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Distributed Voltage Control Strategies in a LV Distribution Network

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Abstract. As the amount of locally installed distributed generation is increasing rapidly, voltage quality problems begin to arise in the LV distribution network. Particularly the introduction of large amounts of distributed generation may cause an excessive voltage rise on a distribution feeder violating the voltage limitations. PV installations specifically are found to trip on days with high solar irradiance and low load. New standards for the connection of locally installed generators to the LV distribution grid will have to be developed in order to enable the large scale implementation of distributed generation in the LV distribution grid, and to avoid unwanted tripping of the locally installed generation units.
In this paper, different voltage control mechanisms are discussed and compared in terms of grid losses and profitability of the installed generation for a typical Belgian distribution network topology.

Key words

Distribution network, distributed generation, voltage control.

1. Introduction

Over the last few years, the amount of locally installed distributed generation has grown significantly, and an even larger further growth is expected in the near future: e.g. a global annual growth rate of 17-32% of locally installed PV panels is expected [1]. The introduction of large amounts of distributed generation may cause an excessive voltage rise on the distribution feeders, and lead to violations of the standardized voltage limitations of the distribution network, set by the EN50160 standard [2]. Standard EN50160 stipulates that the voltage on the distribution line has to be between 230/400 ± 10% V.
Tripping of PV inverters because of excessive grid voltage is already experienced on sunny days with the present, still relatively limited, share of installed PV power. This causes a lower yield of the PV installation, and thus an increased pay-back time for the owner. Up till now, no measures have been taken to tackle this problem. New standards for the connection of locally installed generators to the LV distribution grid will have to be developed in order to enable the large scale implementation of distributed generation in the LV distribution grid.

As the majority of the locally installed generating units has an inverter-based interface, different voltage control strategies can be implemented in these inverters in order to reduce the voltage rise along the distribution feeders. In this paper the voltage rise that can be caused by PV installations on a LV feeder is presented and the influence of different voltage control strategies is assessed in terms of grid losses, profitability of the generating units and technical issues, for a typical Belgian distribution network. A first possible mechanism is that the distributed generator is asked to disconnect from the network when the voltage limit is reached. This is a commonly used approach in presently used inverters in order to keep the grid voltage between its boundaries. A second mechanism is that the generating unit is asked to provide reactive power [3]. A third strategy consists of asking the generator to decrease or limit its active output power according to the value of the grid voltage [4].

2. Voltage rise in the LV distribution grid

Distribution lines have a rather resistive character. When a load is connected to the line, the voltage drops over the line. Due to current injections from local distributed energy resources, the voltage rises instead of drops along the distribution line. In addition to this, the current injections from generating units on the same distribution line probably will not be as stochastically spread out as the load is, e.g. the incoming sunlight is virtually the same for every PV-panel within the same km², resulting in even higher voltage deviations on the distribution feeder.

Voltage problems are especially expected in case of an unbalanced connection of several single-phase installations on a distribution feeder. Unbalance causes shifting of the neutral reference point due to zero-sequence return currents in the neutral [5]. A single-phase connection of a generating unit not only causes a rise of the voltage in the respective phase, but also influences the voltage profile of the other two phases: the neutral reference point shifting amplifies the overvoltage of the phase with the highest injected current, and at the same time causes a decrease of the voltage in the other two phases. This is illustrated in Fig. 1 where a comparison of the voltage profile of a distribution feeder is shown with a balanced and an unbalanced connection of a local generating unit. In the balanced case, shown at the top of Fig. 1, a unit of 5 kW is connected to each phase at the end of the feeder. The feeder is assumed to be a 4*150 mm² EAXVB cable with a length of 1 km. Because of the balanced connection, the voltage rise is equal in each phase, and is approximately 2%. In the unbalanced case, shown at the bottom of Fig. 1, one generating unit of 5kW is connected at the end of phase C of the feeder. In this case, the voltage rise is not equal in each phase: the voltage rises about 5% in phase C, but drops 1-2% in phases A and B. This is due to the shifting of the neutral reference. Although the total injected power of the feeder is much higher in the balanced case (15kW vs. 5kW), the voltage rise in the unbalanced case is more alarming, especially in phase C, the phase the injecting unit is connected to.

