IMPACT OF THE PHOTOVOLTAIC SYSTEM VARIABILITY ON TRANSFORMER TAP CHANGER OPERATIONS IN DISTRIBUTION NETWORKS

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ABSTRACT

This paper aims to quantify the transformer tap changer operations on distribution networks with large penetration of photovoltaic systems. The influence of solar generation variability on transformer tap changer is investigated through the use of five different solar variability day types collected in Malaysia with one-minute resolution. The case studies have been performed on a Malaysian representative distribution network. Results show that high solar variability day could increase the transformer's tap changes by 600% as compared to the clear sky day. The transformer's time delay setting plays a vital role in limiting the tap operations.

INTRODUCTION

The strong governmental support in Renewable Energy (RE) under the Feed-in Tariff scheme in Malaysia has witnessed the exponential growth of solar Photovoltaic (PV) system installation in Malaysia. As of 2015, 1.15GW of RE projects in total were approved by the government, of which approximately 1/3 of the RE capacity is contributed by the solar PV. Interestingly, 88% of the total approved RE projects are from individual residential-scale (less than 12 kWp) PV systems connected at Low Voltage (LV) [1]. The rest of the MW-scale PV projects are normally connected to 11kV or 33kV networks. Technical issues such as voltage rise effect and output variability of PV systems are expected to be the main challenges. Characterized as a tropical region, Malaysia experiences large cloud cover and frequent cloud-passing events [2]. As a result, the electrical power output of a solar PV system could change drastically within a short period of time. This may lead to frequent network voltage variation and subsequently, increase the frequency of transformer tap changes. It is important to note that more than half of the power transformers failure was due to tap changer [3]. On the other hand, given the demand profiles at LV residential network could be significantly different from the demand profiles recorded at the primary substation, the associated technical issues faced by these two network levels would vary. In relation to LV circuits which are typically equipped with off-load tap changers transformer, the use of on-load tap changer (OLTC) transformer is increasingly being considered in the area with high concentration of PV systems [4]. This provides greater flexibility for the network to host higher PV penetrations [5]. In this regard, this paper aims to quantify the transformer's tap changing operations under the influence of solar intermittency on both 11kV (HV) and LV networks. A representative Malaysian distribution network has been considered in the study. The data are based on a full year solar irradiance data with one-minute time resolution collected in Melaka, Malaysia. Extensive case studies have been carried out to quantify the order of magnitude of the transformer tap changes under the five identified solar variability days. Different PV penetration levels and time delay setting of the OLTC transformer have also been considered.

METHODOLOGY

A representative Malaysian distribution network has been considered in this work. The network is supplied by the 33kV network through 2x30 MVA 33/11kV OLTC transformers. In addition, an LV residential distribution network is modelled with an OLTC-fitted 11/0.4kV distribution transformer. This allows the investigation of the effects of solar variability on a localised LV network. Thus, a comparison can be made with the HV network. The network topology is shown in Figure 1. The red square box represents the LV residential network supplied by the 1MVA transformer via four main feeders. Each load point (example L11, L12, and L13) has a group of residential consumers. Time-series power flows simulation is performed using the distribution system analysis software package OpenDSS and MATLAB as the interface.

Principles of OLTC operation

Voltage set point, the bandwidth voltage and the time delay (TD) are the three important basic parameters for the OLTC control. The transformer's tap ratio is changed discretely to regulate the secondary voltage to achieve the predetermined set-point voltage. Once the secondary voltage excursion remains beyond the corresponding voltage, which is half of the bandwidth voltage continuously for a period of time (TD), the tap position will change accordingly. The TD can have values of tens of seconds to even a few minutes [6]. The LV and HV network voltage limits are +10%, –6%, and ±5%, respectively, as specified in the Malaysian standard [7].

Hence, the total voltage regulation range is 16% for LV network and 10% for HV network. The transformer is assumed to have 32 discrete steps. Hence, each step change represents 0.5% and 0.3125% voltage for the OLTC-fitted distribution and primary transformers, respectively. The bandwidth voltage must be at least twice the step-change voltage [8].

