HOSTING CAPACITY OF LV DISTRIBUTION GRIDS FOR SMALL DISTRIBUTED GENERATION UNITS, REFERRING TO VOLTAGE LEVEL AND UNBALANCE

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ABSTRACT

This paper revisits the mechanism of overvoltage and voltage unbalance production in the context of the connection of small single-phase DG units to LV distribution grids. Based on quite simplified models of typical LV distribution feeders, the phenomenon is illustrated and quantified, through the introduction of a new index (distribution factor). Finally, some mitigation solutions are investigated.

INTRODUCTION

Distributed generation (DG) units, especially photovoltaic generators (PV), are nowadays commonly – and even more and more – present in the low-voltage (LV) distribution grids of many countries. In this context, small size units (i.e. a few kW peak) are usually single-phase connected. The connection of these generators to the public distribution grids is generally not submitted to profound preliminary technical investigations. However, their influence on the system may become non negligible, particularly when the number of such connected devices becomes important. For instance, it appears that some problems regularly occur at the post-connection stage. These problems are especially related to the voltage level on some phases (overvoltage) and voltage unbalance [1].

This paper will first revisit the mechanism of overvoltage and voltage unbalance production in the context of the connection of small single-phase DG units to LV distribution grids. Based on quite simplified models of typical LV distribution feeders, the phenomenon will be illustrated and quantified. Some mitigation solutions will also be investigated.

INFLUENCE OF DG ON THE VOLTAGE PROFILE OF LV DISTRIBUTION GRIDS

Basics

In this paper, we deal with voluntarily simplified cases highlighting the worst situations from the overvoltage and voltage unbalance perspective. We typically consider a 1km long overhead LV distribution feeder made of 95mm² copper conductors. It is further assumed that the nodes where energy consumers/producers are connected are equidistant along the feeder. 5 kW single-phase DG units are injecting their power in this feeder and the other loads (power consumption) are neglected. This situation is mainly reached when the generation level is high and almost the same for all the units, while the local consumption (or load) is rather low (e.g. typically when the sun is shining in a deep blue sky, at noon on a regular week day, in a residential area with many PV installations, most of the inhabitants being at work).

Let's first consider the very simple case of the feeder with only one 5 kW PV installation connected at its end. Such a small power unit is generally single-phase (connected between one phase and the neutral conductor). The distribution feeder can be modelled by its series resistance and reactance while the PV unit is modelled by a current source, as illustrated in Figure 1.

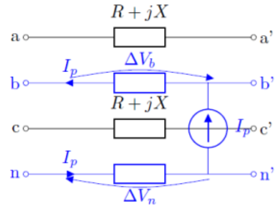

Figure 1 – *Simplified case of a feeder with a single-phase PV installation connected at the end*

The current injected in the grid by the PV installation flows in the phase (i.e. phase b, in this particular case) and neutral conductors, causing voltage variations which are actually observed on all the three phases, according to the phasor diagram shown in Figure 2.

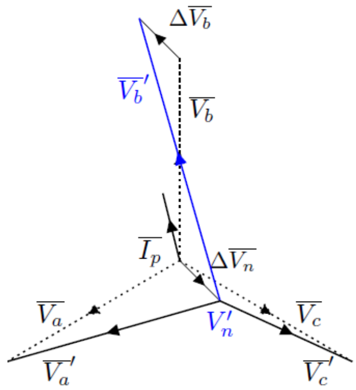

Figure 2 – *Phasor diagram of the three-phase voltage at the end of the feeder*

In this simple illustrative case, it can easily be seen that the phase-to-neutral voltage level is increased for two of the phases (especially the one on which the PV installation is connected), while decreased for the third one, due to the phasor voltage drop on the neutral conductor.

Voltage unbalance : influence of the distribution

The distribution of the various PV installations among the three phases is of course the primary influencing element regarding voltage unbalance. When more than one PV installation has to be connected to the system, the situation will indeed be improved if the installations are connected in a balanced way on the different phases. This is illustrated in Figure 3 and in Figure 4, in the particular cases of a 10 nodes radial feeder hosting respectively 4 and 10 PV installations. In the first situation (Figure 3), the installations are all connected to the same phase (phase a), at nodes n° 1, 4, 7 and 10 (the nodes being increasingly numbered from 1 to 10, towards the end of the feeder). In the second situation (Figure 4), one installation is connected at each node with a cyclic distribution among the three phases.

