PROBABILISTIC ANALYSIS TOOL OF THE VOLTAGE PROFILE IN LOW VOLTAGE GRIDS

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ABSTRACT

This paper analyses with a probabilistic approach the massive integration of distributed photovoltaic (PV) generation sources in low voltage (LV) networks, the main impact being the increased overvoltage risk at nodes located close to PV units. The Distribution System Operator (DSO) needs to quantify this overvoltage risk and to accurately estimate and locate the probabilities of such events. By doing so, it will be able to design adequate mitigation solutions and to increase the PV hosting capacity of the network. Given the uncertainty of energy exchange in LV networks, due to the time varying PV injection and random character of the consumption loads, probabilistic models are highly recommended for their analysis. This paper presents a probabilistic framework, based on real smart metering (SM) measurements in order to simulate LV networks with distributed PV generation. The presented framework can either analyse such networks as perfectly balanced systems or consider the existing loading unbalance between phases, in case their configuration allows neglecting the mutual coupling effects between phases. In order to demonstrate the interest of the proposed framework, the latter is used to simulate an existing LV network in Belgium. The simulation results are thoroughly discussed in this paper.

Abbreviations

MV/LV	Medium Voltage/ Low Voltage
PV	Photovoltaic
SM	Smart meter
TDP	Typical Day Profile
f_i	Time repartition factor of Einj,i or Econs,i
CDF	Cumulative Distribution Function
MC	Monte-Carlo
DG	Distributed Generation
%*VUF*	Voltage Unbalance Factor
V_{nom}	Nominal voltage of the MV/LV transformer
V_{ab}, V_{bc}, V_{ca},	phase to phase voltage between phases *a-b*, *b-c* and *c-a* respectively

INTRODUCTION

In the recent years, the strategies that should be adopted in order to allow a lean transition from the concentrated to the distributed generation model are under ongoing discussion. In order to take decisions, the DSO needs to record, determine and quantify with accuracy the actual profile of LV networks with distributed PV units. The understanding of the actual situation has been lately facilitated by the smart metering (SM) devices placed in some LV networks [1-3]. Although the rolling out of these devices is now a trend in Europe, the total number of LV networks that are actually monitored, as far as individual customers' energy or power exchange are concerned, remains very restricted. It is therefore necessary to develop reliable methodologies that can simulate this natural evolution of LV networks, in a fast optimized way, by elaborating the available SM data.

According to the European standard EN50160 [4], the DSO is responsible for maintaining the voltage profile between certain limits in LV distribution networks. During periods of high PV injection and low consumption, reverse power flows towards the start of the LV feeder can occur. These reverse power flows lead to a voltage rise at the end of the feeder. If the upper limit of the rms voltage is exceeded at a certain PV node, the unit must be temporarily cut off [4-5]. This causes a loss of generated PV power which means a loss of income for the PV owner. Moreover, these frequent cut-offs affect the distributed power quality and accelerate the degradation of the network components. This fact increases the operation cost of the network, currently assigned to the DSO. In order to minimize this impact, the DSO firstly needs to locate the critical points and to quantify the overvoltage risk as well as the voltage unbalance in every LV feeder. Tracing these problems will allow to design adequate solutions and to increase PV hosting capacity of the network.

Up to now the DSO evaluates the function of LV networks using deterministic analysis tools. Thus for means of study, the energy exchange in a network with distributed PV generation is initially determined based on the "worst case" scenario. For example, as far as the evaluation of the overvoltage risk is concerned, the DSO makes its calculations considering the scenario of the highest expected PV injection and the lowest consumption load along each specific feeder. Although the "worst case" approach is safe for the protection of the electrical system, it often discards multiple intermediate network states that may also lead to overvoltage events and frequent cut-offs of the PV units. As a result, the "worst case" approach often leads to over dimensioned and costly technical solutions that do not consider the time fluctuation of the PV injection and the randomness of the consumption loads. Taking this time variance into

account will allow a refined optimized design of mitigation techniques, in terms of efficiency and investment cost. For the above reasons, a doubt concerning the sufficiency of the deterministic "worst case" models has lately arisen in literature [3-4, 6-9].
This paper presents a probabilistic framework [6-7] which elaborates statistical data of energy flow at LV network nodes and of the voltage at the exit of the MV/LV transformer. These data are recorded by SM devices that have been installed by the DSO. They are the necessary dataset for modelling the uncertain and time variable parameters of LV networks. The proposed framework can analyze a radial LV feeder either as a perfectly balanced system or by taking into account the phase loads' unbalance, only if the feeder's configuration allows to neglect mutual coupling effects between phases and to consider them as independent single-phase lines. Beyond the analysis of the actual situation, the probabilistic framework can techno-economically evaluate multiple solutions to network operational problems. It can therefore provide answers for an efficient and secure operation of LV networks.

