Voltage Level Management of Low Voltage Radial Distribution Networks with High Penetration of Rooftop PV Systems

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***Abstract*— *The increasing of rooftop photovoltaic systems can introduce over-voltage problems in low voltage distribution networks, particularly at the end of radial feeder. The conventional voltage control solution by adjusting the off-load tap changing transformer can prevent the voltage level to exceed the statutory limit without the further investment. However, the new tap position, which remains unchanged, may cause the under-voltage problems to occur during the time that total demand consumption is high, especially in urban residential areas. The coordinated voltage control among off-load tap changing transformer and switched shunt capacitors is proposed to manage voltage level in low voltage feeder with high penetration of rooftop photovoltaic systems. The voltage control performances are examined on simulation in DIgSILENT PowerFactory software. The results showed that the proposed voltage control method can maintain the voltage level across the feeder within the statutory limits. Although the shunt capacitors will increase the losses in the networks, this solution is cheaper when comparing to the replacement of new on-load tap changing transformer.*

***Keywords*— Off-load tap changing transformer, OLTC, voltage level control, photovoltaic system, switched shunt capacitors.**

1. INTRODUCTION

The number of rooftop photovoltaic (PV) systems connected to low voltage distribution networks has increased dramatically since the year 2000. Although the PV systems give the benefit of raising the power generation capacity, the high penetration of PV systems can cause the over-voltage problem into low voltage (LV) networks, especially at the end of feeders, when the power production from PV is high during the light load condition. Hence, a number of PV connects is restricted.

To prevent the over-voltage to exceed the statutory standards such as IEEE 1159-2009 and IEC0 610000-6-1, the traditional approach used by distribution network operators is to reinforce the network by replacing conductors to bigger ones. The larger size of distribution line will have lower impedance and therefore will introduce smaller voltage change along the feeder. To compare the cost of network reinforcement with installing a new on-load tap changer (OLTC) fitted transformer, it is found that the network reinforcement is the cheaper option when the level of PV penetrations, based on a real UK residential LV network, is less than 70 % [1].

The business as usual alternative approach to deal with the impacts of PV systems in LV networks is an adjusting the tap position of transformer equipped with off-load tap changers. This approach is the simple and famous solution. The tap changer is usually fitted at the high voltage (HV) side of distribution transformer. In addition, the tap changing will be only operated while transformer is in off-load or no-load condition. Unlike the automatic OLTC, using the off-load tap changing transformer will mitigate the voltage level, according to the new tap position, along the LV radial feeders all the time due to the tap position remains unchanged.

The OLTC fitted transformer can be used to enhance the flexibility of voltage management in the LV networks with high level of PV connections. This is a centralised voltage control method which can regulate the voltage level along the LV feeders automatically. To manage the customer voltage effectively, measurements at critical points of the LV networks are required, especially at the end points of feeders [2]. Moreover, the reliable, fast and high capacity communication systems are required while the short period of data acquisition is necessary in case of high penetration rate of PV system [3]. On the other hand, a generic and practical remote voltage estimation method for the end point of LV feeders is proposed in [4] to substitute the need of remote monitoring without compromising performance and, hence, reducing the further investment in communication systems.

The centralised voltage control in distribution systems with PV systems can be improved by coordinating tap changing distribution transformer with other Volt-Var control devices. The reactive power compensation devices such as distribution static synchronous compensator (DSTATCOM) will act as the secondary voltage controller. The additional Volt-Var control devices will support the reactive power with the aim to maintain the flattened voltage profile across a feeder. The research in [5] shows that the use of OLTC fitted transformer with Grid Edge Var (GEV) devices called ENGO^{TM} can reduce the voltage volatility in LV distribution feeder which is caused by the dispersed PV systems. The results in that work are validated with

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detailed simulations and with preliminary field tests.