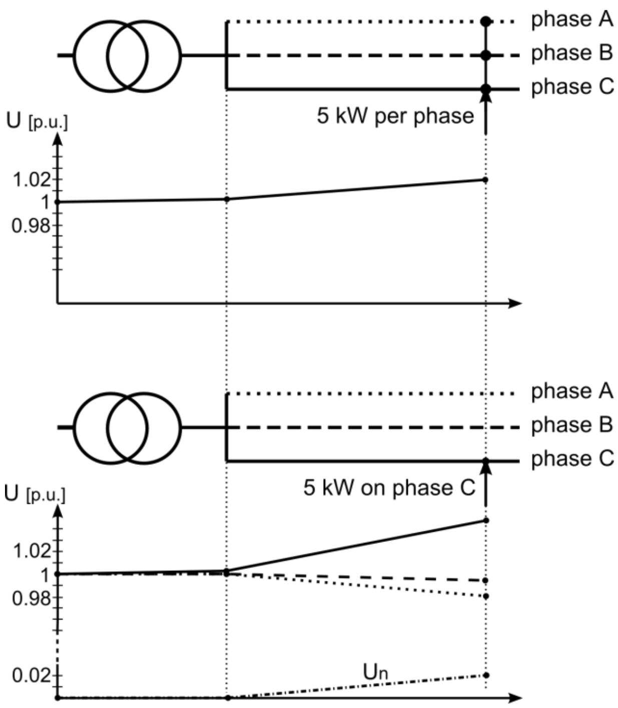

Fig. 1: Comparison of voltage profile of a feeder with balanced (above) and unbalanced (below) connection of local generation.

A second context where voltage problems are also particularly expected is when a larger installation, i.e. an installation with considerable power rating compared to the rating of the distribution transformer, is connected towards the end of a fairly long feeder. Larger installations (>5kW) standard have a three-phase connection, so the effect of unbalance is generally negligible. Usually, the effect of resistive voltage rise on these feeders is predominant, especially when the feeders are relatively long.

3. Simulation of a typical distribution network

In order to define the influence of different voltage control strategies on the voltage profile of a distribution network, load flow simulations were done on a typical distribution network topology found in Belgium.

The distribution network of the case study is supplied by a 250kVA transformer and consists of 3 branch feeders. The feeders are 4*150 mm² EAXVB cables with a total length of 400 m. Each feeder supplies 21 houses, and each house has a PV installation of 3.5 kW. The spur feeder cables, which connect the houses to the branch feeder cable, have a length of 5 m. All houses are equally distributed over the three feeders and the three phases of the network. A single-phase equivalent of the used network topology is shown in Fig. 2. The network parameters are given in Table 1.

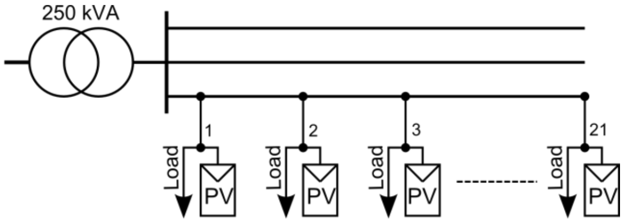

Fig. 2: Single-phase diagram of the modelled distribution network topology.

Table 1: Feeder cable parameters used in simulations.

	R [Ω/km]	L [mH/km]
EAXVB 4*150 mm²	0.227	0.078
Spur feeder cable	1.4	0

A load flow analysis is performed to assess the voltage deviations and the power losses in the distribution network topology. The load-flow is based on a backward-forward sweep method to calculate the node-currents, line-currents and node voltages [6]. All load-flow calculations were carried out in Matlab.

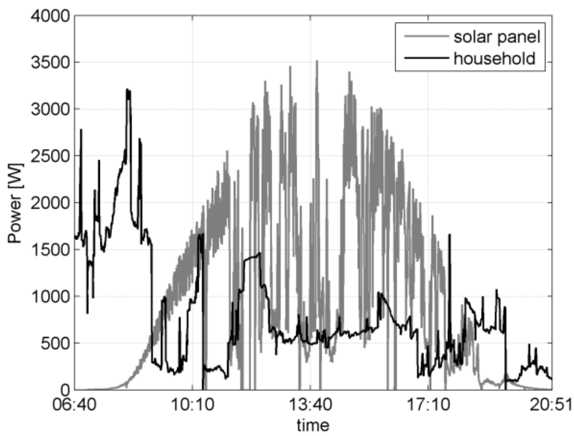

Fig. 3: Example power profiles of a household and a solar panel.

