ASSESSMENT OF THE MV/LV ON-LOAD TAP CHANGER TECHNOLOGY AS A WAY TO INCREASE LV HOSTING CAPACITY FOR PHOTOVOLTAIC POWER GENERATORS

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ABSTRACT

This paper assesses the use of voltage measurements obtained from advanced metering infrastructure (AMI) to control an on-load tap changer (OL1TC with five or nine tap positions) located at the secondary substation, with the aim of increasing the hosting capacity of the low voltage (LV) network for photovoltaic power generators. The future growth of photovoltaic power generators is simulated with and without OLTC on 631 real-world LV networks located in Lyon(**) (France) and we study the maximum growth before a constraint occurs.

The results surprisingly show that, although all our test networks are taken from the same geographical area, there is a large variation from one LV network to the other regarding how the MV/LV OLTC affects their hosting capacity. Indeed, this hosting capacity may be increased significantly in a few networks while the gain is modest or non-existent in the others. Another important finding is that, for the networks we studied, the OLTC with nine tap positions does not substantially increase the hosting capacity when compared with the one with five tap positions.

INTRODUCTION

Traditionally, LV networks were the simplest part (from the technical viewpoint) in the power distribution supply chain and were typically composed merely of transformers, fuses and cables. Sufficient security margins were simply taken when sizing these components, in order to eliminate the need to actually operate any actuator in a typical LV network. The changing habits of power consumption and the rise of distributed generation, however, are currently increasing the risks of exceeding voltage and current limits on legacy LV networks.

In this context, the "hosting capacity of photovoltaic power generation" is defined as the maximum amount of photovoltaic capacity that can be installed in a given LV network before the appearance of technical constraints, which are typically detected during planning studies by means of load flow simulation under several predefined "quite extreme" conditions of loading and solar irradiance. Constraints that are considered in this paper are over voltage, voltage drop and current constraint in a line or in a transformer.

An OLTC is a (usually mechanical) device that is used to control voltage in a (here, low voltage) network. For now, its use in the French electricity system is limited to primary substations, but in the future, it may offer an attractive solution in the LV networks with a high penetration of distributed generation (where high variations in voltage are expected), as presented in [1]. The tendency of using an OLTC as a standard component in the LV networks does exist, however, in some places, for instance in some regions of Germany [2]. In this work, the OLTC receives the information about the maximum and the minimum values of voltage from the AMI. The OLTC is controlled based on this information.

The hosting capacity of photovoltaic power generation is studied in three different cases; no OLTC, 5-tap OLTC and 9-tap OLTC. The first case presents the actual networks that do not possess dynamic voltage control of any kind. In both types of OLTCs, one tap change causes 1.75% change in voltage. Three abovementioned cases are repeated for 631 real LV networks provided by the major French distribution system operator ERDF. All simulations are performed on DIgSILENT PowerFactory by using DIgSILENT Programming Language (DPL). In the whole paper, "voltage" means "phase-to-neutral voltage".

METHOD OF CHOOSING CUSTOMERS TO MEASURE VOLTAGE FOR AN OLTC

The objective of an OLTC is to maintain voltage within the allowed limits (0.90 p.u. and 1.1 p.u. in France) in the whole LV network at any moment. In order to achieve this, the OLTC needs the information about the minimum and the maximum voltage in the network. The objective of the presented methodology is to select a few customers whose AMI measurements could be used as an input to the OLTC so that the maximum and the minimum values of voltage are known with a sufficient accuracy at any given

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moment. In order to minimise the communication capacity between the customers and the secondary substation, and the cost of the required equipment, we wish to select just a few customers, without sacrificing too much accuracy in voltage estimations.

The customers for the voltage measurements are chosen according to the following procedure.

1. Run unbalanced load flow in 10-minute time steps over four typical days (two winter days and two summer days), thus 576 load flows.
   Choose a customer connected to the same terminal and the phase that experiences at least one time the minimum or the maximum voltage in any of 576 load flows.
2. If available, three-phase customers are preferred to single-phase ones since they provide richer readings.

Note that the method uses only the mean load curves (which are smoother than the actual load curves) of each customer. Also, it is optimistically supposed that all (or the majority of the) customers are within AMI.

METHOD OF ESTIMATING THE HOSTING CAPACITY

a) Assumptions

The hosting capacity of photovoltaic power generation is estimated by using fictitious photovoltaic generators. These generators are located to every network according to the following principles.

- One photovoltaic generator is connected to *each* terminal that has at least one connected customer.
- 90% of the generators are single-phase connected and 10% are three-phase connected.
- The locations of the three-phase and the single-phase connected generators are chosen randomly.
- The phase connection of each single-phase connected generator is chosen randomly.
- The capacity of three-phase generators is 10 times higher than the capacity of single-phase connected generators.
- Both, the loads and the photovoltaic generators use mean load and generation curves for the considered day and time of the day. The mean curves for the generators have the same shape due to the fact that they are located geographically close to each other.
- The load curves are given by 10-minute time steps and restricted to a summer day between 11.30h and 14.00h.
- The nominal voltage of the medium voltage (MV) network is set to maintain 21 kV (+5% of the nominal value).