Another voltage level management in LV networks with PV systems is implemented by decentralised voltage control method. This is the local voltage control method which the active power (*P*) curtailment and reactive power (*Q*) control are applied into customer owned PV inverters [6]. The *P* curtailment should be operated as a little due to the PV should produce the power into the network as much as possible. Then, the *Q* control is preference for the voltage control. Although the modern PV inverter, based on the voltage source inverter, can provide the *Q* controllability with the fast response. Most of existing PV systems is still using the fixed - power factor inverter which is unable to provide the automatic *Q* support. In this case, the small *Q* compensation devices, such as the small thyristor controlled reactor in [7], can be installed parallel with the fixed - power factor inverters to enhance the voltage controllability of PV systems.

Despite the use of OLTC fitted transformers as the centralised voltage control is a promising solution to manage the entire voltage level across the LV feeder connected with PV systems, the replacement of conventional distribution transformers with OLTC fitted transformers is required which it is very costly. In contrast, the changing of tap position of distribution transformer equipped with off-load tap changer seem to be a good choice when the financial reason is concerned. Many existed distribution transformers in the LV networks already have a manual tap regulation, which tap position can be adjusted by hand, to prevent the over-voltages without installing a new equipment.

In this paper, the distribution transformer with off-load tap changer is the primary voltage control device which aims to prevent the over-voltage problems caused by PV systems in the LV feeders. However, in some locations such as the urban residential areas, the high electricity demands usually occur in the early morning and in the evening, during that time, the PV system is inactive and there is no impact on voltage change from the PV generation. Consequently, the voltage levels of domestic residents, especially at the end points of radial LV feeders, are relatively low. It can be seen that the stepping voltage down by off-load tap changing solution can intend the voltage level at the end of feeders to below the statutory limit.

To enhance voltage control capability, the switched shunt capacitors are introduced to work as the secondary control device, in associated with the off-load tap changing transformer. The tap position is stepped up at the HV side of transformer to deal with over-voltage from the PV generation while the switched shunt capacitors will support the Volt-Var control to avoid the under-voltage problems during the heavy load conditions. The switched shunt capacitors can be installed at the distribution transformer, as the centralised voltage controller which can support voltage control to remote buses in the network. Alternatively, shunt capacitors can be used as the decentralised voltage controller, located at critical locations such as at the end of feeder, with the local voltage controllability. The performance of voltage control by off-load tap changing transformer associated with shunt capacitors will be evaluated by comparing the simulation result of using OLTC fitted transformer.

The paper is structured as follows: section 2 explains the background of voltage change in radial LV network with/without PV systems. The voltage control operations of OLTC and shunt capacitors are explained in section 3. Section 4 describes the LV network model, load consumption and PV generation profiles and the detail of case study. The voltage control performances are investigated based on DIgSILENT *PowerFactory* software presented in Section 5. Finally, the conclusions are drawn in Section 6.

2. VOLTAGE CHANGE IN LV NETWORKS

In traditional LV distribution networks, without PV systems, the power will flow in one direction, from the substation to the customer loads. However, the injection of electric power from PV systems affects the power flow direction and the voltage level of the network. The change in the voltage level when PV system is injecting power to a certain location of a LV radial feeder, as shown Fig. 1, can be explained as follow.

Adopt from [8], the voltage drop (ΔV), without PV system, can be written as in (1).

$$\Delta V = V_1 - V_2 = \frac{PR + QX}{V_2} \tag{1}$$

where *P* and *Q* are the active and reactive power sent from bus 1, respectively. *R* and *X* are the resistance and the inductive reactance of the circuit, respectively. In per unit, the voltage at the PV bus can be assumed as 1.0 p.u., so (1) can be approximated as:

$$\Delta V = PR + QX \tag{2}$$

In the case that PV system supplies active and reactive power, P_{PV} and Q_{PV}, respectively, to the system, then (2) can be written as:

$$\Delta V = \left(P - P_{PV}\right) R + \left(Q - Q_{PV}\right) X \tag{3}$$

It is found that the injection of apparent power from PV system can reduce the term (P-P_{PV}) and (Q-Q_{PV}), thus the value of ΔV decreases. Then, the voltage at the PV bus, V_2, will be increased. As PV system usually operates at unity power factor, with Q_{PV} equals to zero, the voltage change is mostly due to the *P* injected from PV system.