A Markov chain method [7] was used to generate different load profiles, and these load profiles are used as input for the load-flow calculations. The profiles representing the power drawn by the households in the distribution network are based on measurements done on several households during summer. The generation profiles of the solar panels are made with measurements performed on an actual solar installation during summer. The correlation between the output power of the different solar panels is set to be relatively high, as is assumed that they are located relatively close to each other. The time resolution of the load and generation profiles is set to 0.5 min. Fig. 3 shows an example of a load profile of a household and a generation profile of a solar panel.

4. Reference scenario

As a reference scenario, the voltage profile of the distribution feeder during a reference summer day was analysed, under the assumption that no voltage control strategies are present whatsoever, and that the solar panels keep feeding the grid, even if the grid voltage rises above a preset limit.

The highest grid voltage is found at the end of the feeder, and is shown in Fig. 4. The house at the end of the feeder is connected to phase 3, so only the voltage of phase 3 is shown in Fig. 4. The plot shows that a maximal voltage rise of about 5% above nominal is reached during the day. This maximum is still between the limits set by standard EN50160, as previously stated. However, the voltage at the beginning of the feeder is generally set to a higher than nominal value to make sure that the voltage at the end of the feeder stays within ±10% U_n, because traditionally (without distributed energy resources) power flows only happen from distribution transformer towards the end of the feeders. A voltage of U_n+5% is often found at the beginning of distribution feeders. A voltage rise of 5% and more within the LV distribution network may then lead to an actual voltage rise that is higher than 10% above the nominal voltage. In the rest of the paper is assumed that a voltage rise of 3.5% within the distribution network is the maximal allowable voltage rise in order to maintain the actual grid voltage between the limits set by standard EN50160.

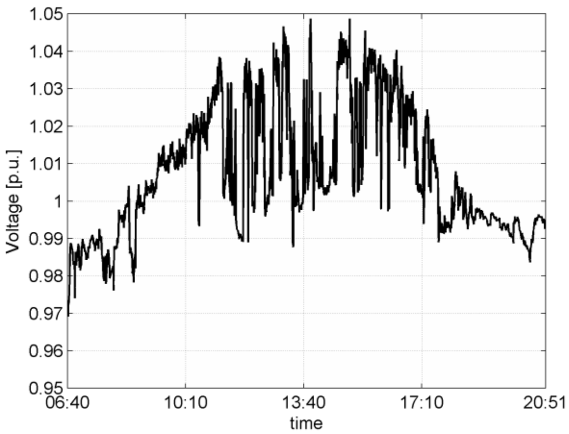

Fig. 4: Grid voltage at the connection of the last house on the feeder.

5. Voltage Control Strategies

A. Curtailing of generating units

Nowadays all small distributed generators are installed according to a ‘fit & forget’ approach: the distribution system operator does not allow the connected distributed generators to provide any sort of voltage control of the distribution grid [8]. When the voltage at the grid interface of the generating units reaches a limit, the inverter trips, and no power is produced by the generating unit, i.e. the output power from the generating unit is curtailed in an automatic way. This means that generating units that are installed further away from the transformer experience more tripping than the units that are closer to the transformer. This is illustrated in Fig. 5, where the simulated production of each solar panel in the first feeder branch of the distribution network is shown, when voltage control by curtailing is applied. The total generated energy by the PV panel connected at the end of the feeder is about 25% less than the generated energy by the panel connected at the beginning of the feeder branch. Consequently, the PV installations close to the distribution transformer have a better cost-effectiveness, which is not a fair situation.

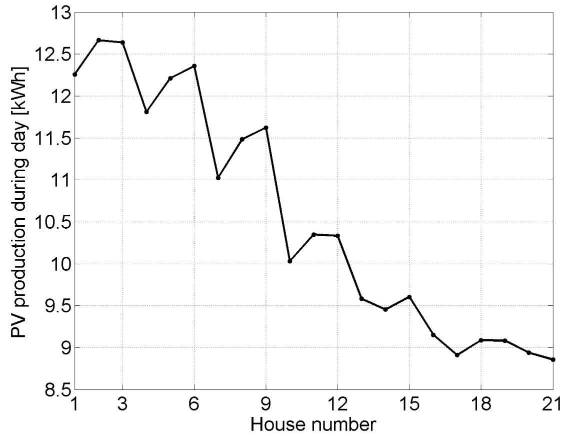

Fig. 5: Production of each solar panel in the first feeder branch of the distribution network, when curtailing is applied as voltage control strategy

B. Reactive Power Control

A second possible voltage control mechanism is that each local generating unit is asked to provide reactive power. Voltage control through reactive power is commonly used in transmission grids, and is often proposed as voltage control technique in distribution grids (see a.o. [9], [10]). LV distribution grids however generally have a more resistive than inductive character, and so providing reactive power will have a smaller impact on the voltage amplitude than in the case of the more inductive transmission grids. In addition to this, the losses in the distribution grid increase when reactive power is produced by every distributed generator.

