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# A Stochastic Assessment of PV Hosting Capacity Enhancement in Distribution Network Utilizing Voltage Support Techniques

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**ABSTRACT** The low voltage (LV) network's constraints are prone to violations with the introduction of distributed energy resources at the customer vicinity. This study assesses the technical aspects of the realistic Finnish distribution network with varying photovoltaic (PV) penetration and quantifies the hosting capacities (HCs) of different regions. Moreover, to maximize the network's HC, having the overvoltage issue, different voltage control strategies are employed comprising on-load tap changer (OLTC), reactive power control (RPC) of inverters, network reinforcement (NR), and hybrid approaches. HC relative to different country-specific over-voltage limits are defined and the best voltage control technique is assessed, utilizing the stochastic approach of Monte Carlo simulations to model the uncertainty in the LV network's probabilistic variables. Moreover, combined medium voltage (MV)/LV network simulations are conducted to compare with the LV only simulations results. Technically, NR is the best approach to maximize the HC of a particular region but economically it is not proven a feasible one. The results presented that the OLTC employment will maximize the PV penetration if the overvoltage limit derived from EN 50160 is implemented and doubles the HC in the stricter-voltage-limits' scenarios, which can be maximized by the RPC inclusion in cohesion with OLTC. Moreover, RPC only strategy can be employed in the cases of low PV penetration scenarios, when OLTC will be proven the more expensive option. As the voltage violation limit becomes stricter, the hybrid approach of OLTC and RPC will be the best strategy.

**INDEX TERMS** Hosting capacity, photovoltaic systems, on-load tap changer, reactive power control, distribution network.

## I. INTRODUCTION

Increasing emphasis on greenhouse gasses emission-reduction is transforming the distribution network towards the modified distribution system. Bidirectional power flow is becoming a norm with the introduction of distributed energy resources (DERs) in the network's downstream. Finland aims to reduce the greenhouse gasses emission by 80-95% until 2050 [1], leading to the exponential rise in the PV installations. However, due to the conflict of interest between the DER owners (a large number of DER integrations) and the distribution system operators (DSOs) (limited integration of DERs to abide by the standards), defining the upper limit of DER integration in the network is the main issue. Therefore,

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maximum hosting capacity (HC) of a network, if known, will be beneficial for the DSO to make amends in the grid codes, to maximize the DER incorporation in the distribution network.

Large integration of photovoltaics (PVs) in the distribution network, leads to the voltage rise above the defined standard [2] that traditionally requires the grid reinforcement, increasing the grid integration cost of DERs. In medium voltage (MV) network, on-load tap changer (OLTC) and reactive power control (RPC) are viable options but for the low voltage (LV) networks normally the off-load tap changer is available that maintains the voltage at the distribution transformer (DT) vicinity. Traditionally, primary substations utilize OLTC transformers but in LV networks, their cost is the bottleneck [3]. However, with the increasing PV penetration, the OLTC equipped DT can be an option that can

enhance the HC in the LV networks and its use has to be reconsidered.

Several studies for maximum HC determination have been made utilizing OLTC in the LV networks. In [4], the effect of OLTC on HC is studied, based on Dutch LV networks. The results indicate that the OLTC is monetarily more effective in comparison with cable reinforcement. Finnish LV networks for rural, intermediate and urban regions are investigated in [5] with balanced and unbalanced PV integration. OLTC improves the HC in the balanced PV scenario with little impact on the unbalanced PV incorporation. In [6], Swedish suburban and rural networks are investigated for the maximum HC of PVs. Overvoltage and thermal overloading are the limiting factors determined and the positive impact of OLTC implementation on HC is validated. In [7], several LV networks are simulated to check the OLTC performance. The observations show the significant increase in the HC. Moreover, in [8], a comparison is made for UK LV networks between two different OLTC operation scenarios; one with remote-end sensing capability and the other with the estimation based operation. The results show the monetary benefits of the estimation-based strategy while having the same voltage control benefits as the remote-sensing scenario. The results of [9], depicts the increase in HC up to 60% with local monitoring (DT bus bar) based voltage control, while remote (last node) monitoring will further enhance the PV penetration to 100%. In [10], a UK's rural network is investigated for high PV penetration with local monitoring based control of OLTC. The result signifies that the voltage problem is not the limiting factor even in very high PV penetration scenarios. However, the simulations considered the peak loading that increases the self-consumption and does not represent the worst-case scenario.

For HC enhancement, RPC and active power control (APC) [11] of PVs utilizing smart inverters are also investigated in the previous researches. Moreover, some countries have their own specific guidelines for DER integration. For instance, in German LV guidelines, the PVs that are not controlled by the utilities and are having the installed capacity less than 30kWp, have a limitation on active power feed-in i.e. at most 70% of the installed capacity can be integrated [12]. Moreover, for voltage regulation using RPC, DERs having a capacity less than 13.8kVA can have a minimum power factor (PF) of 0.95, while for larger than 13.8kVA, PF can be lowered down to 0.9 [13]. However, RPC is mostly implemented in the MV distribution networks due to the smaller R/X ratio. In LV networks, APC is considered more effective than the RPC as R/X ratio is greater than one. Furthermore, RPC strategy also depends on the loading type and network parameters (e.g. cables or overhead lines). Various researches were published on the RPC based HC enhancement strategies. In [14], [15], distribution grids are simulated for the HC determination. Overvoltage and thermal loading are found to be the HC limiting factors and RPC is proven an effective tool in increasing the HC of the specific networks. In [16], combination of OLTC and droop based RPC is applied, to enhance

the HC of the urban LV network. Furthermore, in [17], different OLTC and RPC scenarios are implemented in Thailand's LV network to gauge the HC enhancement potential of the network. OLTC and RPC scenarios are simulated alone as well as in tandem. The hybrid approach enhances the HC to the maximum.

In the literature review conducted, almost all the studies have considered a stiff voltage value of one per unit at DT, which is not a realistic scenario. The DT present farther downstream of the MV network will have a deviation in the voltage value due to the voltage drop. Moreover, the voltage violation standard usually utilized is EN 50160 i.e.  $\pm 10\%$  of the nominal voltage. However, in German LV guidelines, maximum voltage rise at the point of common coupling should not be more than 3%. Therefore, considering the larger violation band might overestimate in the HC quantification. Furthermore, the commercially available OLTC's tapping option should also be considered. Most of the studies are either only considering LV network or MV network in the HC determination calculations. However, a complete distribution network simulation will give numbers that are more accurate to the HC of a particular network.

This paper investigated the HCs of a typical Finnish distribution networks, with different overvoltage standards and defines the limiting constraints. Finnish LV networks are characterized by their small DT capacity, MV network spread very close to the customer proximity and sparsely populated regions. The stochastic framework (Monte Carlo simulation) is utilized in order to cope with the probabilistic variables, for instance, solar irradiation, customer loading, the probability of PV incorporation with a specific node etc. Moreover, the effects of the network reinforcement, OLTC, RPC and hybrid approaches for various PV integration scenarios are investigated and HC enhancements are quantified. The limiting factors are defined for each scenario and different strategies are utilized to maximize the HC of the LV network. Moreover, a complete distribution network (MV/LV) is also simulated to compare it with the observations of the LV only simulations.