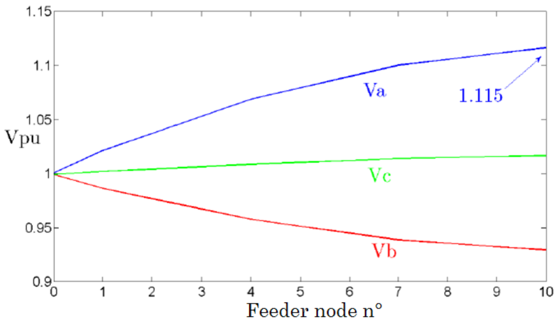

Figure 3 – *Voltage profile along a 10 nodes radial feeder (1km long) with 4 PV installations connected to the same phase (phase a) at nodes 1, 4, 7 and 10*

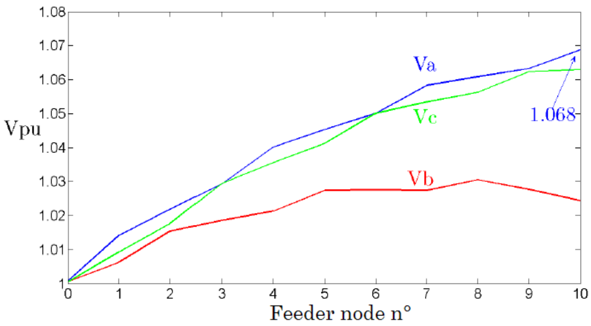

Figure 4 – *Voltage profile along a 10 nodes radial feeder (1 km long) with PV installations connected at each node. PV installations are connected to phase a at nodes n° 1, 4, 7 and 10; to phase b at nodes n° 2, 5 and 8; to phase c at nodes n° 3, 6 and 9*

Distribution factor

In order to take into account the distribution of the connected DG among the three phases, the *distribution factor* f_D is introduced [2]. This factor is defined as:

$$f_D = \left| \frac{n_a}{n_{tot}} + a\,\frac{n_b}{n_{tot}} + a^2\,\frac{n_c}{n_{tot}} \right| \quad \left(a = e^{j\frac{2\pi}{3}}\right)$$

where n_a, n_b and n_c are the number of DG units connected respectively to phase a, b and c, n_{tot} being their sum.

It is the magnitude of the sum of three vectors having sizes corresponding to the relative proportion of DG units connected to each phase. The relative phase shift of these vectors with each other is 120°.

This factor is obviously equal to zero if the same amount of DG units is connected to each phase. It is equal to 0.5 when two phases host the same amount of DG units while there is nothing connected to the third one. Finally, it is equal to unity in the case of one phase hosting all the DG units. It is worth noting that this definition is formally similar to the one of the zero-sequence component, in the frame of the Fortescue transformation for three-phase systems.

For a given N nodes three-phase feeder hosting n_{tot} single-phase DG installations, there is a discrete relationship between the number of DG (n_{tot}) and the distribution factor (f_D). There are only a finite number of possible DG combinations on the different phases. Moreover, different (n_a, n_b, n_c) combinations can lead to the same distribution factor. For instance, the combination (n_a, n_b, n_c) = (4, 2, 1) leads to the same distribution factor as (2, 4, 1) or (2, 1, 4). As an example, all the possible (n_{tot} , f_D) pairs are plotted in the Figure 5, in the particular case of a 30 nodes radial feeder.