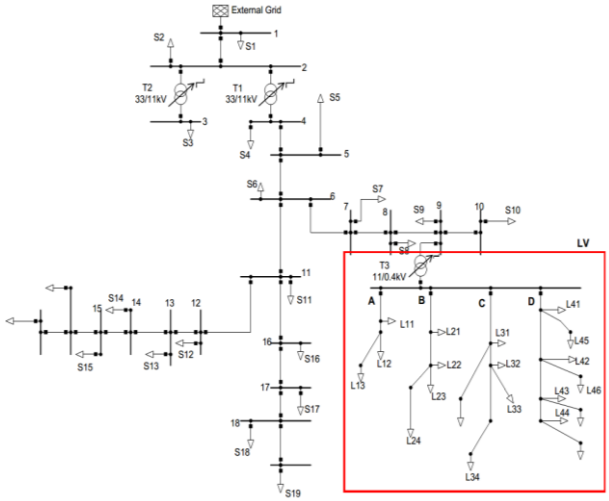

Figure 1: Malaysian representative distribution network model

Demand profiles

The real 15 minutes resolution typical residential demand profile is used in this study [9]. Figure 2 shows the normalised demand profile with 0.66 load factor. It can be observed from Figure 2 that the high demand occurs between 16:00 and midnight of which solar system would have low to zero generation during that period. The peak PV's output generally occurs during the low demand period (10:00-15:00) when most residents are out for work. It is expected that the non-coincident of PV's output and demand will lead to a more severe voltage fluctuation. On the other hand, the aggregated normalised demand profile obtained from the 33/11kV substation is as also shown in Figure 2. It can be clearly seen that it has a higher load factor (0.83) if compared with the residential demand profile (0.66).

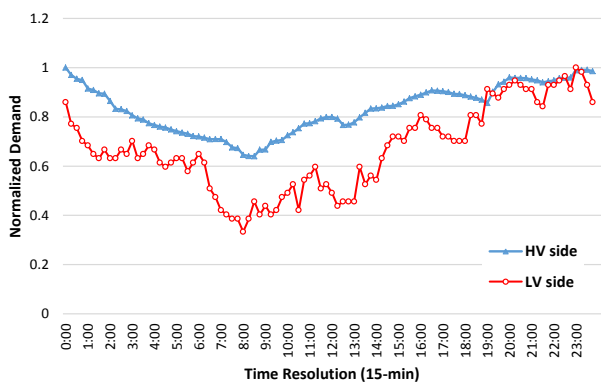

Figure 2: 15-minute resolution LV and HV demand profiles

Solar photovoltaic profiles

One year (2015) solar PV output data have been collected by the Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka. The variability of the profiles was further classified into five solar irradiance day types by using the Clearness Index (CI) and daily Variability Index (VI), namely, clear sky, overcast, mild variability, moderate variability and high variability. One representative profile of each solar day types has been chosen in this work to analyse their relative influence on the tap change operation. Figure 3 shows the five categories of solar irradiance variability profiles. It is worth noting that under the Malaysia tropic environment with large cloud cover; approximately half of the annual days are of moderate variability and one-fifth with high variability. The moving clouds contribute significantly towards the relatively high solar variability in a tropic country like Malaysia. Interestingly, clear sky only represents 1% throughout the annual days [2].

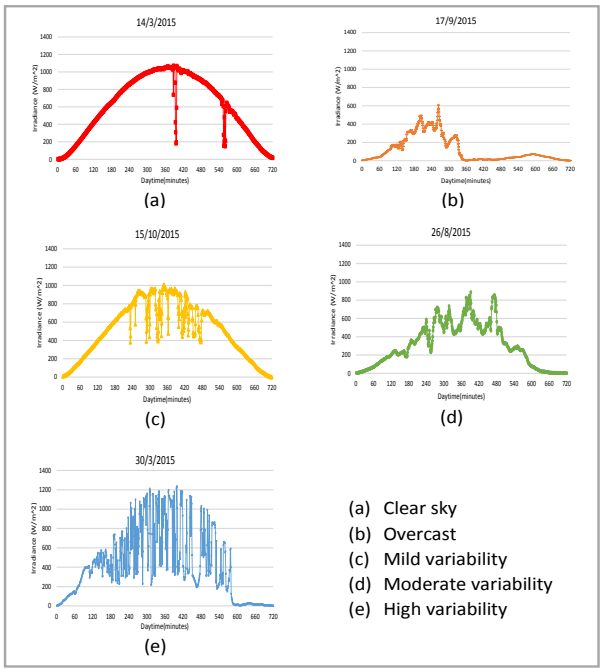

Figure 3: Five categories of solar irradiance variability profiles

CASE STUDY

The simulations were carried out for both LV and HV networks with one-minute resolution time-series power flow calculation. This is to ensure the effect of solar variability on transformer tap changer can be assessed and captured accordingly. Daily profiles of five solar variability days as discussed above are used as the solar generation profiles. Year-around analysis utilising the annual PV profiles have also been carried out for LV and HV networks. In addition, different PV penetration levels and the sensitivity of OLTC time delay setting are considered in this study.

