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Enhancing PV Penetration in LV Networks Using Reactive Power Control and On Load Tap Changer With Existing Transformers

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ABSTRACT Voltage rise beyond statuary limits in low voltage (LV) ac networks due to high photovoltaic (PV) penetration and its mitigation using multiple techniques was assessed. Investigations using a real rural domestic overhead LV network were done through load flow simulations. A three-phase four wire medium length LV network with a fixed tap transformer and PV inverters operating at unity power factor was able to host PV between 79%–98% of transformer ratings for five different PV configurations. For the case studied at this penetration level three, limiting factors (voltage, thermal loading limits of lines, and transformer) come together. Three techniques were utilized to control the voltage across the LV network. On load tap changer (OLTC) control was found more robust than reactive power control (RPC). Hybrid control (OLTC and RPC) was found beneficial only for extra high PV penetration scenarios. Replacement of a few critical line spans and the existing transformer with higher capacity conductors and an OLTC equipped transformer (higher size) enabled the network to host an additional 50%–90% PV. The unequal distribution of single-phase PV systems among three phases has negative effects on penetration. Consideration of PV integration while planning new LV networks and retrofitting of OLTCs with existing transformers, could make the LV system more PV friendly. The RPC option, though less effective than OLTC due to increased current, can be beneficial at medium penetrations where OLTC may become a costly solution.

INDEX TERMS LV distribution network, PV penetration, PV impacts on LV voltage, voltage violations, voltage control, on load tap changer equipped transformer, reactive power control.

I. INTRODUCTION

An exponential rise in installation of solar Photovoltaic (PV) systems has been observed in the past few years [1]. The trend seems to have continued due to many reasons, such as the fall of prices due to mass production, availability of mortgaging, and the global push for curtailing Green House Gases (GHG) [2]. Rooftop PV installations connected to Low Voltage (LV) distribution networks have given rise to many problems. Voltage violation is the most important among these, and it restricts PV penetration in LV networks [3], [4]. A number of techniques have been employed to increase the LV network PV hosting capacity. Reactive Power Control (RPC) through modern inverters has been widely investigated and has been practiced in some countries having considerably high share of LV connected PV systems like Germany [5]. On Load Tap Changer (OLTC) equipped transformers have been in wide use at Medium and High Voltage levels in power systems all over the world for voltage regulation. However the use of OLTC equipped transformers at MV/LV is not common in traditional electricity networks due to higher cost [6]. Presence of a reasonable number of PV systems in the LV network provoked various researchers to find out the effectiveness of OLTC equipped transformers in LV networks. Studies have been performed to investigate the effectiveness of OLTC equipped transformers for voltage control at the LV level to maximize the PV penetration.

Esslinger and Witzmann [6] proposed the use of OLTC and RPC in underground LV distribution grids for voltage control, and a communication assisted central control was proposed. Simulations were performed on a three phase balanced network, and the effectiveness of the system was demonstrated. In [7] three Dutch LV networks were studied. The objective was to defer cable reinforcement by introducing OLTC equipped transformers at the MV/LV level, keeping in view the future load demands and high PV penetrations.

A probabilistic load flow approach was used to investigate the effectiveness of OLTC equipped transformers against the network reinforcement. Results showed that introduction of an OLTC equipped transformer can be more economical than reinforcement in most of the scenarios.

Multiple LV networks with high PV penetration in a vast area were simulated in [8] to investigate the usefulness of OLTC equipped transformers. It was noted that use of OLTC decreased the number of LV networks facing voltage control issues. However the number of networks was relatively small where it was possible to increase the PV hosting capacity as most of the networks were facing current overloading. In [9] a typical UK underground LV network was studied with various PV penetrations and two OLTC control schemes. The first scheme was based on remote end voltage monitoring and the second was based on estimation of remote end voltages. It was found that the estimation based control scheme gave almost the same results as monitoring. The load profiles and PV sizes were typical of the UK.

Coordinated use of OLTC and three phase capacitor banks were analyzed in [10] for a UK underground LV network. Three different control strategies were proposed including remote monitoring. The switching of the capacitor was so designed that it can operate before the transformer tap changing action. Significant reduction in voltage violations was observed with the use of OLTC and capacitors. According to the results presented in [11] the PV hosting capacity of the LV network was increased from 40% to 60% with the use of OLTC. Capacity was further found to have increased to 100% by using the remote end voltage based control strategy for OLTC operation, though there will incur an additional cost for the communication system. A rural cable network has been analyzed in [12] with scattered 7 PV systems. The local control strategy was used for tap changer control. It was found that even at high PV penetrations no voltage violation was seen. It can be noted that the loads were kept high during peak PV generations, so there is no reverse power flow.