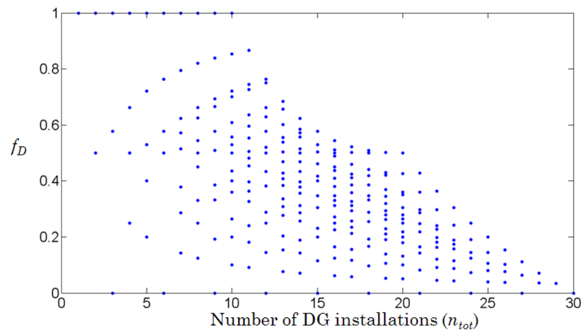

Figure 5 – *Possible (n_{tot} , f_D) pairs for a 30 nodes radial feeder*

GRID HOSTING CAPACITY

The 1km radial three-phase feeder has been investigated as a typical case (e.g. rural LV distribution feeder). Multiple simulations have been performed about this feeder assuming 5, 10 or 30 equidistant nodes. Again the further assumption was made that the single-phase grid users are cyclically connected along the feeder. The simulations were made by using a dedicated MATLAB Simulink® model [2].

As there are obviously various possibilities of practically realizing a given (n_{tot} , f_D) pair, by positioning the DG installations at different nodes along the feeder, this study was intentionally limited to the worst cases (i.e. the ones leading to the highest overvoltage). Therefore, for the performed simulations, DG installations were systematically placed by starting, for each phase, from the end of the feeder. For example, in the particular case of a 10 nodes feeder, the pair (n_{tot} , f_D) = (3 , 1) (corresponding to 3 units all connected to the same phase) was obtained with DG units positioned at nodes 4, 7 and 10. The main observed simulation results were the voltage level and unbalance at the last node (i.e. the end) of the feeder. Figure 6 summarises the results obtained for a 10 nodes feeder.

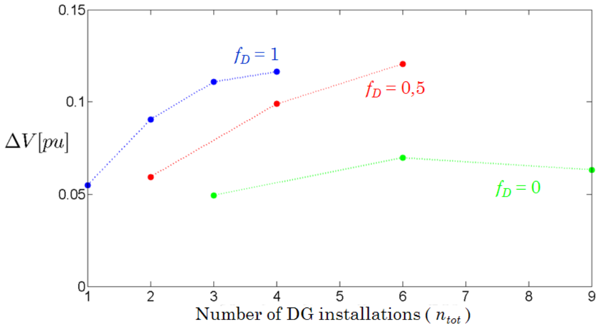

Figure 6 – *Overvoltage at the end (last node) of a 10 nodes feeder, in function of the number of connected DG installations, for various distribution factors*

For a specified amount of DG units, the overvoltage increases with the distribution factor. For instance, with 6 DG units, it is seen from Figure 6 that the overvoltage is almost doubled when f_D goes from 0 (i.e., in this case, 2 units on each phase) to 0.5 (i.e. 3 units on two phases and nothing on the third one).

For a given distribution factor, the overvoltage increases with the amount of connected DG units which is intuitively quite understandable. However, there is clearly a limitation to this reasoning. The overvoltage corresponding to (n_{tot} , f_D) = (9 , 0) is even lightly smaller than for (n_{tot} , f_D) = (6 , 0). As mentioned above, f_D is a global (i.e. macroscopic) quantity which does not take into account the physical location of the generation units along the feeder. In this particular case of f_D = 0, the compensation of currents in the neutral conductor is better in the configuration n_{tot} = 9 compared with the configuration n_{tot} = 6, leading to a reduced voltage drop and hence a reduced overvoltage (although the worst case was considered in both configurations).

The evolution of the negative sequence voltage at the end of the feeder, in function of the amount of DG units and for various values of f_D, is given in Figure 7. It qualitatively illustrates the good correlation observed between the overvoltage and the unbalance at the same location.

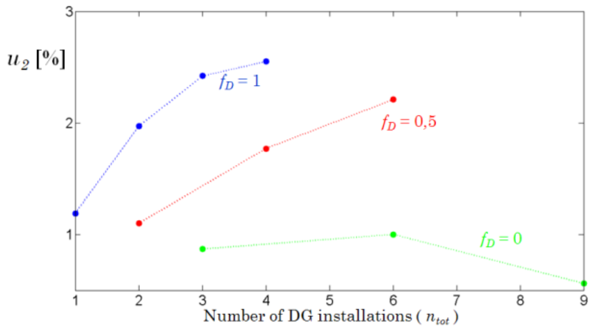

Figure 7 - *Negative sequence voltage unbalance factor at the last node of the radial10 nodes feeder, in function of the amount of connected DG units*

Similar trends are confirmed in the case of the 30 nodes feeder, as shown in Figure 8.