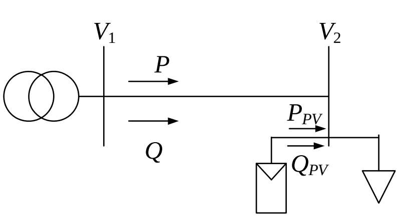


Fig. 1. Simple radial distribution network with PV system.

From (1) to (3), the main factors that have an impact on voltage change in distribution system with PV systems, suggested in [9], are as follows;

Load demand and PV generation: the light load condition, the higher PV generation leading to a higher level of voltage rise especially at the end of feeder.

Line impedance: The higher line impedance, the higher level of voltage changes across the LV feeder. The line impedance can be reduced by increasing the size of distribution line.

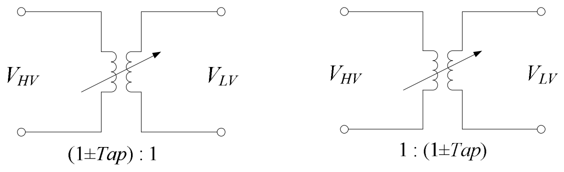
Operating power factor of PV inverter: If PV inverter operates in inductive mode (absorb *Q* from the network), the voltage rise can be reduced. On the other hand, the voltage at PV bus will be increased if PV inverter is in capacitive mode (inject *Q* into the network).

3. VOLTAGE CONTROL DEVICES

The details of automatic on-load tap changer and switched shunt capacitor operations for the voltage control, used in DIgSILENT *PowerFactor*, are explained in this section.

Automatic on-load tap changer control

The on-load tap changer (OLTC) is an automatic tap-changing controller, which does not cut the electricity off before changing the tap position. It can change the tap of the transformer step-by-step to control the secondary voltage at the desired value. The speed of the tap-changing operation depends on the tap-changing mechanism process, which may take from several seconds to minutes per step. The OLTC can be installed at either the HV winding or the LV winding, as shown in Fig. 2, where *Tap* is the tap setting in p.u..

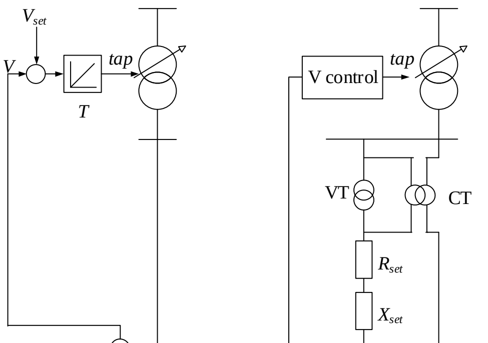


$$V_{LV} = \frac{1}{\left(1 \pm Tap\right)} \times V_{HV}$$

$$V_{LV} = \left(1 \pm Tap\right) \times V_{HV}$$

(a) Tap changer modelled at HV side (b) Tap changer modelled at LV side

Fig. 2. Tap changer transformer models.



(a) OLTC controller with remote voltage control (b) OLTC controller with LDC

Fig. 3. OLTC voltage controllers.

In DIgSILENT *PowerFactory*, the OLTC can be operated in 3 different control modes including; voltage control, reactive power control and active power control [10]. In the voltage control mode, the OLTC controller can be support voltage control to either local bus (HV or LV side of transformer) or a specific bus in the system, as remote control, such as at the end point of feeder. Additionally, in case of remote voltage control, the remote measurement and communication system are necessary. The structure of OLTC controller with the remote voltage controllability is shown in Fig. 3 (a).

The alternative remote voltage control is using the line drop compensation (LDC). This function controls the voltage at the remote bus without measuring the voltage at that bus. The actual voltage value is estimated by measuring the voltage at the HV or LV side of the transformer and, hence, simulating the voltage drop across the distribution line. Fig. 3 (b), illustrates the principle of the LDC where R_{set} and X_{set} are LDC impedance defined as voltage drop at the rated current.

