2.

$$NL = \frac{Network\ energy\ losses}{Energy\ consumption\ of\ base\ case(0\% PV\ penetration)} \times 100\% \tag{3}$$

$$Losses reduction = \frac{NL\ base\ case\ (without\ PV) - NL\ with\ PV}{NL\ base\ case\ (without\ PV)} \times 100\% \tag{4}$$

$$Total losses = NL\ during\ clear\ sky\ days + NL\ during\ overcast\ days + NL\ during\ mild\ VI\ days + NL\ during\ moderate\ VI\ days + NL\ during\ high\ VI\ days \tag{5}$$

where NL during clear sky days = NL with $PV \times$ number of clear sky days

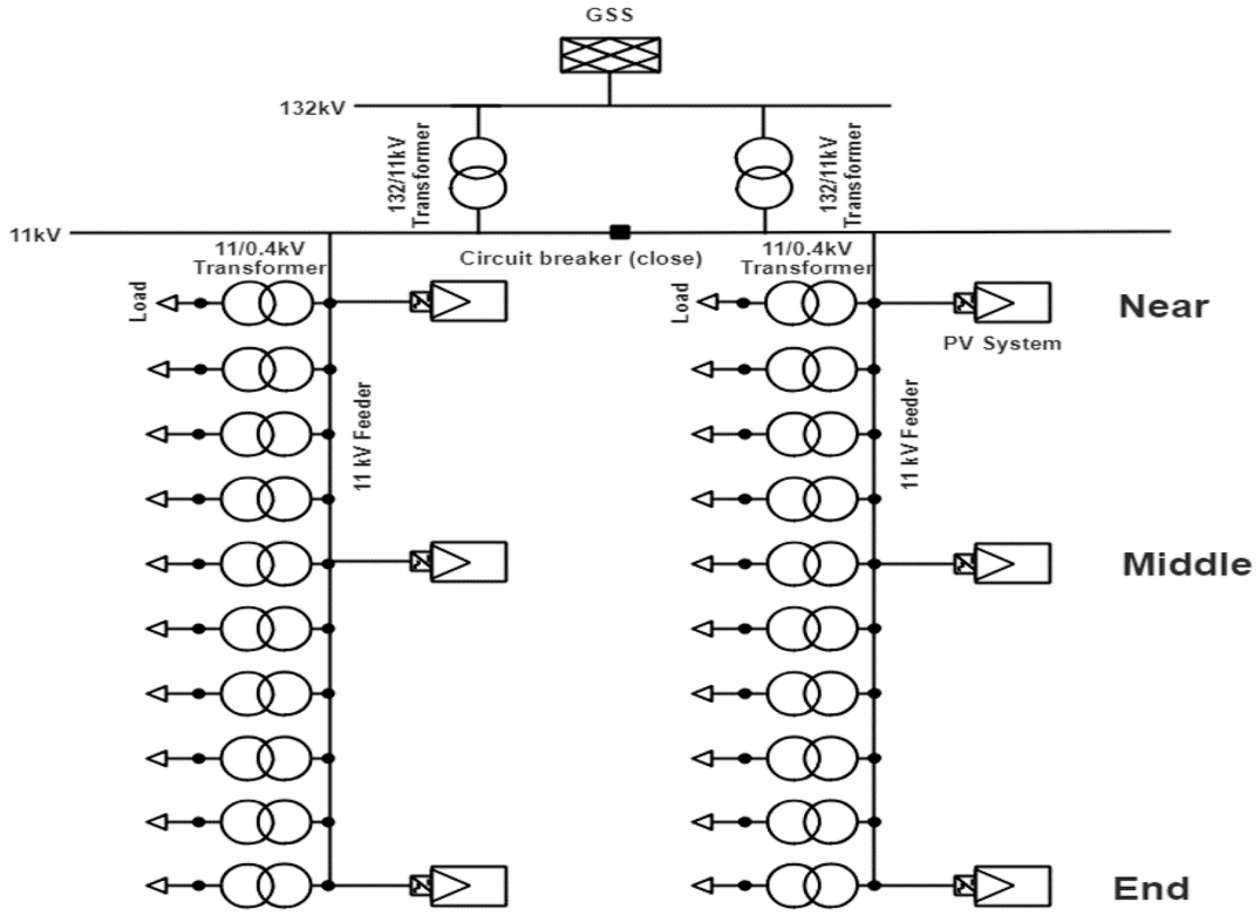

Figure 2: Location of PV system on the 11kV feeder

(e) Voltage Profile

Enhancement of the distribution network voltage profile as a whole is among the essential benefits of using distributed PV systems. Voltage profile improvement (VPI) can be calculated using Equation (6). In this study, simulation was carried out using five different PV variability profiles to examine the impact of solar variability on the distribution network voltage profile. These five different PV variabilities of the days, which are clear sky day, overcast day, mild variability day, moderate variability day, and high variability day, whose generation profiles with one-minute resolution were used to ascertain the impact on the Malaysian distribution network. In this part of study, the PV systems were connected at the end of $11kV$ feeder, while the total installed PV system capacity for urban, sub-urban, and rural networks were $1.286MW$, $0.857MW$, and $0.759MW$, respectively.

$$Max\ VPI = \frac{VP_{w/PV} - VP_{wo/PV}}{VP_{wo/PV}} \times 100\% \tag{6}$$

Where, VPI: Voltage profile improvement, $VP_{w/PV}$: Voltage profile with PV system (p.u.), $VP_{wo/PV}$: Voltage profile without PV system (p.u.).

(f) Transformer OLTC Control Setting

Three major settings that control the OLTC operation are time delay (TD), voltage set-point, and bandwidth (BW). Time series simulation by utilizing DIgSILENT power factory was carried out to model and analyze the effects of five solar variability day types on the transformer tap changer operations and on the quantity of OLTC tap changes. The OLTC control voltage set-point was 1 p.u. in this study. A comparison of the calibrated voltage from the simulation with the specified voltage set-point was then made. The control mode bandwidth was 2V, signifying that only 1/2 BW for each side of the voltage set-point was considered as the range to be used to set the voltage level. The secondary output voltage was supplied by the transformer OLTC, which would be controlled within the range of 0.95p.u. (95%) to1.05p.u., which is 105% of the voltage at primary (input). Hence, the regulation of this kind should produce a total of 33 steps, taking into the count the neutral tap from -16 to $+16$. It consists of 