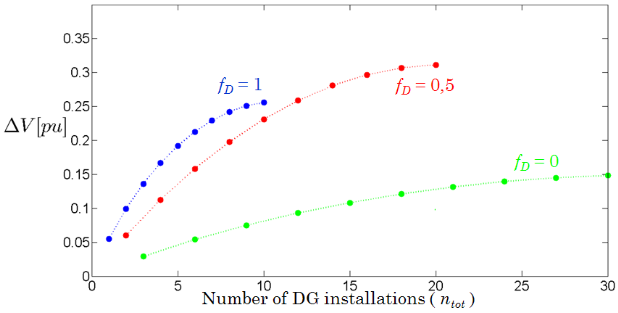

Figure 8 - *Overvoltage at the end (last node) of a 30 nodes feeder, in function of the number of connected DG installations, for various distribution factors*

Note that due to the already mentioned discrete nature of f_D in function of n_{tot} (Figure 5), we can only have up to 10 connected DG units for f_D = 1 and 20 units for f_D = 0.5. Some configurations for which f_D = 0.5 appear to be significantly more severe than those corresponding to f_D = 1 (which was not observed in the 10 nodes feeder).

The evolution of the maximum overvoltage in function of the distribution factor is given in Figure 9.

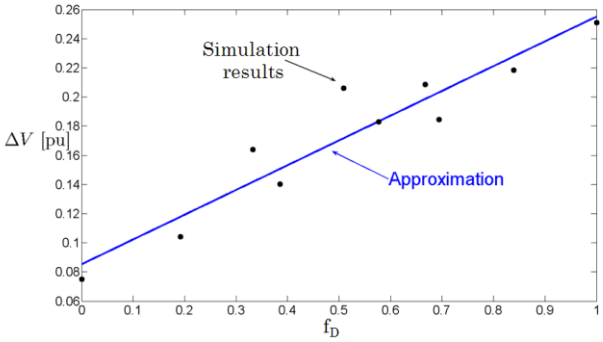

Figure 9 - *Maximum overvoltage in function of the distribution factor (30 nodes feeder)*

VOLTAGE QUALITY ENHANCEMENT

Reactive power consumption

The inverters connecting PV installations to the grid could be operated in such a way that they inject or consume reactive power, instead of working with a unity power factor, as it is the usual practice. Consuming reactive power will positively impact the overvoltage (Figure 10) but, on the other hand, negatively influence voltage unbalance (Figure 11).

The points in these figures represent simulation results obtained for various (n_{tot} , f_D) configurations. They are simply ranked in such a way that the overvoltage (resp. unbalance) curve is monotonically increasing with the configuration No., when cos φ = 1 (blue curve). The corresponding configurations in the case cos φ < 1 are then superimposed (red curve).

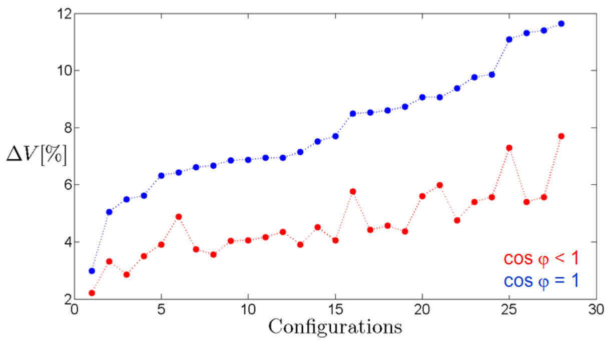

Figure 10 – *Positive impact of reactive power consumption on the maximum overvoltage observed for various configurations*