## II. PRELIMINARIES

### A. HOSTING CAPACITY (HC)

The HC is defined as “the ratio of the total installed PV capacity of the network and the feeding transformer's capacity”. However, some of the researches utilized network loading as the HC scaling factor but the reference is not static as the load changes are quite frequent and depends upon the region-specific network topologies. Therefore, to keep the HC values consistent, transformer capacity is selected as a reference in HC determination algorithms.

### B. PV/OLTC PENETRATION

PV penetration is defined as “the percentage of PV-installed nodes in the LV network”. Several PV penetration scenarios, with their randomness intact, will be implemented in this

**TABLE 1. Test networks for different regions.**

Region	No. of Feeder	Nodes per Feeder	Total Customers
PR	1	8	8
IN	3	4,3,3	40
PU	3	2,2,1	300

study to make the study as close as possible to the realistic scenarios. Similarly, OLTC penetration is the percentage of OLTC installed secondary-substations in the MV network.

**C. LV NETWORK DATA AND LIMITING CONSTRAINTS**

LV test networks utilized for the HC determination were formulated in [5] and are presented in Table 1. The detailed description of the networks is in Appendix, Table 9. The length and number of feeders for the LV networks were quantified by considering the voltage drop and transformer capacity constraints, respectively. The constraints that will be utilized for the HC determination are:

1. Load flow convergence (E1)
2. Under voltage limit (E2)
3. Over voltage limit (E3)
4. Negative sequence voltage unbalance (E4)
5. Cable ampacity violation (E5)
6. Neutral wire ampacity violation (E6)
7. Transformer capacity violation (E7)

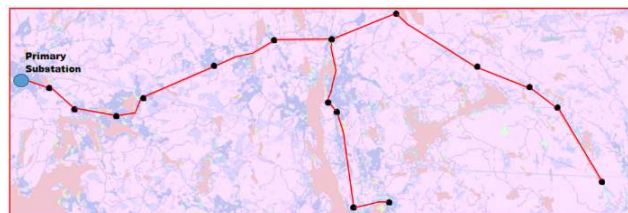
The constraints E2-E4 are derived from the voltage standards and the remaining are the equipment specific limitations. The loading data utilized is of three types, segregating regions into Predominantly Rural (PR), Intermediate (IN) and Predominantly Urban (PU), based on the region-specific percentages of heating modes, as presented in the appendix, Table 10 and was collected in [18]. The Eurostat classification method is utilized that divides the countries into different regions based on the Nomenclature of Territorial Units of Statistics (NUTS) [19].

**D. SOLAR POWER DATA**

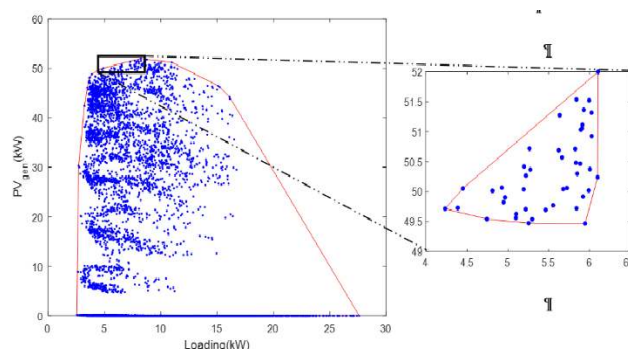
A one-year solar power data is utilized for the PV integration at the nodes, modeled based on the Helsinki region, Finland [20]. The panels are tilted 45° southwards. The power curve obtained gives the theoretical maximum of the PV generation, utilizing the location’s weather conditions and a detailed PV-panel’s power generation model.

**E. MV NETWORK**

For the whole distribution network (MV/LV) simulations, a Greenfield network plan is studied that is formulated utilizing actual loading and geographical data [21], as presented in Figure 1. The distribution network has sixteen 20/0.4 kV secondary substations and a 110/20kV primary substation. There are two radial feeders and the longer one is around 24 km in length. The details of the network are provided



**FIGURE 1. Single line diagram of the greenfield MV network.**



**FIGURE 2. Plot showing the WC hours, selected for the PR region.**

in Appendix, Table 11. Each MV node has an LV network attached to it, having region specific nodes and feeders, presented in Table 1. Moreover, only the overhead lines (OHL) are considered in the planning of the MV network.

**III. HC DETERMINATION METHODOLOGY**

**A. WORST-CASE (WC) HOUR SELECTION CRITERIA**

WC-hours of a particular region are based on the data set pair that represents the maximum PV generation and minimum loading. For the determination of WC hours, data for the whole year is plotted and the data sets from the upper left corner of the convex hull are chosen for the HC determination. Figure 2 demonstrates the stated idea.

**B. LV NETWORK SIMULATIONS**

Figure 3 depicts the algorithm employed for the calculation of the HC of various regions in the LV only simulations. The algorithm comprises three stages. Stage 1 defines the network parameters particular for different regions. Moreover, PV penetration and module size are also defined. Stage 2, constituting 1000 iterations, commences with the determination of the loading data dependent on the region selected, in order to commence with the WC-hours’ calculation. The WC data set is modified based on the loading scenario (based on the heating mode percentage), hence randomizing the load for the region. After the WC hours are selected, in order to calculate the violated constraint, 10 iterations are made from the selected data set. The algorithm quits as the total violations of a particular constraint exceeds 2.5 % of the total iterations.