32discrete steps with 0.3125% voltage per step, which can be calculated using Equation(7). The TD set for this study was60 seconds. The triggering of a tap change could be set off in an event where the voltage level exceeds the bandwidth. In instances that there is no tap change resulting from the sequential control mode, it might be caused by the resetting of TD at the time when the voltage has flowed back within the desired band. In this part of study, the total installed PV system capacity for urban, sub-urban, and rural networks were approximately $6.188MW$, $2.580MW$, and $1.224MW$, respectively. The PV systems in this section were connected at the end of $11k$V feeder.

$$\% \; voltage/step = \frac{\% \; V_{total \; range}}{D_S} \tag{7}$$

Where, % $\mathrm{V}_{total \; range}$: $Percentagevoltageofthetotalregulationrange, DS : Discretesteps$

3. Simulation Results and Discussions

(a) Impact of PV Systems on Network Losses

The effect of network losses caused by PV integration on typical Malaysian distribution MV network was evaluated in this part of study; conducted based on three positions of the PV systems on the $11kV$feeder, which were: near the $11kV$bus bar, in the middle of the feeder, and at end of it. The total network losses occurring in the urban, sub-urban, and rural reference networks with the integration of PV in the different location are presented in Table 3.As shown, the total network losses for the urban network decreased from 1.689% at the base to 1.630%when the PV was placed near to the $11kV$busbar, then decreased further when the PV was fixed in the middle of the $11kV$feeders. The losses decreased to the lowest value of 1.603%when the PV was connected at feeder end. The reduction in the losses was due to the fact that the different position of PV in urban network did not give much effect. The short length of 11kV feeder in MV urban network caused the position of the PV installation to have little effect on the loss reduction. Table 3also shows that the total network losses decreased from 4.661%from the base to 4.472%and 4.257%when the PV was set up at the beginning and middle of the $11kV$feeders, respectively, for rural reference network. The additional result revealed that the loss was 4.179%which was the lowest for the rural network when the PV was integrated at the end of the $11k$ feeder. The position of the PV installation in rural network distinctly influenced the total network losses reduction, due to the length of the 11kV feeder. The length of the feeders contributed towards the greater losses, because as the feeder distance was increased, the losses increased. Therefore, injecting the PV system by positioning in the middle and at feeder end will generate power, which in turn reduce the total network losses.