1 PROBABILISTIC APPROACH FOR THE ANALYSIS OF LOW VOLTAGE NETWORKS

1.1. Need for probabilistic models

In the purpose of taking into account the time variation of the PV injection and the randomness of the consumption loads, probabilistic analysis methodologies were introduced in late research works [8-11]. These methodologies are based on analytical or numerical (such as Monte Carlo (MC) simulation) approaches aiming to simulate the uncertainty of PV injection and its impact on the voltage profile. Nevertheless, most of these studies propose advanced probabilistic models based on solar irradiation data for the PV panels and meteorological data for the consumption loads. Such data are rarely directly accessible to the DSO and most of them do not consider the efficiency of the PV cells.
Actually, the DSOs in several countries have installed SM that record the voltage, the current, the active and reactive powers with a considerable time resolution (10 or 15 minutes), even for domestic customers. According to European Photovoltaic Industry Association (EPIA), large amounts of such data will be available within some years [4-5]. They should then be elaborated by adequate tools for a reliable optimized techno-economic analysis of LV networks.

1.2. Voltage Unbalance

The connection of PV units in single-phase mode usually increases the voltage unbalance in a LV feeder [12]. Indeed, nowadays the common practice is to take no action for a balanced distribution of the PV generation among phases. The voltage unbalance can be quantified thanks to the Voltage Unbalance Factor (%VUF) which is defined by the IEEE as follows [13]:

$$\%VUF = \frac{V_n}{V_p} \cdot 100 \qquad (1)$$

subject to:

$$Vp = \frac{V_{ab} + \alpha \cdot V_{bc} + \alpha^2 \cdot V_{ca}}{3} \qquad (2)$$

$$Vn = \frac{V_{ab} + \alpha^2 \cdot V_{bc} + \alpha \cdot V_{ca}}{3} \qquad (3)$$

where $\alpha = 1 \angle 120^\circ$ and $\alpha^2 = 1 \angle 240^\circ$.
According to the EN50160 standard [4], the %VUF must not exceed the value of %2 for more than 5% of the time (95-percentile limit). In numerous network configurations, the distance between phases allows neglecting their mutual coupling effects. Each phase can thus be considered independently as a single-phase line with its respective single-phase loads/PV connections. The per phase voltage values are then used to calculate the nodal %VUF factor, according to (1) and compare it to the EN50160 requirements.
In the purpose of treating such a network case, [14] presents a voltage unbalance sensitivity analysis and a stochastic evaluation with a MC model, considering different ratings and locations of single-phase PV units in a LV feeder. It is shown that the voltage unbalance at the end of the feeder is highly affected when alternating PV units' size and locations. However, in that study the statistical distributions of the time fluctuating parameters are not based on real SM measurements of PV customers' energy flow. The probabilistic framework presented in this paper can analyze the voltage unbalance in such networks, as long as their configuration allows neglecting mutual coupling effects between phases.

1.3. Contribution of the present study

Unlike previous studies, the probabilistic framework of this paper is based on a MC algorithm that uses statistical distributions (Cumulative Distribution Functions (CDFs)) of 15-min SM data of individual customers' PV injection and consumption load and of the voltage at the MV/LV transformer. The presented framework can be used to analyze LV feeders which, depending on the study objectives, can be either simulated as perfectly balanced systems or unbalanced systems in which the mutual coupling effects between phases can be neglected.
The development of the proposed probabilistic framework is presented §2. The analysis framework is applied for the simulation of an existing LV feeder in Belgium with distributed PV generation in §3.The simulation results are thoroughly discussed in the same section. Finally, in §4 the principal conclusions and the future perspectives concerning the actually developed probabilistic framework are discussed.

2 PRESENTATION OF PROPOSED METHODOLOGY AND SOFTWARE

To start with, Typical Day Profiles (TDPs) are created for every quarter of an hour in a day (96 quarters of an hour) in accordance with the SM data that are also recorded on a 15-min basis [6-7, 15-16]. These profiles are the basis for the development of the probabilistic method. Created independently for each node, the TDPs reflect the variation of energy flow (injection and consumption separately) and the time repartition of the energy flow within the 15 minutes, for every quarter of an hour in day, during the studied period. Similar TDPs are also created to reflect the variation of the voltage at the exit of the MV/LV transformer. It is worth to mention that this methodology can be very easily adapted to another time resolution of SM measurements. In most cases, SM devices in LV networks in Europe record energy flows on a 15 or 10 minute time resolution.

Practically these TDPs comprise 96 (number of quarters of an hour in a day) CDFs of probability for each one of the variable parameters. Once all these TDPs are created for every 15-min interval, the MC algorithm that is integrated in the probabilistic framework samples from them multiple (>1000) random 15-min network states. These randomly generated states are defined by different combinations of the values of the variable parameters that have been recorded within the studied period.

As soon as these network states are sampled for each 15-min interval, an integrated algorithm performs a power flow calculation for each one of them. The rms voltage is in this way calculated node by node for each 15-min network state. These 15-min values are compared to the voltage band that is imposed by EN50160 or to other more restrictive national or local directives [1-2]. In case the analysis takes into account the loading unbalance between phases, and therefore computes each phase as an independent single-phase line with its single phase PV units/loads, the nodal $\%VUF$ is also calculated for each network state according to (1). In this way, the overvoltage probabilities and the voltage unbalance risk can be calculated, node by node, for the studied period.