In [13] simulations of a real underground Danish LV network were carried out. The OLTC was configured to work independently for each phase and reactive power control was also applied through inverters. At a PV penetration of 70% w.r.t number of customers the OLTC control alone was unable to keep the voltage within prescribed limits. By applying reactive power control with one phase OLTC voltage remained within limits. The PV distribution was highly unbalanced among three phases in the cases studied. A distributed static synchronous compensator (D-STATCOM) along with OLTC has been proposed in [14] to mitigate the voltage violations and imbalances in an underground Flemish LV network with high PV penetration. The results show better voltage control and mitigation of voltage imbalances among phases.

Localized and Communication assisted centralized voltage control strategies were investigated in [15] for a PV rich LV network. The inverters were set to control real and reactive power locally and then in coordination with OLTC. Results showed that OLTC control when serving as primary and inverter controls serving as secondary produces the best results among all tested strategies in this study. A rural Brazilian MV network with 45 LV networks of different sizes was simulated and both the reactive power control and OLTC control were analyzed individually and collectively. The hybrid control strategy produces far less over voltage complaints during high PV penetration than the other two cases. There were some LV networks with thermal constraints and in some other LV networks only moderate penetration was tolerable. However in some LV networks up to 100% increase was observed as compared to the case with no control strategy applied.

In a recent study [16] a three phase balanced LV urban network was considered and simulations were performed to investigate the effects of RPC and OLTC control on voltage and PV penetration. A droop based tap changing control was proposed along with the droop based inverter's RPC. The results showed significant improvements in the PV hosting capacity of the LV network.

As the LV networks are more resistive in nature (higher R/X ratio) in comparison with higher voltage networks [16], reactive power control does not provide enough room for voltage adjustment in LV networks with high PV penetrations. Further the effectiveness varies from network to network owing to the nature of the network parameters and loads. The effectiveness of the use of joint Reactive Power Control (RPC) and OLTC control in LV networks has rarely been investigated [13], [16].

For the simplicity of calculations balanced three phase systems has been used in many studies [6], [16] which may not cover some of the more important aspects of unbalanced LV systems. The replacement of hundreds of thousands of MV/LV distribution transforms all over the world is a big challenge. This can be met if we consider the gradual installation/retrofitting of OLTCs on existing transformers along with the installation of new OLTC equipped transformers.

This work investigates the possible increment in network's PV hosting capacity of the typical overhead rural LV network in Thailand using OLTC, RPC and hybrid voltage control strategy (RPC & OLTC) where the retrofitting of OLTCs will be considered with the existing MV/LV transformers[17]. Active power curtailment will be applied as a last resort to avoid any disconnection due to over voltage. It should be noted that most of the studies conducted so far are based on underground cable networks [6], [10], [13], [14], [16] and many researchers use balanced three phase topology [6], [10] and [16].

Further the upgrading of network components (conductors and transformers) will be investigated for the enhancement of PV penetration as, the falling prices of PVs, and the rising targets of green energy, are pushing utilities towards maximizing their hosting capacities for PV.

The paper is divided into 4 sections: In Section 2 adopted methods for the study are presented. Section 3 comprises on results and discussion, while Section 4 describes conclusions.

II. METHODOLOGY

A. CASE STUDY NETWORK

A real domestic overhead LV network was selected from the area under the control of the Provincial Electricity Authority (PEA) of Thailand. The selected network broadly represents the typical Thai rural low voltage networks with two feeders and numerous laterals most of which are single phase. The single line diagram of the network is shown in Fig. 1.

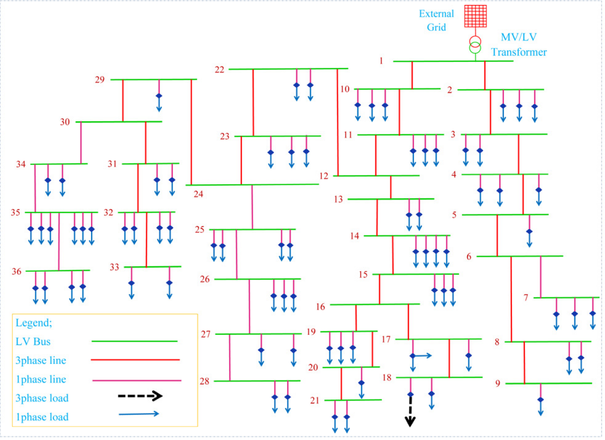

FIGURE 1. Single line diagram of typical domestic rural low voltage Thai network.