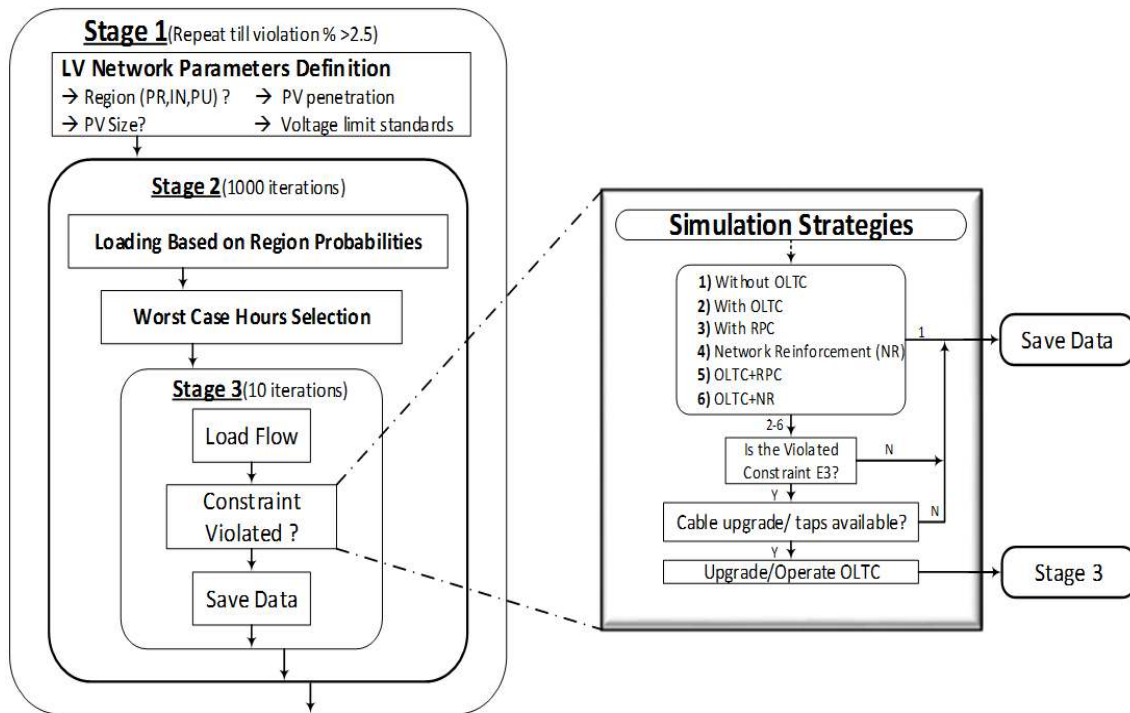


FIGURE 3. MC based algorithm to determine the HCs of the LV networks with various strategies.

C. COMBINED MV/LV SIMULATIONS

As for combined MV/LV simulations, the following steps are simulated.

Step 1: MV network parameters are defined that includes

- Number of nodes and MV line parameters
- PV penetration percentage
- Distribution Transformers’ OLTC penetration percentage
- PV system size

Step 2: In the start of the each iteration, MV network nodes are randomly sampled to select the OLTC and PV integrated nodes, based on the defined penetration levels.

Step 3: LV network parameters are defined, as were in the LV only simulations

Step 4: Integrated load flow, considering both MV and LV networks, is conducted and the network constraints are checked for the violations.

Step 5: Steps from 2-4 were repeated for 1000 iterations. If the total number of violations detected are less than 2.5%, of the iterations simulated, PV value is incremented by a step value. On the contrary, the data will be saved and the simulation will be terminated.

D. NETWORK REINFORCEMENT ALGORITHM

The NR algorithm employed had the following steps:

- If the violated constraint is E3, starting from the line segment closest to the transformer, upgrade to the next conductor size available. Following up-gradation,

run load flow and check for the constraint violation. If E3 violation persists:

- 1 Reinforce the same cable segment with the next bigger conductor until the conductor inventory is exhausted, before moving on to the next line segment (NR 1).
- 2 Reinforce the next cable section with the same conductor size, until the whole network is upgraded to a bigger conductor. If still, the E3 problem exists, again start from the branch closest to the transformer and upgrade it with the next conductor size (NR 2).

- The algorithm quits, when E3 is no more the limiting constraint or when all the cable sections are replaced with the largest conductor size available.

IV. LV CASE STUDIES

A. SIMULATION SCENARIOS

To study the impact of various HC enhancement techniques, different strategies are employed, which are:

- Without OLTC (Base Case)
- With OLTC tapping options
  - ±10% of  $U_n$
  - ±4% of  $U_n$
- With Network Reinforcement (NR)
  - Reinforcement Scenario 1 (NR 1)
  - Reinforcement Scenario 2 (NR 2)



**TABLE 2.** LV networks' mean HCs and limiting constraints with different E3 limits.

Region	$\Delta U$	Balanced (3-Phase)		Unbalanced (1-Phase)	
		Limit	$\mu_{HC}(\%)$	Limit	$\mu_{HC}(\%)$
PR	+10%	E3	105.266	E4	24.772
	+5%	E3	54.192	E3-E4	24.779
	+3%	E3	35.608	E3	17.035
IN	+10%	E7	110.316	E4	58.057
	+5%	E7	110.308	E4	58.059
	+3%	E7	110.326	E4,E3	58.056
PU	+10%	E7	107.832	E6,E4	40.798
	+5%	E7	107.811	E6,E4	40.795
	+3%	E7	107.809	E3	37.878

Moreover, all the scenarios presented above are studied for different overvoltage violation limits:

- +10% of  $U_n$  case (EN 50160 [22])
- +5% of  $U_n$  case
- +3% of  $U_n$  case (German LV standard [13])

### B. BASE CASE: WITHOUT OLTC

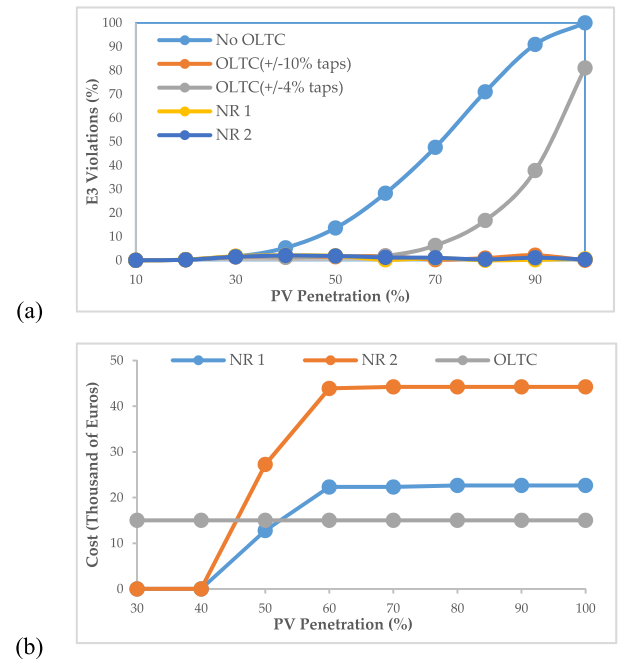
The simulation results with conventional transformers are presented in Table 2. Two sets of simulations were conducted for balanced and unbalanced PV integration in the network. Moreover, various voltage standards are utilized in the constraint violation studies. In this case, MV voltage drop is assumed 0%. The observed results signify that in the unbalanced PV integration scenario, mainly the unbalance related constraints limit the HC of all the regions, except in German LV standards. Moreover, IN and PU regions' HCs are limited by transformer capacity (E7) constraint. However, in the PR region, E3 is the limiting constraint, in all the balanced PV integration scenarios. Therefore, it can be concluded that in the PR region there is still room for HC increment with the application of different voltage support strategies.