Table 3: Total network losses by different location of PV system

PV system location	Urban RN with 33 11 kV feeders	Sub-Urban RN with 33 &11 kV feeders	Rural RN with 33 & 11 kV feeders
	Total losses (%)	Total losses (%)	Total losses (%)
Base case (without PV)	1.689	2.789	4.661
Near	1.630	2.688	4.472
Middle	1.609	2.607	4.257
End	1.603	2.585	4.179

Summary of total network losses reduction with respect to different location of PV integration for the urban, sub-urban, and rural reference networks is shown in Figure 3 . These results clearly signify that different location of PV system in the $11kV$ feeder contributes towards different degrees

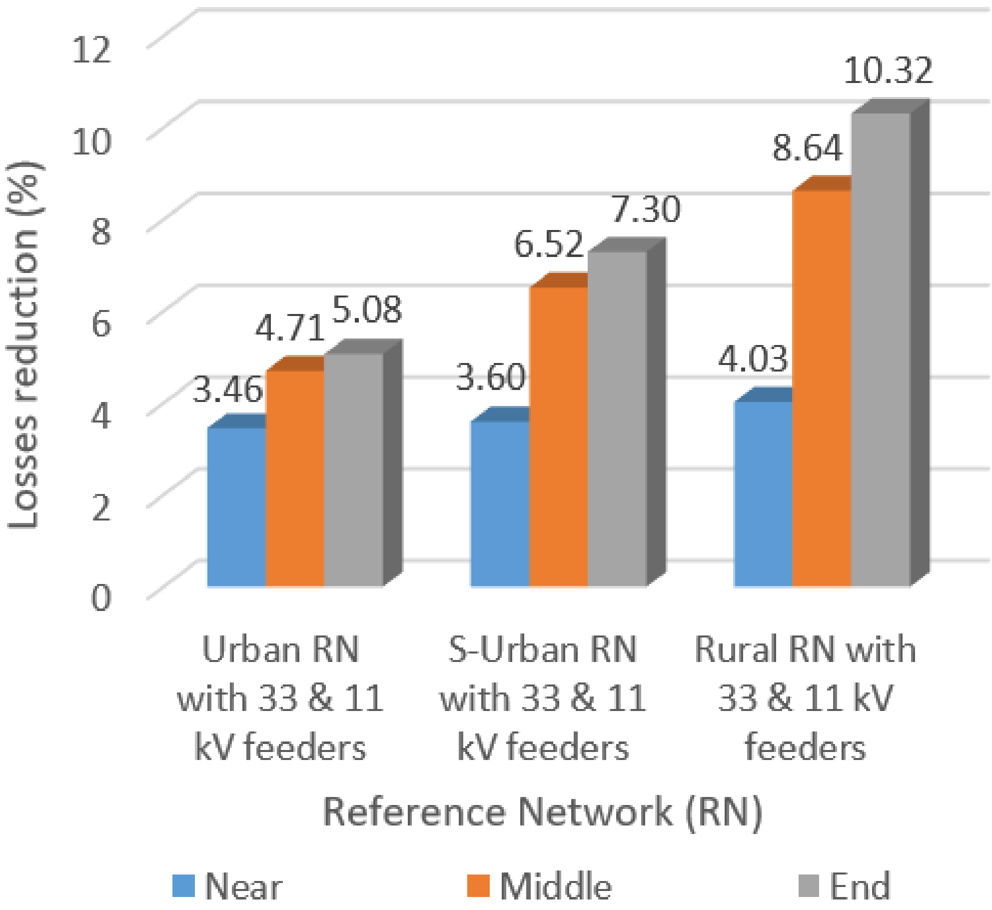

Figure 3: Loss reduction with the position of PV system

of the loss reduction. For urban network, the total network losses decreased when the location of PV system was repositioned from near to far from the 11kV feeder. However, the reduction was not significant. The urban 11kV feeder which had less than 6km gap is considered as short lines, but the increase of total network loss was small throughout the feeder. Thus, the loss reduction is approximately the same as the injection of PV generation in any position of urban feeder. On the contrary, for the sub-urban network and rural network, the location of PV system clearly influenced the total network loss reduction. Meanwhile for the rural network, the loss reduction was more than those of urban and sub-urban networks when the PV system was injected from near to the end of the feeder. The main reason for the huge loss reduction was due to the long length of 11kVfeeder in MV rural network.