It is a three phase four wire system where a 160 KVA, 22/0.4 KV, Delta-Y connected transformer is supplying power to 77 single phase consumers and 1 three phase consumer. The single phase consumers are equally distributed among three phases to balance the currents at the transformer's terminals. Two types of aluminum overhead insulated conductors of 153 and 100 ampere current carrying capacity have been used in this network. All single phase consumers are connected between phase and neutral wire and the farthest consumer in the network is 663 meters from the transformer (TF).

DIgSILENT Power Factory software was used to model the network components. Type data required for these DIgSILENT models was provided by PEA Thailand.

The existing transformer model was modified by the retrofitting of OLTC. The same 5 tap positions as designed for Off Load Tap Changer were used for OLTC operation with a single tap step of 2.5% with respect to transformer ratings, tap 3 was assigned a neutral position. The tap changer was modeled on HV side of the transformer to avoid high currents on LV sides. The built in remote sensing feature of software was used to control the operation of the OLTC by selecting a critical node from the network.

Power Factory's Photovoltaic (PV) system model was used for load flow simulations in the network. The PV system model was configured as a static generator to supply a fixed amount of power. The amount of power supplied is considered after losses and is the actual maximum power injected into the network at that particular time interval. The nominal PV values for this amount of power will be on the higher side as they are temperature, irradiance and conversion efficiency dependent. How much nominal PV power capacity will be required for the injected actual active power varies from location to location. Loads were simulated using After Diversity Maximum Demand (ADMD) values provided by PEA. The ADMD usage may not necessarily be the worst case scenario but is the most often considered by utility organizations.

At higher penetration levels the reactive power control along with the OLTC operation was used to enhance the penetration. The inverters were modeled to supply/absorb reactive power without sacrificing the active power harnessed from PV modules. The capability of LV grid connected inverters to operate at a power factor of 0.95 is essential according to the Thailand grid connection guidelines [18], however due to low penetration levels it is rarely enforced at domestic levels.

B. DEFINITIONS AND ASSUMPTIONS

For the purpose of this study the MV grid was considered stiff and the voltage set point was taken as 1per unit (pu). The active power curtailment is considered a robust tool to cater for any sudden rise in the voltage due to local reasons or resulting from the voltage variations in MV grid. Low voltage tolerance was considered ±10% of the nominal value.

As there is no agreement among researchers on PV penetration level calculations for distribution networks [19], we prefer to use the ratio between actual PV power injected and the LV feeder actual load at that particular point of time as used in [20] and [21]. However in this study penetration level will be calculated and presented using three different approaches for better understanding.

In power systems normally maximum and minimum load conditions are considered for most of the calculations. For PV related calculations though many researchers have preferred to use feeder minimum load as it represents the worst case scenario, we in the presence of active power curtailment option in the inverters consider it a bit stringent. In this study we used the minimum feeder load during the peak PV generation hours (12pm-4pm).

The peak PV generation occurs at midday thus raising the chances of power reversal and hence over voltages at different network nodes. As the feeder load is the key parameter which by utilizing the power locally can minimize the over voltages and power reversal, hence to maximize PV penetration we used the *noon minimum load* value (12pm to 4pm) to calculate the PV penetration percentage. Analysis of the transformer's load profile revealed that minimum loading conditions does not occur during the peak PV generation hours (12pm to 4pm). We decided to use the minimum value of actual load during these hours for simulations. However a few simulations were also carried out using minimum load conditions to constitute the worst scenario and to calculate the difference in PV penetration limits between these two cases.

Unbalanced 3 phase AC load flow was used for all the simulation scenarios. Maximum load of the network was 99KW, minimum load was 34KW, and noon minimum load was 42KW. All the PV systems installed were equally divided (up to possible extent) over the three phases to minimize the unbalanced loading.

C. SIMULATION SCENARIOS

Multiple operational scenarios were considered for this study as described below.