### C. WITH OLTC TRANSFORMER

As per HC values, presented in the previous section, only PR region is limited by the E3 constraint that can be alleviated by the installation of OLTC transformer at the secondary substation and can enhance the region's HC. Table 3 presents the effect of the OLTC inclusion on the network's HC and their limiting constraints. For the commercially available OLTC transformer, GRIDCON transformer data is utilized that comes with the maximum of nine on-load tapping steps. The utilized range of tapping for these simulations is  $\pm 4\%$  [23]. The range of tapping is selected considering both the high PV generation scenario as well as the high loading scenario in which E2 is the limiting factor. The results depict that OLTC inclusion increases the HC greatly. Both tap ranges, slightly increase the HC in +10% overvoltage limit case with the shift of limiting constraint to E7. Further increment in HC will require a transformer with larger capacity. However, in the remaining two scenarios, E3 remains the limiting factor. OLTC inclusion more or less doubled the HC, with slightly

**TABLE 3.** PR region's HCs and limiting constraints with and without OLTC.

$\Delta U$	Without OLTC		With OLTC (A)		With OLTC (B)	
			$\pm 10\%$ tapping		$\pm 4\%$ tapping	
	Limit	$\mu_{HC}(\%)$	Limit	$\mu_{HC}(\%)$	Limit	$\mu_{HC}(\%)$
+10%	E3	105.26	E7	113.03	E7	113.02
+5%	E3	54.19	E3	100.65	E3	91.34
+3%	E3	35.60	E3	80.52	E3	71.23

**FIGURE 4.** (a) Comparison of E3 violation percentages, (b) Reinforcement cost vs OLTC employment cost.

more in case of larger tapping range of case A in comparison to case B.

### D. OLTC VS NETWORK REINFORCEMENT (NR)

The simulation results presented in previous Section quantify the HC of the network with 100% PV penetration, however, 100% penetration is far from the realistic PV integration scenario. This section simulates the HC determination algorithm for varying penetration of PV to observe the effect on the E3 violation percentage. The maximum PV value attached per node is restricted to the 10kW value. Moreover, NR scenarios are also considered for comparison with the OLTC based cases. Traditionally, DNOs usually tackle the load growth problem with the network up-gradation to a larger diameter conductor, for voltage drop and cable-ampacity violation removal that in turn can reduce the voltage-rise problem as well.

Figure 4 (a) depicts the results of the rural LV network's sensitivity to over-voltage violations with varying PV penetration. Without OLTC, E3 will be the limiting constraint above 30% PV penetration. With the application of OLTC (tapping range of  $\pm 10\%$ ), the over-voltage problem can be eradicated. However, with the commercially available OLTC

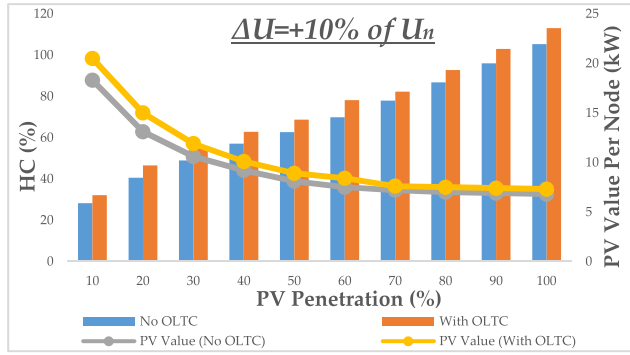


FIGURE 5. HCs and PV values per node with varying PV penetration, with and without OLTC.

transformer taps, E3 will be the limiting factor above 60% of the PV penetration scenarios. Moreover, the overvoltage problem is not observed with the implementation of the NR strategies.

The analysis conducted for the economic assessment assumes the investment on the OLTC transformer to be 4 times the price of the normal distribution transformer price of the same capacity, as presented in [9]. Moreover, the investment cost for NR strategy is taken as mentioned in [24]. The installation cost of the cable is assumed to be 24 £/m (ordinary environmental conditions). The costs related to cables and transformers are presented in Appendix, Table 12. The analysis of the results with varying PV penetration, presented in Figure 4 (b), depicts that the NR strategies will lead to a larger investment in comparison to the OLTC when the PV penetration is 60% or more. Moreover, NR 2 strategy costs more, in contrast to NR 1, despite utilizing smaller conductor wire. The analysis depicts that installation price has more impact on the reinforcement scenarios. For instance, in 70 % PV penetration case, scenario 1 requires three-cable segment replacement in comparison to scenario 2 that requires all the network cables to be replaced with a larger conductor. Moreover, the installation price considered in this analysis are for the ordinary environmental conditions. As the conditions for the installation worsen, the price almost becomes double.

**E. HC RELATIVE TO OVERVOLTAGE LIMIT OF +10%**

The previous section demonstrates the effectiveness of the OLTC and NR strategies, with respect to E3 violations reduction and their economic comparison. OLTC employment was proven the cost-effective option for HC enhancement in Finnish LV networks. In order to calculate the maximum PV capacity that can be connected per penetration level, another set of simulations is conducted.

Figure 5 demonstrates the rising HC trend with PV penetration increment in the network. However, without OLTC, E3 remains the limiting factor. Moreover, at 10% PV penetration, more or less 18kWp PV can be attached per node, which plummets to 6.8kWp at 100%. The increase in the HC and in the per-node PV value is evident, with the employment

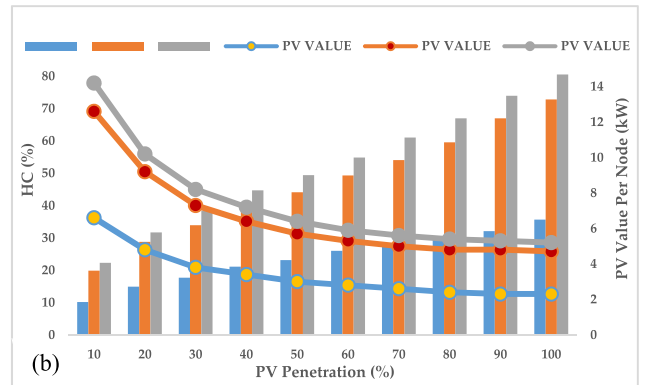
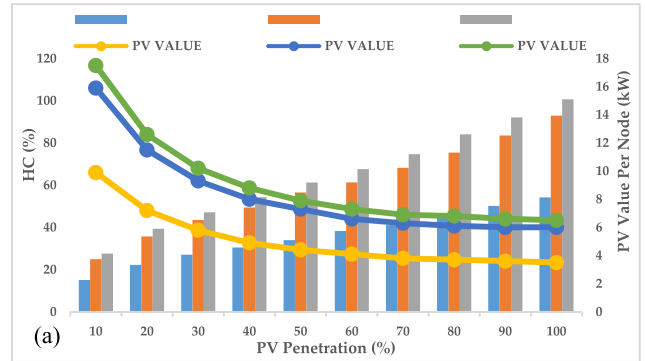


FIGURE 6. Comparison of different scenarios' HC and PV values per node for overvoltage limits of. (a) +5% of  $U_n$  (b) and +3% of  $U_n$ .

of OLTC. Moreover, transformer capacity is limiting the HC rather than the overvoltage. The minimum tap position attained by the transformer in any of the MC simulation iterations was 0.98 per unit. Therefore, it can be concluded that if standard EN 50160 is observed in the LV network, HC can be enhanced to the theoretical maximum value, with the commercially available tapping options of OLTC transformers.