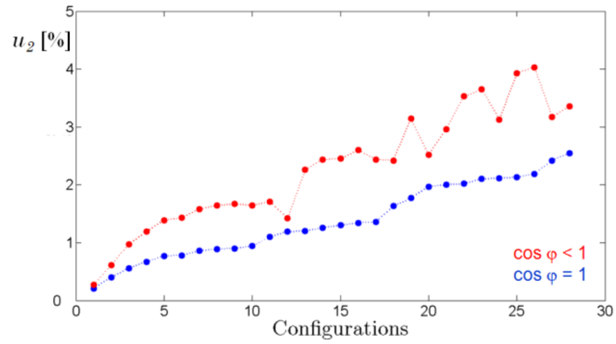

Figure 11 – *Increase of the voltage unbalance due to reactive power consumption for various configurations*

Feeder loop configuration

Transforming the radial structure of a feeder into a loop could be beneficial as well. Two possible configurations, depicted in Figure 12, have been investigated.

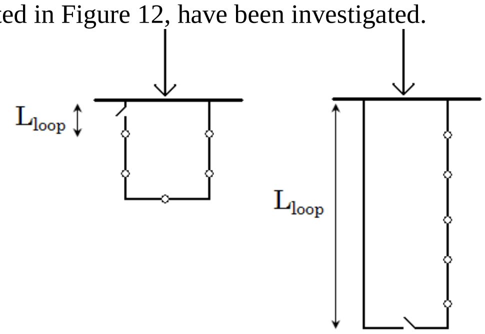

Figure 12 – *Looping a radial feeder: two possible topological configurations*

In the left-hand case of Figure 12, L_{loop}, the length of the loop connection line (i.e. the piece of line added in order to loop the feeder) is equal to the distance between two (supposed equidistant) nodes along the feeder while in the right-hand situation, it has the same length as the whole feeder itself.

The benefit of looping the feeder is illustrated in Figure 13. The points corresponding to different (n_{tot} , f_D) configurations are again ranked in order to get a monotonically increasing curve, for the case of the initial radial feeder (without loop).

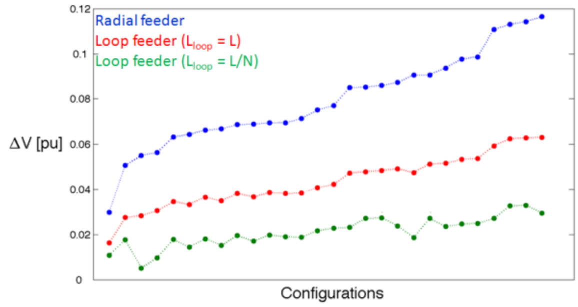

Figure 13 – *Overvoltage reduction by looping the feeder*

Similar results are obtained for the voltage unbalance, with a reduction factor up to 5.

CONCLUSIONS AND PERSPECTIVES

The influence of single-phase DG units in LV distribution feeders has been highlighted by thorough simulations.

Relying on the fact that voltage level and unbalance problems are not only arising due to the number of connected DG units, but also due to their distribution among the three phases, a new index was introduced in order to quantify this distribution effect (the so-called "distribution factor"). This index is well suitable for the description of overvoltage and voltage unbalance in radial LV distribution feeders. It can be used for the investigation and further quantification of the hosting capacity of a given grid. From a very practical point of view, the connection of new single phase units could be assessed in order to minimize this index, knowing the actual distribution of already connected ones. It could be considered in the frame of future standardization works.

Finally, some possible mitigation solutions were investigated (other than balancing the DG units over the phases), either in the topology and operation mode of the grid or at the DG side. Controlling the DG units in order to consume reactive power can appear to be a solution to reduce the maximum overvoltage but it has a negative impact on the voltage unbalance. Looping radial feeders can also be a valuable option.

The proposed approach and obtained results, corresponding to simple worst cases, should be extended and further refined, by considering more realistic feeder topologies and taking the actual load into account.

REFERENCES

[1] C. Reese, L. Hofmann, "Analysis and reduction of effects of single-phase loads and generators on low voltage distribution grids", *21st International Conference on Electricity Distribution* (CIRED 2011), Paper 1226

[2] A. Du Bois, B. Martin, *Capacité d'hébergement des réseaux publics de distribution basse tension pour des petites installations photovoltaïques*, MSc thesis (in French), Université catholique de Louvain, 2012.