Base Case: With no PV systems installed in the network load flow simulations were carried out in Power Factory to establish bench marks for voltages and loading positions of different network components. As the peak PV generation and peak load in domestic feeders in Thailand does not coincide like many other countries of the world, the voltages at the end of feeders must be kept within statutory limits at peak load hours. In the case of Off Load Tap Changers (which is the usual case) the tap position needs to be set so that the voltage at tail end consumer's premises must fall within statutory limits. For the base case off load tap changer was used with the transformer and starting with the neutral tap load flow was performed to find the appropriate tap position. Load flow calculations were also performed for the minimum load conditions in off peak hours without any PV in the system.

(a) PV clustered at tail. 20 houses located at end of feeders (laterals) were selected for PV system installation. PV power was injected in progressive steps to study the network behavior using load flow simulations.

(b) PV at every home. This scenario was created by assigning a PV system to all 78 homes supplied by the same transformer. The network behavior was studied as described in above case.

(c) PV scattered all over the network. Thirty five houses were selected for installation with an even distribution approach for this case. Load flow simulations were performed for different PV penetrations.

(d) PV clustered at center. PV systems were installed at 21 houses located in the central area of the network. Different PV penetrations were simulated.

(e) PV clustered close to the transformer. The cluster of houses located close to the transformer was selected to install 21 PV systems. Simulations were performed for multiple PV configurations.

Except the base case all the above cases were simulated with four different conditions as given below.

1- Transformer with fixed tap and inverter operating at unity power factor.
2- Transformer with OLTC and inverter operating at unity power factor.
3- Transformer with fixed tap and inverter operating at 0.95 leading power factor.
4- Transformer with OLTC and inverter operating at 0.95 leading power factor.

A case with minimum load and scattered PV. To estimate the difference in PV penetration caused by using the *noon minimum load* for analysis instead of *minimum load* a case was prepared using minimum load and PV was considered scattered over the network. The results were compared with the *case c* above.

A case with random PV phase selection. This case was designed to estimate the effect of single phase PV if connected randomly without careful allocation of PV connections per phase. Only condition 1 was applied for this case.

III. RESULTS AND DISCUSSION

A. BASE CASE (No PV)

With the transformer at neutral tap (tap-3) and maximum load the voltages at feeder ends were very low but were within the statutory limits. As with the low voltages and high currents, energy loss increases, so tap was raised to 4, and the resultant voltage profile improved.

The load flow carried out for feeder minimum load revealed that at tap 4 position there were no over voltages at the buses close to the transformer. Fig. 2 shows the voltages in per unit (pu) for selected buses in both minimum and maximum load conditions.

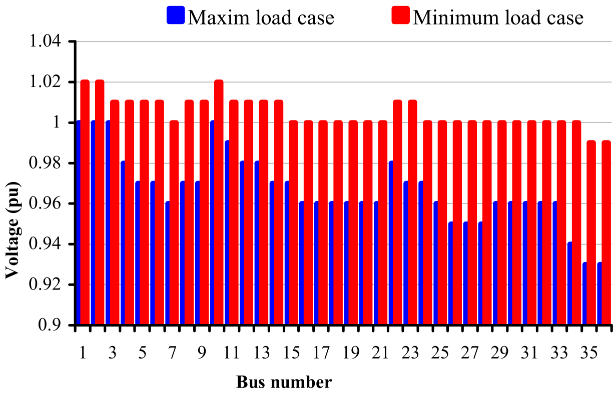

FIGURE 2. **Network voltage profile during minimum and maximum load conditions.**

It can be seen that during the maximum load condition the voltage at all buses remains well above the statuary limit (0.9 pu) and for the minimum load condition voltages at all buses remains close to nominal (1 pu). A lower tap setting is always beneficial for high PV penetrations, but it must retain the voltage at the feeder end within statuary limits during the peak load hours. The peak load in Thai domestic feeders occurs from dusk until approximately 11 PM, so during that period the voltage needs to be maintained within limits without PV support. The minimum load occurs in the morning when solar irradiance is not high, thus PV power is limited and there are no chances for voltages to rise. At noon, PV generation reaches its peak and load is slightly higher than minimum. The chances of voltages rising above limits, thus occurs only during this period.

B. PV PENETRATION SCENARIOS

The results of simulations carried out to estimate PV penetration levels for all the scenarios discussed in section II have been presented in Table 1. Interestingly the limiting

TABLE 1. Allowable PV penetration for simulated scenarios (%).