**F. HC'S FOR OVERVOLTAGE LIMITS OF +5% AND +3% WITH DIFFERENT STRATEGIES**

Figure 6 (a) and (b) depict the HC increase with the employment of different tapping ranges of OLTC, for +5% and +3% overvoltage limits, respectively. The largest PV value per node is for the minimum PV penetration (10%) that tends to decrease as the penetration increases. However, E3 remains the limiting constraint for all the different cases that are simulated for the both stated standards. The resulted HCs for the OLTC based cases are risen up to twice of the base case value but the  $\pm 10\%$  tapping-case has slightly larger HC value compared with the  $\pm 4\%$  tapping-scenario.

**G. HC COMPARISON OF DIFFERENT STRATEGIES FOR STRICTER OVERVOLTAGE LIMITS**

With the employment of OLTC, network's HC is enhanced but E3 still remains the limiting constraint. This section will employ NR and RPC strategies, solitary and in tandem

**TABLE 4.** HC values of different scenarios with different overvoltage limits.

Limit	+5% of $U_n$				+3% of $U_n$						
	E3		E7		E3			E7			
	Base Case	OLTC	RPC (0.975)	NR	Base Case	OLTC	NR	RPC (0.975)	RPC (0.95)	RPC (0.975) + OLTC	OLTC + NR
10	15.1	27.57	24.38	31.2	10.1	22.27	26.6	15.48	19.91	23.75	30.32
20	22.2	39.3	34.61	44.9	14.9	31.66	38.1	22.60	29.23	34.65	44.24
30	27.1	47.15	42.86	54.1	17.7	38.39	46.2	27.47	35.60	41.46	52.65
40	30.5	54.24	47.72	60.3	21.1	44.67	53.1	32.39	39.28	46.74	58.80
50	33.9	61.22	51.96	67.5	23.1	49.37	59.6	37.15	42.54	50.12	65.11
60	38.3	67.59	60.53	75.9	26.0	54.83	65.9	40.82	50.16	58.40	74.52
70	41.1	74.67	62.67	80.3	28.3	61.01	73.6	45.56	52.10	60.37	79.05
80	45.8	84.04	70.41	90.2	29.8	66.94	81.7	49.54	59.53	69.41	86.87
90	50.2	92.12	79.27	98.9	32.1	73.93	90.6	55.70	65.50	76.68	96.30
100	54.2	100.7	86.71	110	35.6	80.52	99.1	61.93	72.78	85.18	106.84

with OLTC, to enhance the HC to its maximum (remove E3 as the limiting factor), within the stricter overvoltage limit.

Table 4 presents the HC's of the different scenarios studied. In the case of +5% overvoltage limit, OLTC was not able to remove the E3 violation, but doubled the HC of the network. However, the RPC strategy changed the limiting constraint to E7 but the HC quantification leads to a smaller value than the OLTC employment scenario. However, at small PV penetration, the difference between the HC values of the OLTC and RPC strategies are small and the decision between the employments of the two strategies will be dependent on the economically feasible option. Moreover, the largest HC values are obtained for the NR scenario, but this strategy is not a cost-effective solution. Therefore, the best strategy for improving the HC in +5% overvoltage violation limit scenario is the OLTC employment.

Moreover, for +3% limit scenario, all the strategies when employed alone will enhance the HC in comparison to the base case but the E3 remains the HC's limiting constraint. Therefore, the combinations of different techniques are employed. Maximum HC is observed in the scenario when OLTC employment is assisted with the partial up-gradation of the network's cables to the larger conductor. However, the investment to gain ratios and PV penetration levels should be evaluated before considering RPC or NR in tandem with the OLTC employment.

## V. COMBINED MV/LV CASE STUDIES

### A. SIMULATION SCENARIOS

Combined MV/LV network study is performed for different overvoltage mitigation strategies; however, the LV-network's reinforcement strategy is not considered. The considered scenarios are:

- Without OLTC (Base Case)
- With OLTC
  - Varying penetration of OLTC and PV
  - Random OLTC penetration
  - OLTC with the PV penetrated LV feeder

**TABLE 5.** Rural distribution network's HCs and limiting constraints with and without OLTC.

$\Delta U$	Without OLTC		With OLTC $\pm 10\%$ tapping		With OLTC $\pm 4\%$ tapping	
	Limit	$\mu_{HC}$ (%)	Limit	$\mu_{HC}$ (%)	Limit	$\mu_{HC}$ (%)
+10%	E3	89.81	E7	113.48	E7	113.50
+5%	E3	46.45	E3	86.705	E3	78.96
+3%	E3	30.96	E3	71.213	E3	61.94

- PV Clustering
- MV network reinforcement
  - Larger diameter of overhead conductors
  - Replacement of OHL with underground cables

### B. BASE CASE: WITH AND WITHOUT OLTC

In LV only simulations, the effect of MV network was not completely taken into account. This section studies the realistic distribution network consisting of MV and LV networks to quantify the HC values as accurately as possible. Table 5 presents the HCs and their limiting constraints with and without OLTC employment. Comparison of this section's simulations with the LV-only simulations (Table 3) depicts that with the MV network consideration, LV network's HC is decreased by a minimum of 10 % in all the simulated scenario of the base case (No OLTC). However, the limiting constraints and the HC decreasing trend with the reducing overvoltage-limit, remain the same i.e. E3 is still limiting the HC in the stricter overvoltage violation criteria.

### C. HC'S RELATIVE TO OLTC PENETRATION

In the base case, both the penetration of PV and OLTC is taken to be 100% (all the nodes in the MV network have OLTC and all the nodes in LV have PV). However, to analyze the effect of the varying percentage of the OLTC on the HC, two scenarios are simulated:

- Scenario 1: Random allocation of OLTC penetration
- Scenario 2: OLTC penetration starting from the far end

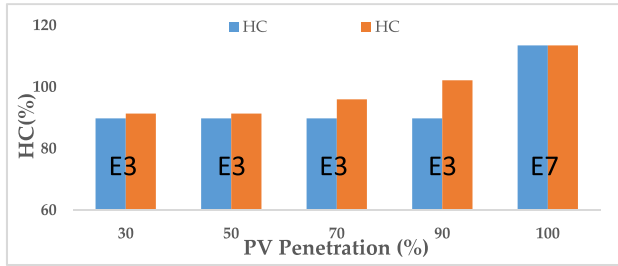


FIGURE 7. PV penetration with varying percentages of the OLTC, for the overvoltage limit of +10%.

The PV penetration is assumed to be the maximum, in both scenarios. The simulated results for overvoltage limit of +10% are presented in Figure 7, which depicts that the random allocation of OLTC will not affect the HC of the network in comparison to the base case. However, a slight increase in HC is observed as the OLTC is distributed, starting from the end of the feeder, until the 50% OLTC penetration level. Above 50% penetration, the increment margin increases with the increasing OLTC penetration. Moreover, E3 violation in LV network remains the limiting constraint until the 100% OLTC penetration is reached that changes the constraint to E7. The results depict that if the OLTC penetration is less than 100%, the LV feeder without OLTC will violate the E3 limit way before the OLTC equipped feeders. However, in the MV network all the constraints are within the allowed limits.

The similar trend of the HC variation with changing OLTC penetration is seen for the overvoltage limits of +5% and +3%. However, 100% penetration of OLTC was not able to remove the E3 limit in both the cases.