The tap position is changed discretely which only integer tap positions are considered. The speed of control actions is specified by a controller time constant (*T*, see in Fig. 3 (a)). In case of remote control, the voltage set point (V_{set}) and voltage range setting (maximum and minimum voltages) are taken from the controlled bus.

Switched shunt capacitors control

The switched shunt device in DIgSILENT *PowerFactory* can be applied in 3 modes including; voltage control, reactive power control and power factor control [11]. The automatic step adjustment in case of voltage control can be written as

$$\Delta step = \frac{K}{sT}\left(V_{set} - V\right) \tag{4}$$

where $\Delta step$ is step changes of shunt device, V_{set} is voltage set point (in p.u.), V is measured voltage (in p.u.), T is time constant and K is controller factor which depending on the number of steps. In addition, the voltage set point is calculated from the upper and lower voltage limits, according to (4)

$$V_{set} = \frac{V_{set}(upper) - V_{set}(lower)}{2} \tag{5}$$

Moreover, the time constant, *T*, is determined from

$$T = \frac{T_{ctrl}}{T_{\min ctrl} \times k_{relax}} \tag{6}$$

where, T_{ctrl} is controller time constant. $T_{\min ctrl}$ is the fastest controller time constant of all automatic adjusted shunt devices. k_{relax} is the minimum controller relaxation factor (typical is 1.0).

The controller factor *K* is calculated from

$$K = 100\% \times n_{capx} \times K_{ctrl} \times orientation \tag{7}$$

where K_{ctrl} is sensitivity dQ/dV in p.u./%, n_{capx} is maximum number of steps and *orientation* is step orientation (+1 for capacitive shunts).

The size of shunt capacitor depends on the location of controlled bus, which can be determined by using *Q/V* curve or voltage sensitivity matrix [12]. Moreover, the switched shunt capacitor can be used as the remote voltage controller, which supporting voltage control to specific bus in the network, if the remote monitoring and communication system are available.

4. TEST SYSTEM AND CASE STUDY

The test system is a three phase, 0.4 kV, 50 Hz radial distribution network adapt from a real LV system in the urban area of Thailand. It consists of 20 customers, which the phase connection of each house is identified in Fig. 4. It is found that there are 8, 10 and 2 customers in phase A, B and C, respectively. Each house is fed by 3 phase 4 wire distribution system with the total length is approximately 326 meters. The parameters of the main feeder and branch lines are brought from [9], as shown in Table 1.

All customers have the same electricity demand profile using the average residential load profile surveyed by the Energy Policy and Planning Office of Thailand in 2008, as shown in Fig. 5. The power factor of each customer is 0.85 lagging. Assuming the 5 kW rooftop PV system is installed to each house which has the power generation profile collected by School of Renewable Energy Technology, Naresuan University, Thailand, as also shown in Fig. 5. Both residential load profile and PV generation profile are in 15-minute resolution. It can be seen that during noon time the PV generation is very high while the residential load demand is very low. Moreover, the distribution transformer has the tap changing of -5% to +5% at 2.5% per step (overall is 4 steps). The statutory limits of this study is defined as between ±5%.

Table 1. Parameters of LV Distribution Line

Parameters	Main feeder lines	Branch lines
Cross-section	50 mm^2	25 mm^2
Type	THW	THW
R (ohm/km.)	0.4723	0.8698
L (mH/km.)	0.8168	0.8906
C (μF/km.)	0.0134	0.0124
Installation	Overhead aerial system	Overhead aerial system

The 24-hour voltage profiles across the LV feeder are simulated by using the time sweep load flow calculation on DIgSILENT *PowerFactory* software. The test system is examined in 6 different scenarios to investigate the voltage control performance of different type of voltage control devices, as follows:

1) No voltage control devices (based case)
2) Only off-load tap changing transformer
3) Adjusting power factor of PV inverters to 0.9 lagging
4) OLTC fitted transformer with remote voltage controllability
5) OLTC fitted transformer with internal LDC
6) Off-load tap changing transformer with 66 kVar switched shunt capacitors located at the distribution transformer (bus 00)
7) Off-load tap changing transformer with 21 kVar switched shunt capacitors located near the end of feeder (bus 10)