Case	Condition	% Penetration w.r.t			Limiting Factor
		Min. Load	Max. Load	TF Rating	
a	No Control	374	159	98	V &I
	OLTC	374	159	98	I
	RPC	345	146	91	I
	RPC- OLTC	345	146	91	I
b	No Control	345	146	91	V &I
	OLTC	345	146	91	I
	RPC	345	146	91	I
	RPC-OLTC	345	146	91	I
c	No Control	338	143	89	V&I
	OLTC	338	143	89	I
	RPC	338	143	89	I
	RPC-OLTC	338	143	89	I
d	No Control	300	127	79	I*
	OLTC	300	127	79	I
	RPC	276	117	73	I
	RPC-OLTC	276	117	73	I
e	No Control	350	148	92	I**
	OLTC	350	148	92	I
	RPC	350	148	92	I
	RPC-OLTC	350	148	92	I

*Max. Voltage was 1.08 pu. **Max. Voltage was 1.05 pu

factor for PV penetration in most of the cases is conductor overload. As the voltage profile is very much network dependent, this limiting factor may change over longer feeders or with various load types. For conditions one and three (i.e., Transformer with fixed tap, inverter operating at unity power factor and Transformer with fixed tap, inverter operating at 0.95 leading power factor) the transformer tap was kept at 4. In the cases a, b, and c when condition 1 was applied it was only a coincidence that at certain PV penetration levels both the voltage and ampacity limits were reached, however for cases d and e the ampacity limit was reached prior to the voltage limit, which shows that PV clustered at the center and close to the transformer contributes less towards bus voltage rise compared to other cases. PV clustered close to the transformer contributes only half the voltage rise compared with cases a, b, and c.

A transformer with fixed tap and PV inverters without Reactive Power Control (RPC) can tolerate a reasonable amount of PV (as shown in Table 1) but the voltage reaches the upper limit at most of the buses. Use of OLTC brought the voltages back closer to the nominal level for most of the busses, as shown in Fig. 3. However due to conductor ampacity limit and TF loading, more PV penetration was not possible. The ampacity limit was also a limiting factor for further PV penetration in the network under study.

The use of RPC and OLTC showed effective voltage control for high PV penetrations. The representative voltage profile for *case c* has been shown in Fig. 4. The most effective control is provided by OLTC equipped transformer where voltage remains close to the nominal. For the same amount of PV when both OLTC and RPC (power factor 0.95) were applied, voltage goes down further but at the same time current flow through the system increases, resulting in further network congestion and increased losses. RPC with fixed tap transformers helps to bring voltage down but at the expense of increased current flows.

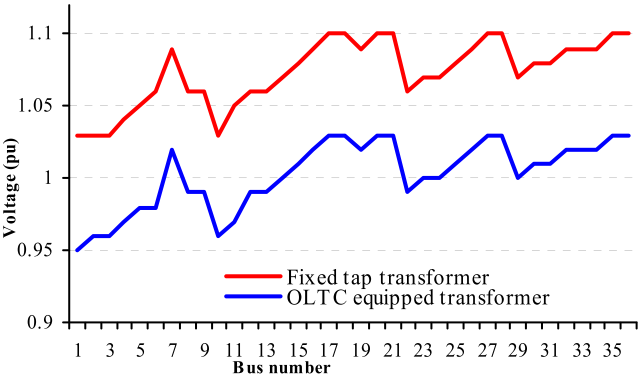

FIGURE 3. Voltage profile of case a with high PV penetration using fixed tap and OLTC equipped transformer.

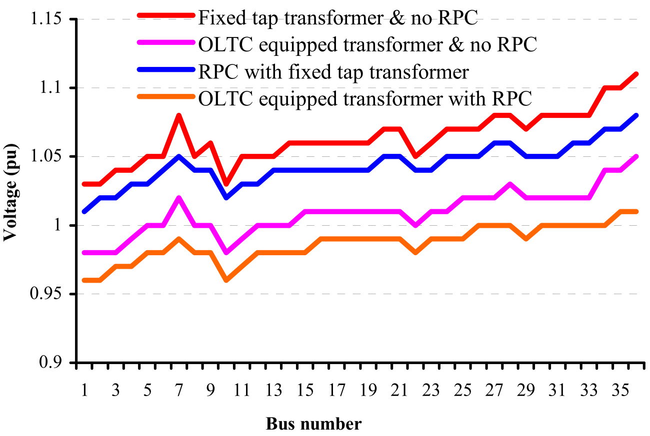

FIGURE 4. Voltage profile of case c for four different conditions.

Higher penetrations are possible with PV clustered at tails and scattered all over the network as compared to centered and near transformer clustered PVs, due to differences in the resulting current flows. However voltages rise more rapidly with PV at tails and scattered over the network when compared with close transformer PV clustering.