Power flow simulations were carried out on the reference distribution network with reactive power control: in the reactive power control algorithm every generator is asked to provide an amount of reactive power that is proportional to the local voltage deviation. The power flow analysis shows that the total ohmic loss in the reference distribution network is 15.4 kWh in the reference scenario. When using reactive power control the network losses are 17.4 kWh, an increase of more than 10 % with respect to the reference scenario. The maximal voltage rise in the distribution network was 4 % with the use of reactive power control.

Each local generating unit can only deliver reactive power until the maximal output current of its inverter is reached. PV inverters will have to be overdimensioned if a considerable amount of reactive current the installations will have to deliver reactive power in order to limit the grid voltage. Overdimensioning inverters not only results in a higher installation cost, but also leads to lower overall inverter efficiencies. PV inverters operate at maximal efficiency near full load, but when the inverters are overdimensioned, they will operate most of the time at reduced load, and thus at a lower efficiency.

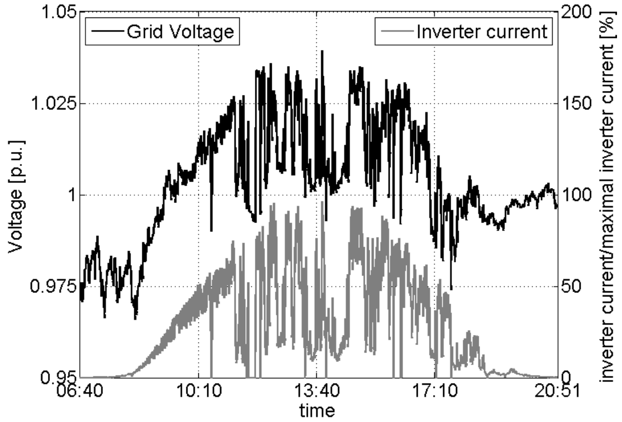

Fig. 6: Grid voltage at house number 40 (black), with the corresponding inverter output current, relative to the maximal inverter current (gray).

When no telecommunication connection is provided between the different generating units on the feeder, the generators can only provide an amount of reactive power based on information that is locally available, i.e. the local grid voltage, or the active power locally provided by the generator.

When large voltage deviations need to be suppressed, the relatively small amount of reactive power each generating unit can deliver, might not be sufficient, especially not when no coordination of reactive power production is present between the different generators on the feeder, because of the absence of communication infrastructure. This is illustrated in Fig. 6, where the grid voltage at house number 40 is shown when reactive voltage control is applied (black line); this connection has the highest node voltage in the load flow simulation. The highest grid voltage at this connection is reached around midday and is 1.04 pu. This value is still higher than the enforced voltage limit of 1.035 pu, yet voltage control through reactive power is applied. The plot also shows the inverter output current at this particular connection (gray line), and from the current plot can be seen that at moments of high output voltage, the inverter output current is also high, mainly due to high active power injection. The margin for reactive power control is thus too small to regulate the local grid voltage below 1.035 pu. If communication would be possible between the different inverters, other inverters that are present on the same feeder could help to lower the grid voltage by injecting more reactive current than is strictly needed, based on their local grid voltage.

C. *Active Power Control*

Instead of fully curtailing the local generating units when the grid voltage is unacceptably high, one can also slightly lower the active output power that is supplied by each local generating unit. For example, limiting the active output power proportionally to the deviation of the grid voltage is a possible active power control algorithm. This type of control is an extension of the previously explained curtailing voltage control strategy, where the generating units are completely switched off when the grid voltage is too high.

The use of active power control, compared to reactive power control, is more beneficial in terms of grid losses. As previously mentioned, the power flow analysis shows that the total ohmic loss in the reference distribution network is 17.4 kWh in case reactive power control is applied, where every generator is asked to provide an amount of reactive power that is proportional to the local voltage deviation. When active power control is applied, i.e. every generating unit lowers its active output power proportionally to the deviation of the grid voltage, the network losses are 14.8 kWh, an decrease of 15 % with respect to the reactive voltage control scenario.