The automatic OLTC fitted transformer is examined in 2 voltage control modes: 1) remote voltage control when assuming the communication system is available, and 2) using the internal LDC. These 2 modes aim to control the voltage level at bus 10 to stay between 0.95 p.u. and 1.05 p.u.. The OLTC controller in the remote voltage control mode has the controller time constant, T = 0.5 s and V_{set} = 1.0 p.u.. Alternatively, in case of the OLTC is using LDC as the voltage controller, R_{set} and X_{set} are 0.082 V and 0.044 V, respectively when the current transformer rating is set as 1 A.

The switched shunt capacitors are a three-phase shunt device with a single step switching operation. To see the performance of shunt capacitors, there are 2 locations to be examined. Firstly, the switch shunt capacitors with remote controllability are located at bus 00, near the distribution transformer, aiming to maintain the voltage level at the end of feeder, bus 10, via the remote measurement and communication system. On the other hand, the switched shunt capacitors with local voltage control capability are installed directly at the critical bus, bus 10, which will provide Volt-Var support without communication requirements.

The size of shunt capacitors is determined by using voltage sensitivity matrix, which can be calculated in DIgSILENT *PowerFactory*. The controller parameters of switched shunt capacitors in these both cases are setting as controller time, T = 0.5 s, and controller factor, K = 10.

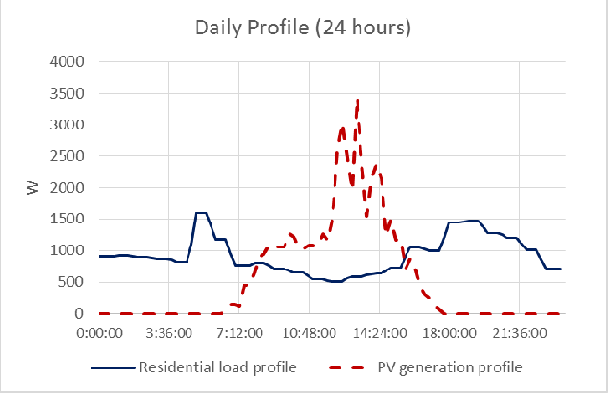


Fig. 5. Daily residential load and PV generation profiles.

5. SIMULATIONS AND RESULTS

The simulation results in Fig. 6 show that, without any voltage control devices, the voltage levels in phase A and B exceed the statutory limit (>1.05 p.u.), which occur at the latter end of feeder starting from bus 5 to bus 10. It is found that the maximum voltage level is about 1.07 p.u. at phase A of bus 10 which is the end point of feeder.