Case a parameters have been presented (as a representative case) in Table 2 for all four simulated conditions. It can be seen that the OLTC provides more robust voltage control than RPC. The Bus voltages dropped to the range of 1.03pu with the use of OLTC (in contrast to the fixed tap transformer case where the range was 1.1pu), but at the cost of 3% increased TF loading. In a hybrid case (OLTC and RPC combined) no significant reduction in voltage (just 0.01pu) is seen, but transformer loading increases from 84% to 91%.

TABLE 2. **Max. voltage and transformer loading at 42KW Load and 157KW PV for tail clustered PV case.**

Parameter	No Control	OLTC	RPC	RPC & OLTC
Maximum Bus Voltage (pu)	1.1	1.03	1.1	1.02
Transformer Loading (%)	81	84	90	91

Further when RPC was applied with the fixed tap transformer, the transformer loading increased 9% but voltage reduction was not seen for all Buses. Instead there was rise in voltage at Bus 7 as shown in Fig. 5. Reactive power control is not only less effective than OLTC control in this case study, it also results in congestion of the LV network. The situation for other cases studied (*Case b, c, d, and e*) was nearly the same as reported for *Case a* in Table 2.

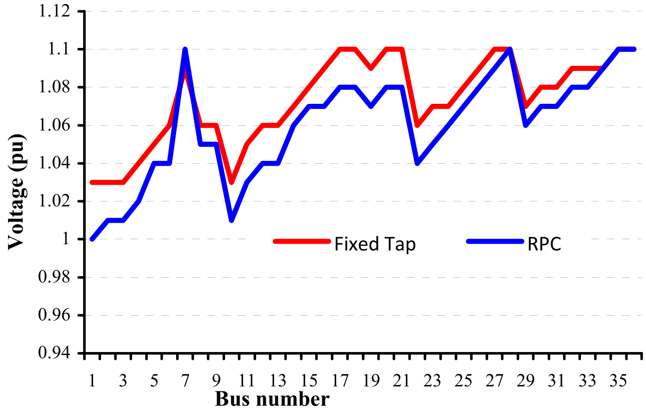

FIGURE 5. **Voltage profile of case a with high PV penetration using fixed tap and RPC (pf 0.95 leading).**

According to PEA regulations [18] PV generation of only 15% w.r.t transformer rating is allowed for LV networks. The capacity of single phase PV installation is restricted to 5KW. A case study scenario was designed to observe the behavior of the network under study for voltage rise with the maximum PV percentage allowed (15% of TF rating), and load flow simulations were performed by placing the 5KW PV systems at tails of sub-feeders to assess the maximum impact on voltage. As discussed earlier in this section, tail connected PV raises the bus voltages at a higher rate when compared to other cases.

Results revealed that maximum PV generation allowed by PEA raised the voltage at an average of 0.017pu, while the maximum increase was 0.03pu at buses closer to the PV installations when compared with the no PV case as shown in the Fig. 6. The allowed limit (15%) apparently seems very tight with regard to the voltage rise parameter. As shown in Fig.6, 25% PV penetration w.r.t TF rating, which in this case is nearly equal to the noon minimum load (95% penetration w.r.t minimum load), raises the voltage (at the farthest three buses) 0.02 pu further. The highest voltage in the network is 1.05pu which is very well below the upper limit of PEA (i.e., 1.1pu).

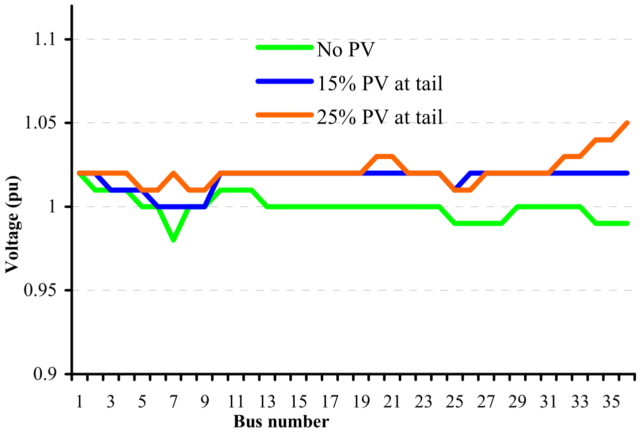

FIGURE 6. **Voltage profile of the network without PV, with 15% and 25% PV penetration.**