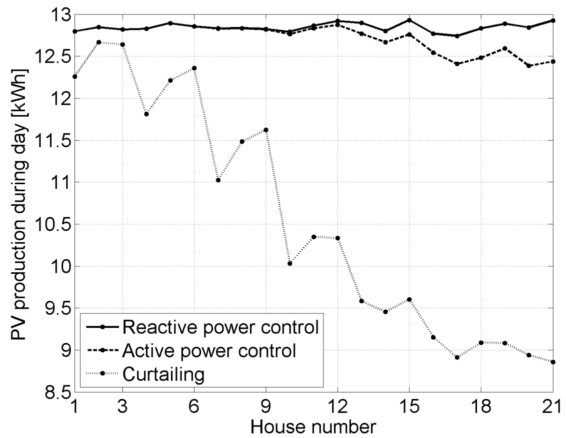

Fig. 7: Comparison of the production of each solar panel in the first feeder branch of the distribution network, when reactive power control, active power control and curtailing are applied as voltage control strategy.

In terms of cost-effectiveness of the distributed generation installations, the reactive power control performs best, because with this strategy the active power output of the photovoltaic installations is never limited. Fig. 7 shows a comparison of the production of each solar panel in the first feeder branch of the distribution network, when reactive power control and active power control are applied as voltage control strategy. The plot shows that the active power generated by the solar installations is only slightly lower when active power control is applied. The largest difference in generation is found at the end of the feeder branch where the production over one day is lowered by about 4 %, when active power control is used instead of reactive power control. As an illustration, the production is also shown when curtailing is applied, in that case the production at the end of the feeder branch is lowered by more than 30% with respect to applying reactive power control.

In order to avoid the loss of income the owners of the distributed generators experience because of the restriction of generated active power, the installations can be equipped with electrical storage, so that the generated power is not lost but can be delivered to the grid at other times, when demand is high. Of course, in this case, one should also take into account the efficiency of the electrical storage unit.

D. Additional Voltage Control Strategies

The problems with an excessive voltage occur when power production is high while at the same time the load is low, as can be seen in Fig. 3. The voltage rise on distribution feeders due to overproduction of locally installed generators may be avoided by shifting the loads. A demand response control mechanism can be installed in the different loads present on the same distribution feeder, in order to decrease the voltage problems on the feeder. An advantage of this approach is that the grid losses are not increased, nor is the profitability of the installed generators decreased. A probable issue with demand response as a voltage control strategy is the fact that enough shiftable loads have to be present.

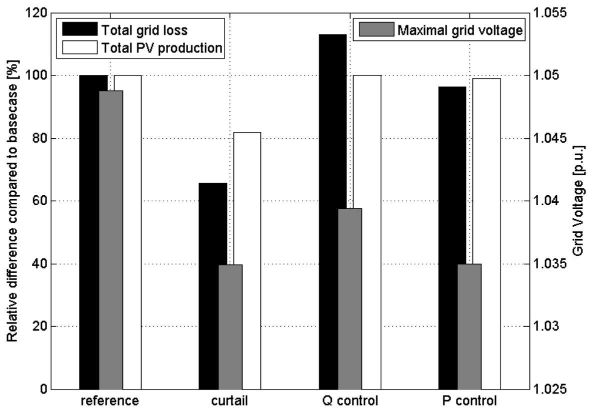

Fig. 8: Overall comparison of the discussed voltage control strategies.

6. Conclusion

In order to enable the large scale implementation of distributed generation in the LV distribution grid, new standards for the connection of locally installed generators to the LV distribution grid will have to be developed.

In this paper the influence of different voltage control strategies on distribution grid operability is assessed using power flow analysis on a typical Belgian distribution network with a considerable amount of local PV installations. The issues and advantages are discussed of three different strategies: curtailing, reactive power control and active power control. Fig. 8 shows an overall comparison of the discussed strategies. It is clear that in terms of grid losses the reactive power control strategy performs worse. Least grid losses are found when curtailing is applied, this is obvious as less power is transferred over the network. In terms of injected solar power the curtailing strategy performs worse. Only a slight amount of PV power is lost, compared to the reference scenario when active power control is used. Finally all voltage control strategies are able to lower the grid voltage, however the reactive power control strategy performs worst as the maximal grid voltage is still higher than the voltage limit set on 1.035 pu.

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