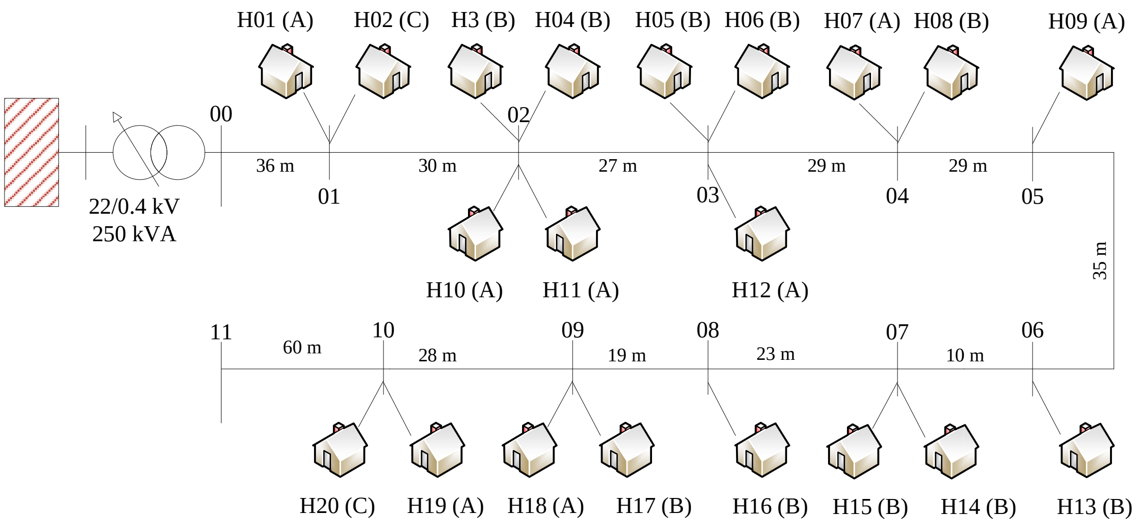
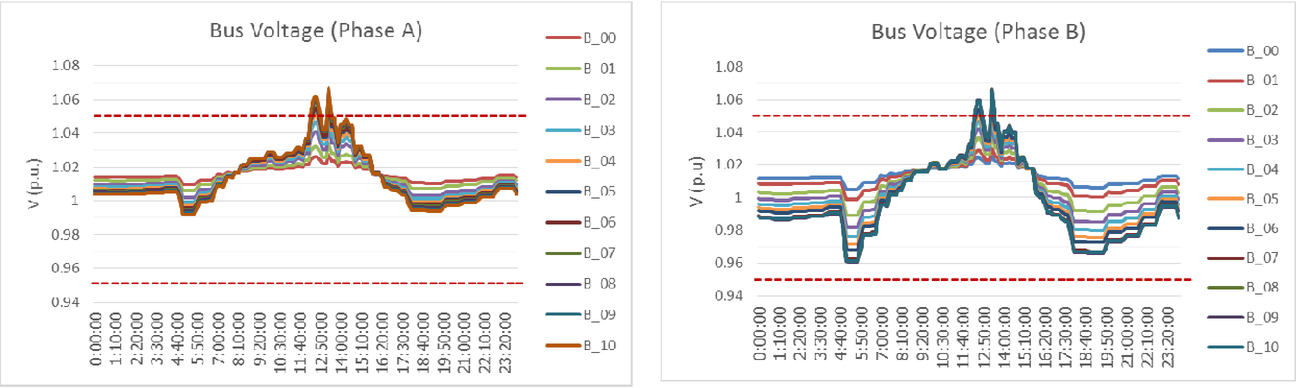
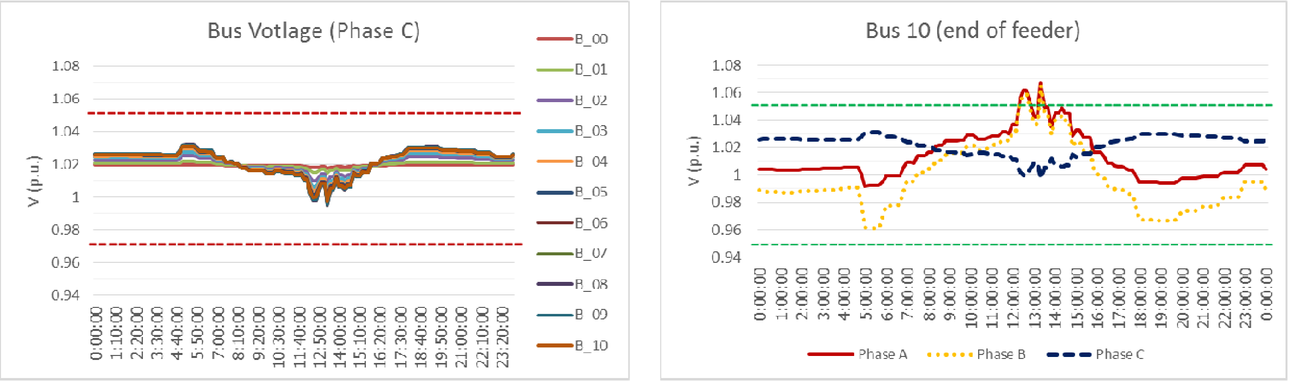


Fig. 4. Test system.