The simulation is carried out during a typical day in July and for mid-day hours only, because the photovoltaic power production is higher and the networks are more lightly loaded at that time than during the winter. If the simulations were carried out, for instance, using winter loading, the estimated hosting capacities would be high and overly optimistic. The simulation is executed over the time period when the photovoltaic power generation is as its highest.

Although, it is unlikely that there would be exactly one photovoltaic generator connected to each terminal with customer connections, we chose to locate generators in this way because we are only interested in the order of magnitude of the relative (percentage) and *typical* increase in hosting capacity with and without an OLTC, not in the absolute value of hosting capacity itself in all possible PV growth scenarios. As explained in [3], choosing an accurate scenario for the placement of the photovoltaic generators is a complex issue; and subsequent calculations are computationally more costly. Thus, only one scenario for the locations of the photovoltaic network is used.

In practice, a distribution system operator chooses phase connections for new PV generators rationally, not randomly; but for the purpose of our simulations, selecting the phase connection of the photovoltaic generators in a random manner was simply a way to spread single-phase generators more or less evenly on the grid.

The voltage of the upstream MV network is set to 21 kV (+5%), purposely leaving relatively small margin for LV voltage rise, in order to account for the fact that voltage rise is likely to occur also on the MV side (not only in LV) when the output of distributed generation is strong.

a) Simulation

The hosting capacity is estimated according to the following procedure.

1. Place the photovoltaic generators in the network as described above.
2. Run unbalanced load flow calculation.
3. If a constraint occurs, operate the tap changer (if any) to solve it. If not possible, finish the procedure and save the essential results.
4. Otherwise (no constraint), increase the output of all photovoltaic generators by 5% of their original output value during that hour and repeat from Step 2 above.

The first step is executed only once per network but Steps 2 to 4 are repeated over and until an unsolvable constraint occurs. Note that if the constraint is a voltage constraint, the procedure is finished only if it cannot be overcome by changing the tap position in the transformer. The actual strategy used to choose the next tap after a change is not important here, since it only determines how many changes will be performed, not the hosting capacity itself.

OBSERVATIONS ON THE OLTC CONTROL

When estimating the impact of an OLTC on the hosting capacity for photovoltaic power generation, the control method of the OLTC must be considered in detail. This section explains three pitfalls in the control of an OLTC that may occur under a high penetration of photovoltaic power generation which have to be taken into account. Otherwise, they may lead to a biased estimation of the hosting capacity.

Firstly, a high power output from the photovoltaic generators leads to increasing voltage. Regardless of the manner how voltage is measured in order to control an OLTC, it has to be made sure that no local voltage peaks remain unnoticed from the voltage sensors.

Secondly, changing the tap position in a transformer changes the current. This means that when decreasing voltage, current increases. This, in turn, can cause a modest overloading of a line or a transformer.

Thirdly, if the voltage sensors are poorly placed, the full range of voltage control of the OLTC is not exploited, which means that the hosting capacity is not increased as much as it could be increased. In an extreme situation, an OLTC can decrease the hosting capacity rather than increase it, if the voltage measurements are poorly placed with respect to distributed generation.

RESULTS

The simulations are carried out on 631 LV networks that are geographically close to each other. The size of the network varies from 1 to up to more than 400 customers. The average network size is 128 customers.

According to the methodology, four customers are required on average and eleven at most, in order to obtain an accurate estimation of the maximum and the minimum values of voltage. The required number of customers in every network is illustrated in Figure 1. .

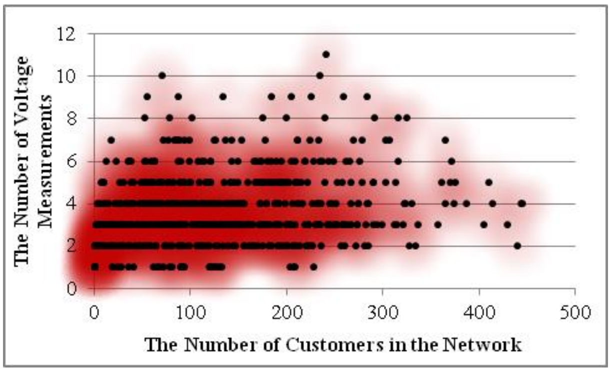

Figure 1 – The required number of voltage measurements in the networks of different sizes. Each point presents one network, thus the figure contains 631 points. The red colour around the points makes the density more visible.

When an OLTC is not used, 37% of the networks are limited by voltage, 25% by current in the transformer and 38% current in a line. When an OLTC with five tap position is applied, the figures are 6%, 39% and 55%, in the corresponding order. When an OLTC with nine tap positions is used, the same figures are 4%, 39% and 57%, respectively.

Figure 2 presents the hosting capacity per peak load (in per cent) in the three cases; no OLTC and the OLTC with five and with nine tap positions. Only the networks (236) where the hosting capacity through the use of an OLTC is increased are presented. This figure shows the impact of an OLTC on the medians (the intersection between the purple and the green areas) and on the extreme values (see the upper whiskers).