**D. PV CLUSTER SCENARIOS**

In the above simulations, the PV penetration is taken to be 100%. However, there is a possibility of PV clustering based on the MV network nodes. For the study of PV clustering effect on the network’s HC, the following scenarios are considered.

- PV clustered at the end of the MV feeder (S1)
- PV clustered closest to the transformer (S2)

To evaluate the OLTC penetration effect, different OLTC integration cases are studied:

- Without OLTC (Case 1)
- With random OLTC employment (Case 2)
- OLTC with the PV Penetrated LV feeder (Case 3)

The results of the simulations are presented in Table 6. The results signify that the PV cluster at the end of the MV feeder will have slightly reduced HC in comparison to the PV cluster closer to the primary transformer. Larger HC quantification, in S2, will increase the PV per node value i.e. the larger PV system can be incorporated closer to the transformer. The random OLTC inclusion will not have any effect on the network’s HC. However, the OLTC employment with the PV installed LV feeder will maximize the HC and

TABLE 6. HC values for various overvoltage limits in different PV clustering scenarios.

Case	ΔU	+10%		+5%		+3%	
		μ <sub>HC</sub> (%)	Limit	μ <sub>HC</sub> (%)	Limit	μ <sub>HC</sub> (%)	Limit
1	S1	95.99	E3	51.07	E3	32.52	E3
2		96.02	E3	51.08	E3	32.51	E3
3		113.03	E7	96.01	E3	77.42	E3
1	S2	103.74	E3	54.19	E3	35.61	E3
2		103.75	E3	54.19	E3	35.61	E3
3		113.01	E7	102.2	E3	82.08	E3

TABLE 7. HC values for the varying PV and OLTC penetration scenarios.

PV Pen. (%)	Case	+10%		+5%		+3%	
		LV μ <sub>HC</sub> (%)	limit	LV μ <sub>HC</sub> (%)	limit	LV μ <sub>HC</sub> (%)	limit
30	1	99.09	E3	54.20	E3	35.61	E3
	2	113.03	E7	94.46	E3	75.87	E3
50	1	94.45	E3	52.65	E3	34.06	E3
	2	112.99	E7	89.82	E3	72.78	E3
70	1	92.91	E3	49.54	E3	32.51	E3
	2	113.05	E7	88.25	E3	71.22	E3
90	1	89.79	E3	48.00	E3	32.51	E3
	2	113.02	E7	86.71	E3	69.68	E3
100	1	88.26	E3	46.45	E3	30.97	E3
	2	113.04	E7	86.71	E3	71.21	E3

E7 will be the limiting constraint, in +10% overvoltage limit case. In S2, the increment in HC is 8% compared with S1. In cases of +5% and +3% overvoltage limits, the HC increment is almost twice in the OLTC employment case, with E3 limitation defining the HC.

**E. HC’S FOR VARYING PV AND OLTC PENETRATION**

To calculate the maximum HC for a particular penetration level of OLTC and PV, two scenarios were simulated and compared. The cases implemented are:

- Without OLTC (case 1)
- With OLTC on the PV connected LV feeder (case 2)

Table 7 presents the HC values for varying PV and OLTC penetration scenarios. Increasing HC trend is seen with the increasing PV penetration for the whole distribution network i.e. MV network HC increases. However, LV network HC is reduced with the increasing penetration i.e. with the increasing PV penetration the PV per node value decreases. Moreover, with the OLTC inclusion there is an increase in HC but only in the case with +10% overvoltage limit, the E3 limitation is changed to E7. In stricter overvoltage-limit scenarios, the same HC increment and decrement trends are noticed, in MV and LV networks, respectively. However, even with the OLTC employment E3 remains the primary concern.

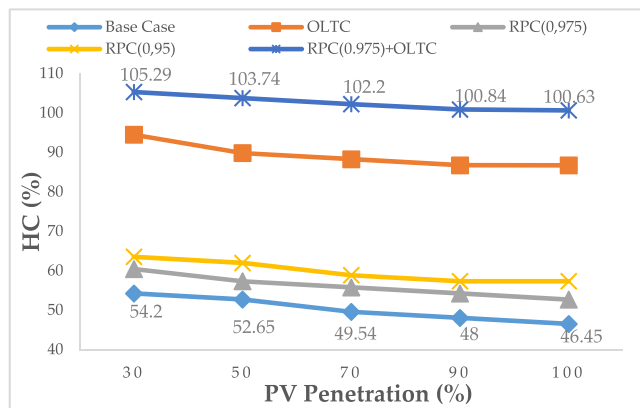
**F. HC’S FOR OVERVOLTAGE LIMITS OF +5% AND +3% WITH RPC EMPLOYMENT**

OLTC employment is able to maximize the HC of the Finnish PR distribution network if the voltage standard EN 50160 is



**TABLE 8.** Summarization of the HCs for different scenarios' simulations for 100% PV penetration.

$\Delta U$	Cases	LV Simulations		MV+LV Simulations			
		$\mu_{HC}$ (%)	Limiting Constraint	$\mu_{HC}$ (%)	Limiting Constraint	MV Line Reinforcement	
				MV OHL 1	OHL 2	OHL 3	
+10%	No OLTC	105,28	E3	89.81	E3		
	With OLTC	113,04	E7	113,48	E7		
+5%	No OLTC	54,2	E3	46,45	E3		
	With OLTC	100,7	E3	86,70	E3		
	RPC (0.975)	86,71	E7	53,64	E3		
	RPC (0.95)	X	X	57,29	E3		
	RPC (0.975)+OLTC	X	X	100,63	E3	103,74	103,72
	RPC (0.95)+OLTC	X	X	100,63	E7		
	NR	109,93	E7	X	X		
+3%	No OLTC	35,61	E3	30,96	E3		
	With OLTC	80,52	E3	71,21	E3		
	RPC (0.975)	61,93	E3	35,61	E3		
	RPC (0.95)	72,78	E7	37,16	E3		
	RPC (0.975)+OLTC	85,18	E7	80,52	E3	85,16	89,80
	RPC (0.95)+OLTC	X	X	86,72	E3	92,90	95,99
	NR	99,1	E3	X	X		
	NR+OLTC	106,84	E7	X	X		



**FIGURE 8.** HCs for different strategies of +5% overvoltage limit.

observed. However, for stricter voltage violation bands, E3 is limiting the HC. In this section, RPC will be utilized to observe its effect on the network's HC. Different scenarios of RPC, with the varying power factor for the PV inverters, as well as the combined utilization of OLTC and RPC will be studied.