In brief, for urban network, the losses can be reduced between one to three times when the PV system is positioned from near to the end of the 11kVfeeder. For the sub-urban network, the losses can be reduced between two to five times by positioning the PV system from near to end. However, there can be a huge reduction of loss between two to seven times when the PV system is integrated from near to the 11kVfeeder end in the rural network.

(b) Impact of PV Systems on Voltage Profile

This section is to examine the impact of several PV variability profiles on Malaysian MV network, such as clear sky day, high variability day, overcast day, mild variability day, and moderate variability day profiles. In this study, voltage profile is considered as measured parameter for the evaluation purpose. Injection of PV power in the network should contribute to improve the voltage profile. Therefore, the voltage profile in every simulation of various PV variability cases had been analyzed. Figure 4shows the maximum voltage profile improvement for urban, sub-urban, and rural RNs from five different PV variabilities.

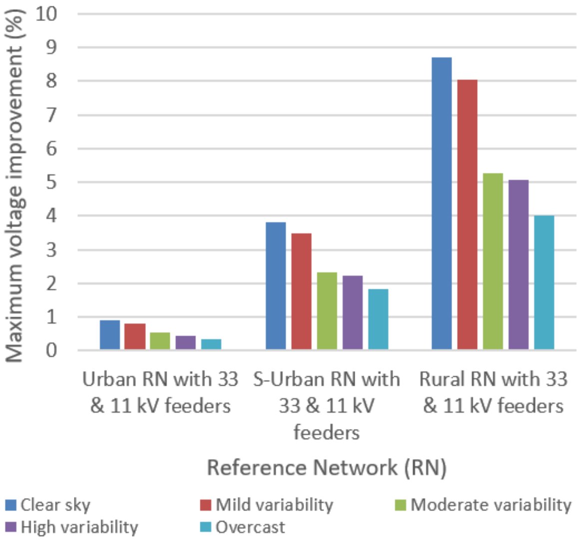

Figure 4: Maximum voltage profile improvement for urban, sub-urban, and rural RNs from five different PV variabilities

This study was simulated with a one-minute resolution. Figure 4 also shows that the voltage profile improvement was higher in rural network as compared to urban and sub-urban networks. Consequently, this occurred as a result of the 11kV feeder length for rural network being longer than the urban and sub-urban networks.

(c) Impact of PV Systems on 33/11 kV Transformer Tap Changer

This section explains the voltage step change due to the integration of PV under five different PV variability indices. The number of voltage step changes can be used to analyse the On Load Tap Changer (OLTC) tap changes in the transformer. Typical voltage control devices in transformers are fitted with On-Load Tap Changers (OLTC), which regulating the voltage magnitude within the acceptable range. Table 4 shows the number of voltage step changes for urban, sub-urban, and rural reference networks with the integration of PV generation due to five different PV variabilities. As predicted, rural network with longer feeder was much more susceptible to PV power variation. Figures 5to 7 present positions of tap changer with voltage profile of $33/11kV$ transformers located at MV side of the urban, sub-urban, and rural reference networks. As can be seen in these figures, the step change for OLTC's operation was followed by their voltage variations. For example, when the voltage rise (around $8:40a.m.$) which exceeded the normal range, OLTC stepped down to bring down the voltage level. However, when the voltage dropped (for example at $9:05p.m.$), the OLTC started to operate to step up the voltage level. Clearly, the OLTC tap change operation is fully dependent upon the voltage variations to maintain the network voltages.

Table 4: Number of voltage step changes for urban, sub-urban, and rural reference networks

PV system	Urban RN with 33 & 11 kV feeders	Sub-Urban RN with 33 & 11 kV feeders	Rural RN RN with 33 & 11 kV feeders
Clear sky (5 days)	85	90	100
Overcast (11 days)	187	220	220
Mild variability (42 days)	630	756	840
Moderate variability (114 days)	1938	2052	2280
High variability (193 days)	2895	3474	3860
Total (365 days)	5735	6592	7300