(a) Voltage Profiles: all buses, phase A

(b) Voltage Profiles: all buses, phase B



(c) Voltage Profiles: all buses, phase C

(d) Voltage Profiles: bus 10, phase A, B and C

Fig. 6. Voltage Profiles in the base case (no voltage control devices).

Moreover, the voltage profile of phase B at bus 10 illustrates the high voltage volatility, which voltage level has swung between 0.96 p.u. and 1.07 p.u. during the day. The over-voltage problem occurs between 12.20 p.m. and 13.20 p.m., which, at that time, the PV generation is higher than load demand very much. The 24-hour load demand and PV generation are 179.774 kWh and 210.017 kWh, respectively. Whereas, the daily energy loss in this case is around 30.624 kWh, as seen in Table 2.

Fig. 7, demonstrates that stepping-up the tap position of off-load tap changing transformer +1 step can prevent the over-voltage problem from the PV generation during light load condition. It is also found that the 24-hour energy loss is reduced to 30.035 kWh when comparing to the based case. However, the remained tap position at +1 step all the time will introduce the under-voltage problems to phase B which occur during heavy load conditions in the early morning (5.00 a.m. – 6.00 a.m.), and in the evening (18.00p.m. - 20.00 p.m.), respectively.

When changing the power factor of all PV systems from unity to 0.9 lagging, each PV system will absorb reactive power as shown in Fig. 8 (a). It is found that the *Q* control from PV systems can maintain the voltage levels within the statutory limits only in phase B and C whilst the voltage level in phase A is still over the limit during the peak PV generation, as seen in Fig. 8 (b). This occurs due to the most customers in phase A are located near the sending end of feeder. Therefore, the amount of *Q* support from PV system in phase A is insufficient to prevent the voltage rise problem for the customers located near the end of feeder. Moreover, the absorbing *Q* from all PV systems produces the higher 24-hour energy loss, which the daily loss is increased to 33.153 kWh.

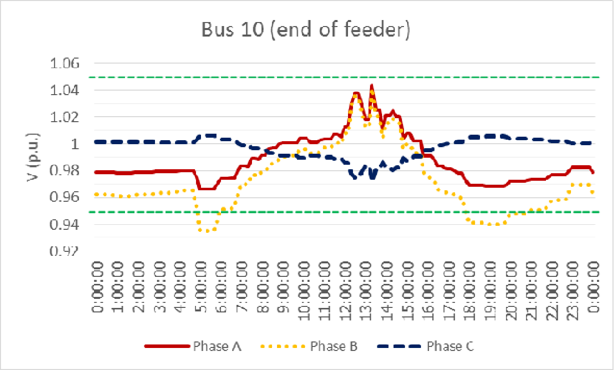
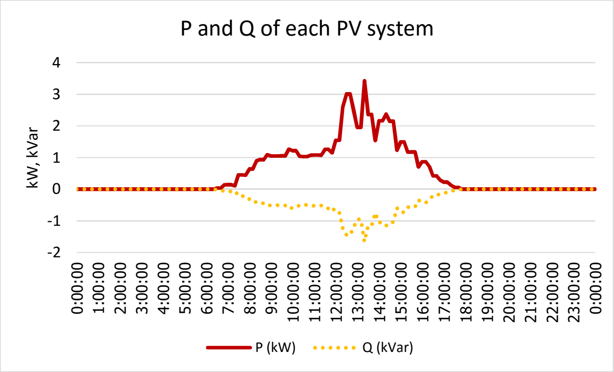
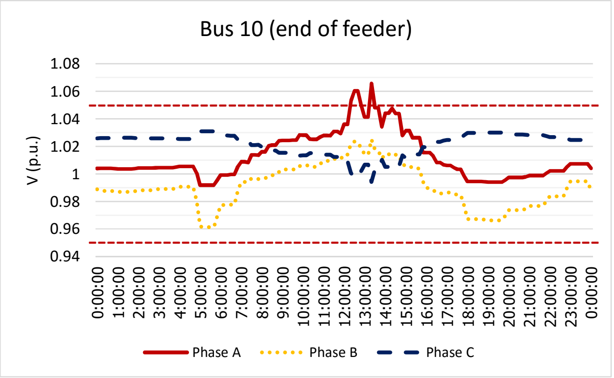


Fig. 7. Voltage Profiles at bus 10 (using only off-load tap changing transformer).