Figure 8 shows the HC values, with different strategies' employment, for +5% overvoltage limit. RPC employment, alone, will slightly increase the HC, in comparison to the base case. However, OLTC employment in tandem with the RPC (0.975) of inverters will provide the maximum margin for PV integration in the network, by doubling the HC capability of the network. If RPC (0.95) is employed, the increased flow of the reactive current in the network will reduce the HC, making E7 as the HC limiting constraint. Moreover, the similar trend of HC variation with the varying PV and OLTC penetration is observed for the +3% overvoltage limit. However, to maximize the HC of the network RPC power factor has to be reduced to 0.95 in tandem with the OLTC

**TABLE 9.** LV grids' parameters.

Region	Transformer (kVA)	Cable Length (m)	Customer per Node	Cable
PR	50	150	1	AXMK 4 × 70 mm <sup>2</sup>
IN	200	100	4	AXMK 4 × 185 mm <sup>2</sup>
PU	1000	100	60	2 × AXMK 4 × 185 mm <sup>2</sup>

employment. In both E3 limit scenarios, overvoltage remains the limiting factor.

**VI. DISCUSSION AND RECOMMENDATIONS**

In the HC determination algorithm, the number of iterations in each of the stages define the accuracy of the results. In stage 2, a small number of iterations will yield a large deviation in the computed results. However, a large number of iterations will require excessive time and computational resources. For instance, the standard deviation among corresponding simulation results, for 100 iterations each, is 0.5977. However, for the larger number of iterations, 500 and 1000, computed variances in the subsequent results are 0.2019 and 0.0939, respectively (results are for PR region in LV only simulations). As the small deviation from the mean result will change the decision about the primary limiting constraint of the network when the scrutiny margin among the constraints is not very large. Furthermore, for stage 3, the number of iterations considered are small, as simulations are utilizing the data from the WC hours' data set that has a small number of values (right of Figure 2). A large number of iterations will simulate the same data set recurrently, resulting in excessive computation, without affecting the result.

Different strategies for overvoltage mitigation are employed in order to enhance the HC of the networks. However, OLTC is observed to greatly enhance the HC values in all the simulation scenarios. Table 8 summarizes the HC

**TABLE 10.** Heating modes distribution of different regions.

Regions	Heating Modes		
	Storage Heating (%)	Non-Electric Heating (%)	Direct Electric Heating (%)
PR	5.9	52.9	41.2
IN	7.6	52.5	39.9
PU	0.4	95.3	4.2

**TABLE 11.** 16-node MV network specifications.

From	To	R	X
1	2	0.971265	0.419385
2	3	1.007092	0.434855
3	4	1.284516	0.554645
4	5	1.123558	0.485144
5	6	2.444195	1.055385
6	7	2.032785	0.877741
7	8	1.739624	0.751157
8	9	2.032804	0.87775
9	10	0.356806	0.154066
10	11	3.048102	1.316148
11	12	1.148505	0.495916
8	13	2.155002	0.930514
13	14	3.024276	1.30586
14	15	1.763267	0.761366
15	16	1.021538	0.441093
16	17	2.730975	1.179214

values for most of the scenarios presented in the paper. The result signifies that, for +10% overvoltage limit, OLTC maximizes the HC in LV simulations as well as combined MV/LV simulations. However, for +5% limit scenario, NR can maximize the PV penetration, but due to the monetary benefits of OLTC and less margin of improvement in HC with NR, OLTC is recommended for the stricter overvoltage limit, if only LV simulation is considered. Nevertheless, at smaller PV penetration scenarios, RPC will be a better option than OLTC (due to HC gain to investment ratio being very small). However, with MV network inclusion in the study, RPC involvement in cohesion with the OLTC will maximize the PV integration. For +3% overvoltage limit, OLTC in tandem with partial NR will bring forward the best results, considering only LV simulations. However, based on whole distribution network simulations, the OLTC+RPC is the best option to enhance the HC of the network. In a nutshell, OLTC or OLTC+RPC will be recommended as the best option for the HC improvement in the LV network based on the conducted study. Moreover, larger PV systems can be integrated into the LV feeders closer to the primary transformer rather than the downstream (closer to the end of the feeder).

Moreover, MV network reinforcement is simulated to check for the HC enhancement. But the increase in the MV overhead line diameter will only enhance the HC by 3-5%, in all the PV penetration cases, when upgraded to the next larger size. Furthermore, the sensitivity to the varying percentages of network up-gradation is very minute. For instance, the whole network up-gradation to the larger

**TABLE 12.** Cost of the components utilized for LV network reinforcement.

Components	Cost/km (Euro)
Cable 1 (AXMK 4 × 70 mm <sup>2</sup> )	10,900
Cable 2 (AXMK 4 × 95 mm <sup>2</sup> )	12,100
Cable 3 (AXMK 4 × 120 mm <sup>2</sup> )	14,300
Cable 4 (AXMK 4 × 150 mm <sup>2</sup> )	16,500
Cable 5 (AXMK 4 × 185 mm <sup>2</sup> )	18,100
Cable 6 (AXMK 4 × 240 mm <sup>2</sup> )	20,300
OLTC Transformer	15,000

**TABLE 13.** MV Overhead line data.

MV Overhead Lines	R/km	X/km
Sparrow (35 mm <sup>2</sup> )	0.887	0.383
Raven (55 mm <sup>2</sup> )	0.534	0.284
Pigeon (95 mm <sup>2</sup> )	0.336	0.271

conductor, in +5% overvoltage limit scenario of RPC+OLTC (presented in Table 8), only increases the HC by 3% with E7 as the HC limiter. The data related to OHLs is presented in Appendix, Table 13. Furthermore, OHL replacement with the cable does not have a significant impact on the HC values.

The results signify the PV penetration enhancement in the LV network with OLTC and RPC strategies. Instead of replacing the old transformers with the new OLTC transformers, the retrofitting of OLTC with the existing transformer will be a more economical alternative, in highly PV penetrated LV feeder. Moreover, for RPC employment, rather than spending more on the smart inverters, a slightly larger size inverter, operating in the constant power factor mode, will greatly affect the HC increment of the network. The study conducted will be a benchmark for the utilities and grid codes can be revised in order to increase PV absorption in the network.

## VII. CONCLUSION

This paper investigated different strategies for enhancing the realistic Finnish LV networks' HCs. PR region's HC was found to be limited by the overvoltage issue. To mitigate the problem, different strategies were investigated comprising RPC, OLTC transformer and network reinforcement (NR). Moreover, the economic assessment for OLTC employment and NR was made. A probabilistic approach based on Monte Carlo simulation had been formulated that deal with the uncertain variables of the LV network. Lastly, the whole distribution network (MV/LV) was modeled and simulated, to get the reliable results.

In LV only simulations, if the penetration of PV risen above 50% then OLTC will be a viable option in comparison with the NR scenario. Moreover, the OLTC employment will maximize the HC value for +10% overvoltage limit and change the limiting constraint to E7. For other stricter overvoltage standards, HC was doubled in comparison to the base case. However, E3 remains the limiting factor of the HC. Maximum HC was achieved by utilizing NR strategy but was not proven to be economically feasible. For +3% overvoltage limit, partial NR in tandem with OLTC employment was able

to provide maximum HC results. However, OLTC and RPC employment in cohesion would be best suited to maximize the PV penetration (economically).