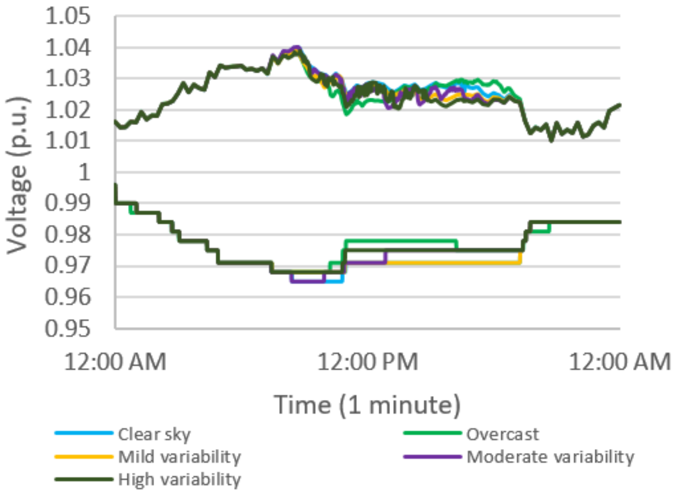

Figure 5: OLTC step changes and voltage profile at low voltage side of 33/11kV TX for urban RN with 33 and 11 kV

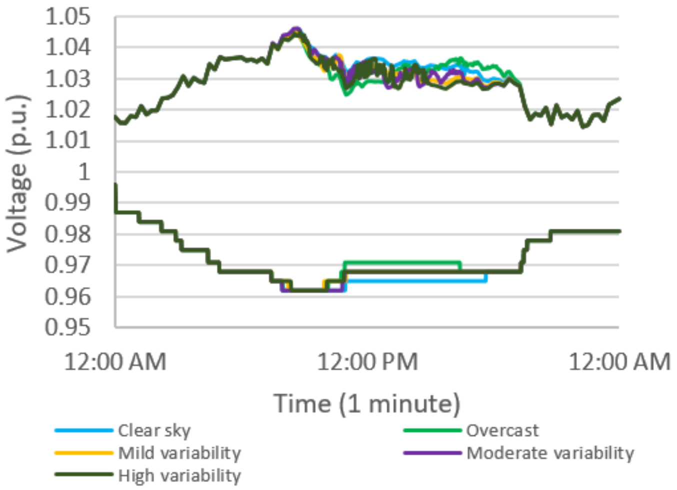

Figure 6: OLTC step changes and voltage profile at low voltage side of 33/11kV TX for sub-urban RN with 33 and 11 kV feeders

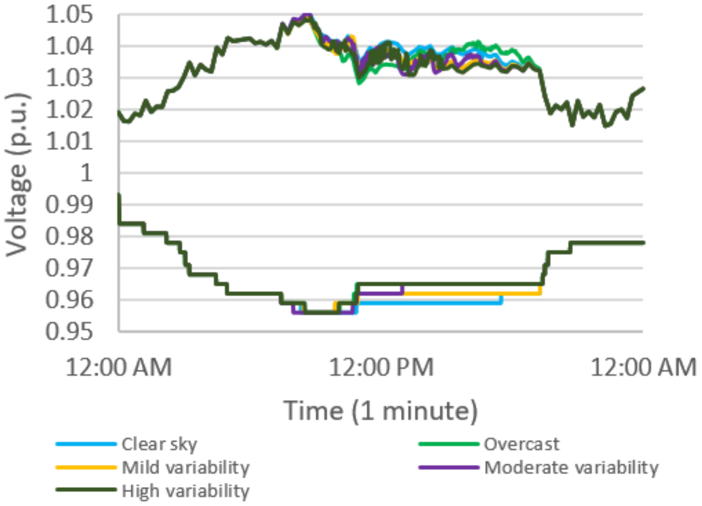

Figure 7: OLTC step changes and voltage profile at low voltage side of 33/11kV TX for rural RN with 33 and 11 kV feeders

4. Conclusion

The findings presented in this paper emphasize the impact of PV system integration on Malaysian MV reference networks. Solar generation profiles for different variability types had been utilized for network impact assessment, particularly on network losses and voltage profiles. In addition, this work highlights the effects of five solar variability day types on the transformer tap changer operations in Malaysia. DIgSILENT power factory had been used as a simulation tool for time-series power flow studies on the selected urban, sub-urban, and rural RNs. The results clearly indicate that proper active power generation in PV systems can improve voltage profiles and reduce network losses. Furthermore, the results show that rural network with longer feeder is much more susceptible to PV power variation, compared to urban and sub-urban networks.

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