(a) *P* and *Q* of each PV inverter at power factor is 0.9 lagging



(b) Voltage Profiles: bus 10, phase A, B and C

Fig. 8. *P* and *Q* of each PV system and voltage profiles at bus 10 (adjusting power factor of PV inverters).

Table 2. Daily Energy Loss in Each Case

Case	kWh
1) Based case : no voltage control	30.624
2) Only off load tap changing transformer	30.508
3) Adjusting power factor of PV inverters	33.153
4) OLTC fitted transformer: remote control	30.505
5) OLTC fitted transformer: using LDC	30.035
6) Off load tap changing transformer and switch shunt capacitors at bus 00	32.007
7) Off load tap changing transformer and switch shunt capacitors at bus 10	32.059

The use of automatic OLTC fitted transformer with the remote voltage control to the critical bus, which is bus 10, can deal with over- and under-voltages effectively, as seen in Fig 9 (a). The tap will be stepped up +1 step during the afternoon, which start at 12.20 p.m. and then stop at 17.50 p.m., to keep the voltage level especially phase B within the statutory limits. Furthermore, Fig. 9 (b) demonstrates that using OLTC with internal LDC can give the voltage control performance to bus 10 similar to the case of remote voltage control. It is observed that the daily losses in both voltage control technics are slightly reduced from the based case, which are 30.508 kWh and 30.505 kWh, respectively. Although the OLTC fitted transformer provides the decent voltage control to the LV networks with high penetration of PV systems, this solution requires the investment of new OLTC fitted transformer due to the most existed transformer is the off-load tap changing type.

To enhance voltage controllability of off-load tap changing transformer, the shunt capacitors are used to deal with under-voltage problems introduced by the switching operation (single step). The results in Fig. 10, show that installing the switched shunt capacitors at the distribution transformer and at the end of feeder, both solutions can support voltage control efficiently. It can be seen that the switched shunt capacitors will support Volt-Var control in 2 periods which are in the morning (from 5.00 a.m. until around the noon time) and in the evening (starting since 18.00 p.m).

The reactive power supported by switched shunt capacitors, located at either bus 00 or bus 10, causes the rise of energy losses. It is found that the 24-hour energy losses of both cases are increased approximately 4.5 % and 4.7 %, respectively, compared to the based case. It should be noted that the size switched shunt capacitors used as centralised voltage controller, fitted at near the LV side of distribution transformer, is bigger and requiring communication systems to provide the remote voltage support to the specific location in the system. Furthermore, the switching operation of shunt capacitors at the distribution transformer may affect to all connected LV feeders and then possible making unforeseen voltage problems to some feeders, especially the raising up of voltage level.

6. CONCLUSION

The growth of rooftop PV systems and residential electricity consumptions, particularly in the urban area, can cause the voltage quality problems in LV radial distribution networks. It was found that the customers especially at the end of feeder can face the over-voltage problems during the noon time which PV generation is high. Whereas, the voltage level will be very low during in the early morning and in the evening due to the heavy demand consumptions. The results from simulations showed that the off-load tap changing transformer associated with the switched shunt capacitors can provide under- and over-voltage controls in LV networks with high penetration of PV systems satisfyingly.

The shunt capacitors should be used as decentralised voltage control which installing locally at criticised locations in the network, rather than using only the big one at the distribution transformer. Although the shunt capacitors can increase the total losses in the network, this is the cost effective solution comparing to the use of automatic on-load tap changing transformer. It can be seen that the switched shunt capacitors are the optional voltage control device which they are not necessary if the peak electricity demand, especially in the morning and in the evening, of each residential house connected to the same feeder is not relatively high.

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