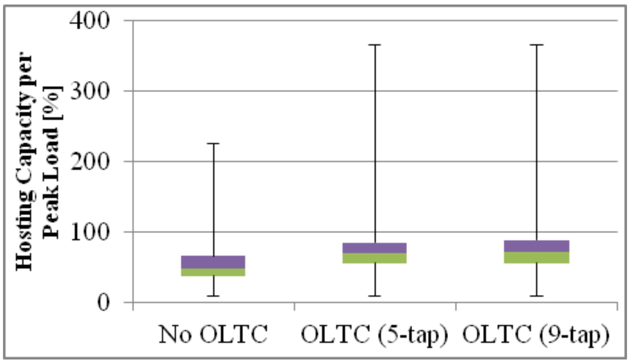

Figure 2 – Hosting capacity per peak load. The cases of no OLTC, the OLTC with five tap positions and the OLTC with nine tap positions are presented for 263 networks.

In Figure 2, the median value can be seen as the intersection between the green and the purple areas. The purple area represents the upper 25% (from the median) of the networks and the green area represents the lower 25% (from the median) of the networks. Thus 50% of the networks are within the purple or the green areas and 50% of the networks are within the whiskers.

The average hosting capacity per customer increases about 35% when an OLTC of five tap positions is used in comparison with the case that no OLTC is used. The same figure of the OLTC of nine tap positions is 38%. It should be noted that these figures are obtained by considering only the networks (37% of them, thus 236 networks) constrained by voltage when no OLTC is used. The increase of the hosting capacity is compared with the number of customers and with the load per customer (the full details are not presented here in order to save space) but no correlation is found.

ANALYSIS OF THE RESULTS

As stated above (Figure 1), the number of required voltage measurements per network varies from one to eleven, on average, four voltage measurements (three per cent of the customers), are required. It is discovered that the hosting capacity for photovoltaic power generation is limited by voltage in 37% of the networks when no OLTC is used. These are the potential networks where hosting capacity can be improved through the use of an OLTC. Needless to say, the hosting capacity cannot be increased by using an OLTC in the networks with the hosting capacity limited by current. When an OLTC is used, the share of voltage-limited networks decreases from 37% to 6% in case of a 5-tap OLTC and to 4% in case of a 9-tap OLTC. That is, there are still voltage-constrained networks even if an OLTC is used. Noticeable difference cannot be seen between the 5-tap and the 9-tap OLTC. These figures express the share of networks, where hosting capacity can be incremented, but do not quantify the level of the increment.

Figure 2 shows that the number of networks where hosting capacity is increased vastly is very small. When the OLTC with five tap positions is used, the median increases from 48% to 69%. When the OLTC with nine tap positions is used, the median is 71%.

Figure 2 shows that hosting capacity is not improved much if the OLTC of nine tap positions is used instead of the one with five tap positions.

It can be observed that an OLTC has a significant impact on hosting capacity of photovoltaic power generation only in a minority of the networks. This implies that the installation of an OLTC in order to increase the hosting capacity is justified only in a few networks. Thus, the benefits of an OLTC should be studied carefully on a case-by-case basis.

REMARKS

The methodology to estimate the hosting capacity considers only one way to place the photovoltaic power generators. Undoubtedly, the placement, the sizing and the phase connections of the photovoltaic generation have an impact on the estimate of the hosting capacity. If a more in-depth estimate of the hosting capacity is wished, a Monte Carlo -based technique should be used, such as in [4]. However, this would multiply the computational costs of the method.

The networks are located in a geographically small area, which means that the results cannot be extrapolated to the whole country. In addition, all used networks are urban or semi-urban networks. Since rural networks tend to be relatively long and lightly loaded (a bottleneck for the hosting capacity of photovoltaic generation is caused rather by voltage than the thermal rating of a component), they may have more potential to increase the hosting capacity by using an OLTC.

The scripts are written directly on a platform that is widely used in the industry, which makes the gap between the script development and the practical use narrow.

CONCLUSIONS

This paper presents the results of the hosting capacities for photovoltaic power generation carried out on 631 real-world LV networks in three different cases; no OLTC, an OLTC of five tap positions and an OLTC of nine tap positions. AMI is used in order to control the OLTCs.

When the impact of an OLTC on the hosting capacity is estimated, it is essential to include the control strategy of the OLTC in the study. Here we used a relatively elaborate control strategy that requires coupling AMI with the OLTC, and from which we expect better behaviour than simpler methods (such as measuring only the voltage at the secondary side of the distribution transformer).

The studies show that the hosting capacity can be increased more than 50% in about 16% and more than 100% in about three per cent of the studied networks by using an OLTC. An interesting result is that among the networks where the hosting capacity can be increased, the increment remains under 40%. Another discovery is that there is no considerable difference in the hosting capacity between the 5-tap and the 9-tap OLTC in the studied networks. The impact of the OLTC on the hosting capacity does not depend on the size of the network or the level of loading among the analysed networks.

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