C. PV PENETRATION SCENARIOS CONSIDERING NETWORK UPGRADING

To estimate the possible PV penetration in the network under study with upgrading of a few conductor spans and the transformer, simulations were performed for all cases (*Case a-Case e*) applying the four conditions as earlier. The results have been summarized in Table 3. The amount of PV power injection was gradually raised in order to exhaust the voltage rise option, ignoring any other limitations like availability of roof space. Results revealed that in all other cases except *case e* (i.e., close TF clustering) the voltage upper limit was reached at very high PV penetration levels, as shown in Table 3. The increase in PV penetration that was possible with the use of higher sized OLTC equipped TF and replacement of conductors in three spans with higher sizes was between 150% -200%. With the use of RPC and the same conductors' replacement, however, increase in penetration was comparatively low. The hybrid technique, though, allowed very high penetrations (which may not be feasible otherwise) but the needed conductors' replacement is very high (40% -80% of spans). For *case e* the upper voltage limit could not be reached due to thermal limits of the conductors that connect customers.

In the case of PV installation at every home (*case b*) the penetration could easily be doubled (from 1.5KW to 3KW per home) simply with the use of a higher rated OLTC equipped transformer and the upgrading of 3 line spans.

The results demonstrate the need for a new design approach in LV distribution networks at the planning stage. The sizes of conductors/cables and transformers and tapering of conductors should be designed considering the possible PV penetration, along with the load to be supplied. A comparatively small investment can generate considerable benefits by increasing the PV penetration in the network.

TABLE 3. Allowable PV penetration for simulated scenarios (%) considering partial upgrading.

Condition	% Penetration w.r.t Max. Load	% Penetration w.r.t TF Rating	Remarks
Case a			
No Control	159	98	Few lines face high current at noon
OLTC	255	158	3 lines & TF need upgrading
RPC	223	138	3 lines & TF need upgrading
RPC-OLTC	404	250	80% lines & TF need upgrading
Case b			
No Control	146	91	Few lines face high current at noon
OLTC	239	148	3 lines & TF need upgrading
RPC	224	139	3 lines & TF need upgrading
RPC-OLTC	419	259	50% lines & TF need upgrading
Case c			
No Control	143	89	Few lines face high current at noon
OLTC	251	155	3 lines & TF need upgrading
RPC	178	110	3 lines & TF need upgrading
RPC-OLTC	462	286	50% lines & TF need upgrading
Case d			
No Control	127	79	Few lines face high current at noon
OLTC	297	184	3 lines & TF need upgrading
RPC	233	144	3 lines & TF need upgrading
RPC-OLTC	425	263	40% lines & TF need upgrading
Case e			
No Control	148	92	Few lines face high current at noon
OLTC	445	276	7 lines & TF need upgrading
RPC	445	276	7 lines & TF need upgrading
RPC-OLTC	445	276	7 lines & TF need upgrading

*Voltage upper limit reached for cases a-d.
**Ampacity limit of customer connection conductors reached for case e.

Relocation of the MV/LV transformer to a more appropriate place in some cases will result in reduction of high currents in some critical lines, thus deferring the need for line upgrading. In that case, by simply upgrading the TF, the PV penetration will be enhanced.

Interestingly, in the case studied, the upper voltage limit, conductor thermal limit, and TF loading limit occurred at nearly the same PV penetration level under the condition of a fixed tap transformer and inverters at unity power factor. However simulations performed considering the partial upgrading showed that use of OLTC and RPC can increase the penetration significantly. This finding can be generalized for any such networks where voltage upper limit is reached before the thermal limit of lines and/or the TF loading limit. The current flow can be limited locally to avoid network congestion. Storage and Demand Response (DR) can be good options to limit the reverse current flow.

In this study relatively higher PV penetrations have been found acceptable, which can be attributed to the higher capacity conductors in the feeder tails and laterals, more flexible LV voltage tolerance (±10%), careful distribution of PV systems across three phases, consideration of the MV grid as stiff, the nature of the loads, and the length of the feeder. OLTC control seems more effective and beneficial than RPC. It decouples the voltage control from the MV system and avoids network congestion. Retrofitting of OLTCs with the existing transformer can be worthwhile, as it provides effective control and, due to higher voltage step (2.5%) per tap, a reduced number of tap changes during the operation.