In the combined MV/LV studies, observed HC values were lesser than the LV only simulations. With OLTC employment, +10% overvoltage-limit scenarios' HC was capped by the E7 constraint while the stricter E3 violation limits will have overvoltage as the primary constraint. In PV cluster scenarios, the tail end cluster will cause more voltage-rise than the cluster which was closer to the primary transformer i.e. larger PV systems can be attached to the LV networks closer to the primary substation. With the varying penetration of OLTC in the MV network, random employment of OLTC had a minute effect on the region's HC. However, if OLTC is associated with the largely PV penetrated LV feeder, HC can be maximized. Combined employment of OLTC and RPC will maximize the HC in the stricter overvoltage limits. Lastly, MV network reinforcement was considered and the results depicted that very small increase in HC was detected in case of OHL up-gradation to a larger conductor and no significant improvement was observed, with the replacement of OHL with the underground cable.

## APPENDIX ACKNOWLEDGMENT

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## REFERENCES

- [1] (2016). *IEA-PVPS Annual Report*. [Online]. Available: [http://www.iea-pvps.org/index.php?id=6&elD=dam\\_frontend\\_push&docID=3951](http://www.iea-pvps.org/index.php?id=6&elD=dam_frontend_push&docID=3951).
- [2] J. P. Lopes, N. Hatziaargyriou, J. Mutale, P. Djapic, and N. Jenkins, "Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities," *Electr. Power Syst. Res.*, vol. 77, no. 9, pp. 1189–1203, 2007.
- [3] P. Esslinger and R. Witzmann, "Improving grid transmission capacity and voltage quality in low-voltage grids with a high proportion of distributed power plants," *Energy Procedia*, vol. 12, pp. 294–302, 2011.
- [4] M. Nijhuis, M. Gibescu, and J. F. G. Cobben, "Incorporation of on-load tap changer transformers in low-voltage network planning," in *Proc. IEEE PES Innov. Smart Grid Technol. Conf. Eur. (ISGT-Eur.)*, Oct. 2016, pp. 1–6.
- [5] A. Arshad, M. Lindner, and M. Lehtonen, "An analysis of photo-voltaic hosting capacity in finnish low voltage distribution networks," *Energies*, vol. 10, no. 11, p. 1702, 2017.
- [6] T. Walla, J. Widén, J. Johansson, and C. Bergerland, "Determining and increasing the hosting capacity for photovoltaics in Swedish distribution grids," in *Proc. 27th Eur. Photovoltaic Energy Conf. (EU-PVSEC)*, Frankfurt, Germany, Sep. 2012.
- [7] K. Rauma, F. Cadoux, N. Hadj-Said, A. Dufournet, C. Baudot, and G. Roupioz, "Assessment of the MV/LV on-load tap changer technology as a way to increase LV hosting capacity for photovoltaic power generators," in *Proc. CIRED Workshop*, Jun. 2016, pp. 1–4.
- [8] A. T. Procopiou and L. F. Ochoa, "Voltage control in PV-rich LV networks without remote monitoring," *IEEE Trans. Power Syst.*, vol. 32, no. 2, pp. 1224–1236, Mar. 2017.
- [9] A. Navarro-Espinosa and L. F. Ochoa, "Increasing the PV hosting capacity of LV networks: OLTC-fitted transformers vs. reinforcements," in *Proc. IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf. (ISGT)*, Feb. 2015, pp. 1–5.
- [10] D. E. Mawarni, M. M. V. M. Ali, P. H. Nguyen, W. L. Kling, and M. Jerele, "A case study of using OLTC to mitigate overvoltage in a rural european low voltage network," in *Proc. 50th Int. Universities Power Eng. Conf. (UPEC)*, Sep. 2015, pp. 1–5.
- [11] N. Etherden and M. H. J. Bollen, "Increasing the hosting capacity of distribution networks by curtailment of renewable energy resources," in *Proc. IEEE Trondheim PowerTech*, Jun. 2011, pp. 1–7.
- [12] *German Federal Law: Renewable Energy Sources Act (Gesetz fr den Vorrang Erneuerbarer Energien)*, Anonymous, Jul. 2011.
- [13] *VDE Guidelines for the Connection and Parallel Operation of Generation Units at Low Voltage Level VDE-AR-N 4105:2011-08*, Anonymous, Aug. 2011.
- [14] T. Stetz, F. Marten, and M. Braun, "Improved low voltage grid-integration of photovoltaic systems in Germany," *IEEE Trans. Sustain. Energy*, vol. 4, no. 2, pp. 534–542, Apr. 2013.
- [15] F. AlAlamat, "Increasing the hosting capacity of radial distribution grids in Jordan," Tech. Rep., 2015.
- [16] S. Hashemi, J. Østergaard, T. Degner, R. Brandl, and W. Heckmann, "Efficient control of active transformers for increasing the PV hosting capacity of LV grids," *IEEE Trans. Ind. Informat.*, vol. 13, no. 1, pp. 270–277, Feb. 2017.
- [17] T. Aziz and N. Ketjoy, "Enhancing PV penetration in LV networks using reactive power control and on load tap changer with existing transformers," *IEEE Access*, vol. 6, pp. 2683–2691, 2018.
- [18] M. Z. Degefa, "Energy efficiency analysis of residential electric end-uses: Based on statistical survey and hourly metered data," Tech. Rep., 2010.
- [19] Eurostat. *Urban-Rural Typology-Statistics Explained*. [Online]. Available: [http://ec.europa.eu/eurostat/cache/RCU/#?vis=urbanrural.urb\\_typology&lang=en](http://ec.europa.eu/eurostat/cache/RCU/#?vis=urbanrural.urb_typology&lang=en)
- [20] J. Ekström, M. Koivisto, J. Millar, I. Mellin, and M. Lehtonen, "A statistical approach for hourly photovoltaic power generation modeling with generation locations without measured data," *Solar Energy*, vol. 132, pp. 173–187, Jul. 2016.
- [21] R. J. Millar, S. Kazemi, M. Lehtonen, and E. Saarijarvi, "Impact of MV connected microgrids on MV distribution planning," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 2100–2108, Dec. 2012.
- [22] H. Markiewicz and A. Klajn, "Voltage disturbances standard en 50160-voltage characteristics in public distribution systems," *Wroclaw Univ. Technol.*, vol. 21, pp. 215–224, Jul. 2004.
- [23] *Gridcon Transformer Voltage Regulation For Distribution Grids*. [Online]. Available: <https://www.reinhausen.com/XparoDownload.ashx?raid=97813>
- [24] *Regulation Methods Inthe Fourth Regulatory Period of 1 January 2016 31 December 2019 and the Fifth Regulatory Period of 1 January 2020 31 December 2023*. [Online]. Available: [https://www.energiavirasto.fi/documents/101091/0/Appendix\\_2\\_Regulation+methods+draft\\_DSO\\_2016-2023.pdf/3fb120b9-97ba-4226-a7a8-6f0b3cb39f15](https://www.energiavirasto.fi/documents/101091/0/Appendix_2_Regulation+methods+draft_DSO_2016-2023.pdf/3fb120b9-97ba-4226-a7a8-6f0b3cb39f15)



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