LV network assessment

The demand profiles, as shown in Figure 2, are applied to all the residential consumers. For the sake of simplicity, the 15 minutes residential demand profile is further interpolated to achieve the one-minute resolution, consistent with the data used for PV. The PV system is then randomly allocated to the residential consumers with its capacity adjusted accordingly to the desired PV penetration level. Figure 4 shows the voltage profiles with 100% PV penetration at the secondary side of 11/0.4kV transformer. The voltage rise effect can be clearly observed particularly during the low demand, high generation periods (10:00 to 15:00). In the high solar variability day, a significantly higher number of voltage fluctuation events are observed as compared to the number in the clear sky day. However, voltages are still maintained within the limits. Similar findings have been reported in [10] that utilises a specific actual residential LV network in Malaysia. As it is a common practise for the local utility to install 3x185 mm^2 cable for the LV main feeder. Hence, the network is relatively strong. Nevertheless, since the value of voltage changes exceeds the previously specified value, it will still trigger the tap operations.

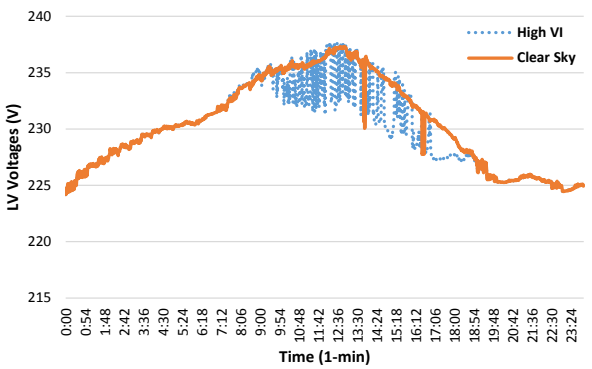

Figure 4: Voltage profiles at the secondary side of distribution transformer for clear sky and high solar variability day

As expected, the number of distribution transformer's tap changes increases as the PV penetration increases as shown in Figure 5. The high variability day could increase the number of tap changes by 400% to 600% as compared to the clear sky day under various PV penetration levels. Interestingly, the mild variability day causes a higher number of tap changes when compared to moderate variability day. This is mainly due to the lower frequency of irradiance changes (mild), but of higher magnitude that triggers the tap change.

The sensitivity of the OLTC tap changes with respect to the TD setting has been examined in this work. Four different TD settings namely 1, 2, 3 and 5 minutes have been considered in this study. The purpose of the TD is to prevent the hunting effects of tap change operations due to the temporal voltage fluctuations. The results suggest that longer TD setting can reduce the tap changes significantly. For example under the high variability day, the changes of TD setting from 1-min to 5-min could reduce the tap counts by 240%. This is shown in Figure 6. Nevertheless, the maximum allowable TD setting will need to comply with the relevant local authority voltage disturbances standard. Malaysian utility refers to European EN50160 standard which defines the 10-min mean rms voltage variation should not exceed ±10% of nominal voltage [11]. It is a general practice for the primary transformers in Malaysia to have 60s TD setting.

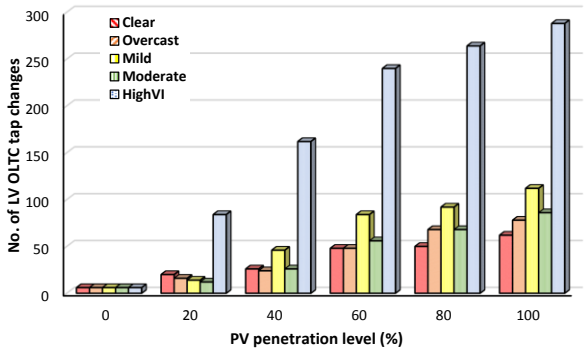

Figure 5: Number of tap changes for LV transformer under various PV penetration levels