D. SPECIAL SCENARIOS

1) MINIMUM LOAD VS. NOON MINIMUM LOAD

Only case c (even distributed PV) was chosen to investigate the difference between the results with *minimum load* and *noon minimum load*. A reduction of 3%-5% in line loading and 4%-5% in transformer loading was observed for the *noon minimum load* compared to the *minimum load*, as shown in Table 4. The use of *noon minimum load* for calculation thus provides the benefit of a little more room for PV penetration.

TABLE 4. Critical line and transformer loading at min. and noon min. load with 142KW PV for even distributed PV case.

Condition	Parameter	Minimum	Noon
	Load (KW)	34	42
	PV (KW)	142	142
No Control	Critical Line Loading (%)	101	98
	Transformer Loading (%)	92	88
OLTC Control	Critical Line Loading (%)	101	96
	Transformer Loading (%)	92	87

2) RANDOM CONNECTED SCATTERED PV

In this case, PV systems were connected randomly across the network and phase distribution was kept random too. The results were compared with the previously discussed case c, and it was found that with the random distribution among phases, less PV was tolerated by the network. As shown in Table 5, the total PV installation was reduced by 12% and current in the critical line was increased, violating the thermal limits. However there were no significant changes in voltage profile in either case, as shown in Fig. 7.

TABLE 5. Difference of penetration between equal and random distribution of PV among phases.

Case	Parameter	Minimum
Equal PV distribution among phases	PV (KW)	142
	Critical Line Loading (%)	98
	Transformer Loading (%)	88
Random PV distribution among phases	PV (KW)	125
	Critical Line Loading (%)	103
	Transformer Loading (%)	88

Special attention must be paid to the phase distribution of single phase PV systems. Unequal distribution of PV among phases can negatively affect the penetration level and system.

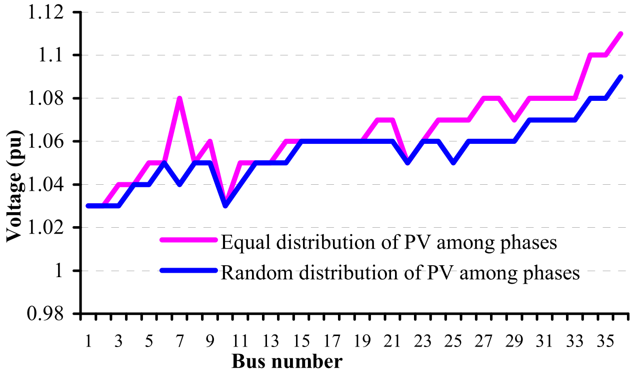

FIGURE 7. Voltage profile with equal and random distribution of single phase PV systems.

IV. CONCLUSION AND RECOMMENDATIONS

This work was undertaken to estimate the possible PV penetration in a domestic rural overhead LV network. Five different PV configurations were simulated for multiple voltage rise mitigation techniques in a case study based on a real network considered typical for rural areas of Thailand. Simulation results revealed that relatively higher amounts of PV generation (79%-98% w.r.t TF) could be tolerated by such networks owing to many reasons, such as a wider voltage tolerance band, larger conductor diameters, and moderate lengths of feeders. The level of penetration can be further increased by using OLTC, RPC and partial network upgrading. The thermal limits of some critical lines and the transformer become limiting factors in addition to the voltage rise above statutory limits. The use of OLTC, RPC, and the combination of both was found very effective for voltage control. However, to resolve the ampacity limit issues, upgrading of a few lines and the transformer is required. Thus PV penetration will be increased further (an additional 50%-90%). Although the PV penetration level is very much network dependent, the results of the cases studied are in line with the findings of [8], [12], [15], and [22]–[24]. From the results it can be concluded that by using OLTC and RPC, voltage was controlled effectively without violating statutory limits. Furthermore retrofitting the existing transformer with an OLTC can be just as effective as installation of a new OLTC equipped transformer. Providing reactive power control by the use of slightly oversized inverters can bring many benefits to the power system in addition to PV penetration enhancement. The electricity utility companies will be able to review the grid codes in light of these findings to absorb more PV.

The flow of the current across the network requires upgrading of the system components. In order to minimize the current flow, local storage and demand response strategy needs to be integrated. The use of Battery Storage Systems (BSS) at the MV/LV substation is more effective for voltage rise control in an MV network, as it limits reverse power flow. Integrating the BSS with the roof top PV can limit the current flow towards the transformer, thus resolving ampacity issues. Investigations in those areas will also be helpful in developing a framework for high PV integration in LV networks.

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