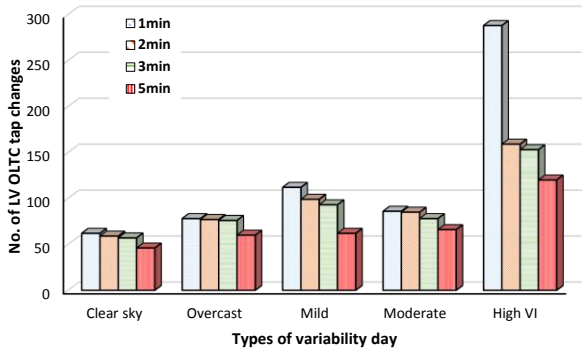

Figure 6: Number of tap changes for LV transformer under various TD settings

HV network assessment

A set of studies has also been performed for HV network with the use of interpolated 1-min HV demand profiles and the five solar variability day types. As the majority of the tap changes occur during 10:00 to 15:00 when the solar generation peaks, the better coincident of PV's outputs and HV demand profiles has helped to reduce voltage fluctuations and hence decrease the number of OLTC tap changes. This can be observed from Figure 7 that the number of tap changes in the primary transformer is significantly less than the number for LV distribution transformer. For example, at 60% PV penetration level, the number of tap changes of the primary transformer is only 1/3 of the LV transformer during the high solar variability day. As expected, similar results were observed for the sensitivity of TD setting on the primary transformer.

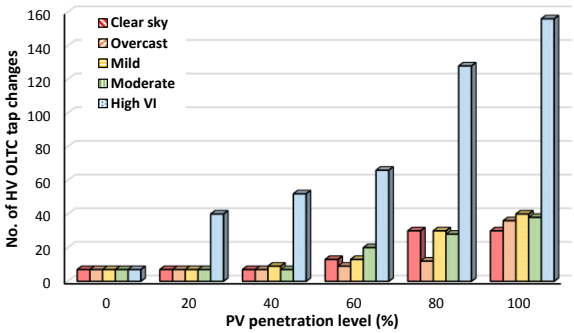

Figure 7: Number of tap changes for primary transformer under various PV penetration levels

Year round analysis

A year-round analysis has been performed to quantify the number of tap changes for both the distribution and primary transformers under Malaysia tropic climate condition. Due to the higher mismatch of demand and generation profiles in a residential area, the distribution transformer's tap may operate 20 times more frequent in the LV residential network with 100% of PV penetration. This is in contrast to only 7.4 times in the HV network, mainly driven by its higher load factor. The annual tap changes for LV and HV transformers under various PV penetration levels analysed in these studies are shown in Figure 8.

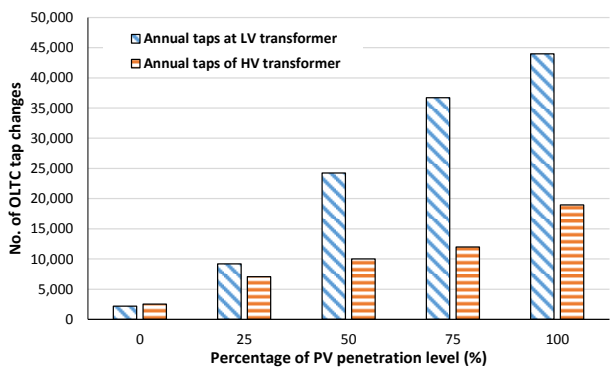

Figure 8: Annual tap changes for LV and HV transformers under various PV penetration levels

CONCLUSION

Five solar variability day types have been used to quantify the effects of increased PV penetration on the transformer tap changer operations in Malaysia. Both LV and HV networks have been considered in this work by utilizing a generic Malaysian representative distribution network model. One-minute interval time-series power flows has been performed for the network with various PV penetration levels. The results show that high solar variability day could significantly increase the number of tap operations by six folds if compared with clear sky day. The year around analysis also suggests that the tap could operate 20 times more in an LV residential network when compared with the network without PV connections. This necessitates the need for proper mitigation measures to minimize the number of tap changes as it will reduce the lifetime of power transformers. The appropriate selection of the time delay setting within the permitted range could help to limit the tap operations accordingly. It is important to note that this observation is location centric. Countries with less cloud cover may experience much fewer tap change operations.

Acknowledgments

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