3 SIMULATION OF AN EXISTING LOW VOLTAGE NETWORK IN BELGIUM

In this paper, the probabilistic framework simulates a real LV feeder with distributed PV units for every month of a typical year, considering SM data recorded on a 15-min basis over a period of two years. The LV feeder, which is located in the city of Flobecq in Belgium, is illustrated in figure (1) and technically described in [15-16]. In total, 16 clients are connected to the feeder and in reality 3 out of them are equipped with a PV unit (5kVA at node 4, 2.65 at node 12 and 5kVA at node 3). In order to clearly demonstrate the influence of the PV generation on the voltage variation, 6 more PV clients have been considered at nodes 5, 6, 8, 10, 11 and 14 for this simulation. For these units, the same PV injection SM data as for the PV unit at node 13 were considered.

Time variation of the voltage profile at node 14 is shown in figure (3). Since the probabilistic calculation considered a different combination of energy exchange values for each quarter of an hour, the calculated voltage is also variable on a 15-min basis. In case of a deterministic analysis, the calculated voltage would have been a stable "worst case" value characterising the whole day. However, it is clear that the voltage rises only during certain hours of the day, usually between 11:00A.M. and 16:00P.M. On the other hand, a significant voltage drop takes place between 18:00P.M. and 21:00P.M., due to peak electricity demand, that increases undervoltage risk (<0.90Vnom) during this period. Therefore, it is wise to refine actions against this important voltage variation and to adapt them to such observations, taking each time into account current network state; otherwise the measures can be too restrictive for potential PV hosting capacity of the network or much less optimised in terms of efficiency and the cost.

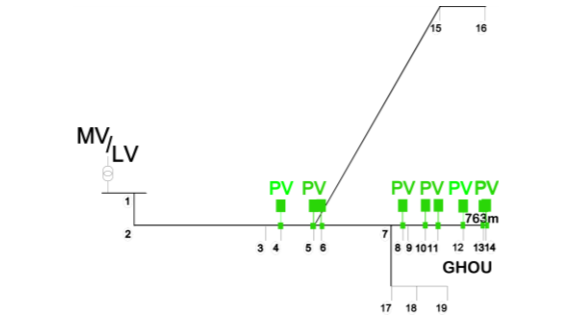

Figure 1: The simulated LV feeder (3φ/balanced configuration)

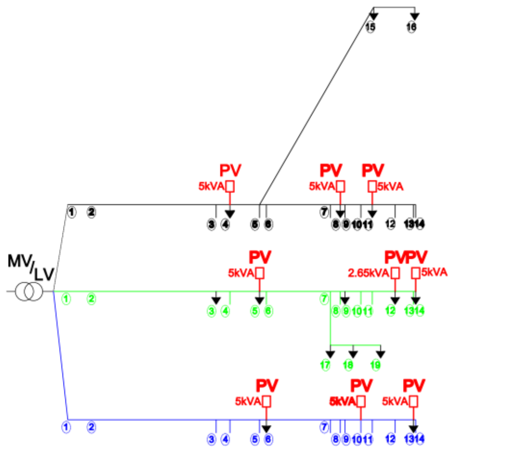

Figure 2: The simulated LV feeder (1φ/unbalanced configuration)

The results of the probabilistic simulation for the overvoltage risk are presented for each node in figure (4). This risk is defined as the probability of overpassing the limit (>1.10Vnom) suggested in the European standard EN50160. According to the standard, the PV unit must be instantaneously disconnected in case the mean node rms voltage during the last ten minutes exceeded the $1.10V_{\mathrm{nom}}$ limit or in case the node rms voltage instantaneously exceeded the $1.15V_{\mathrm{nom}}$ limit. In general, these events must not take place for more than 5% of the time. Looking at the diagrams, it is clear that the overvoltage risk is higher during the months with high solar irradiation (June to August) or with a long sunny period (March to June). This is expected for periods of low energy consumption along the feeder and high PV generation, since reverse

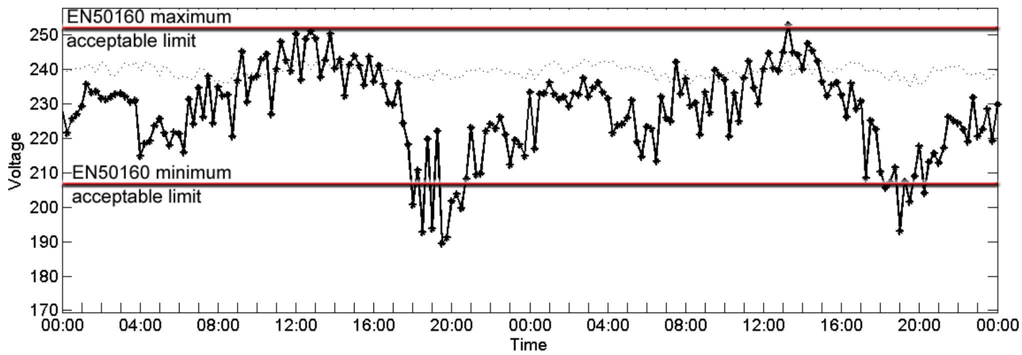

Figure 3

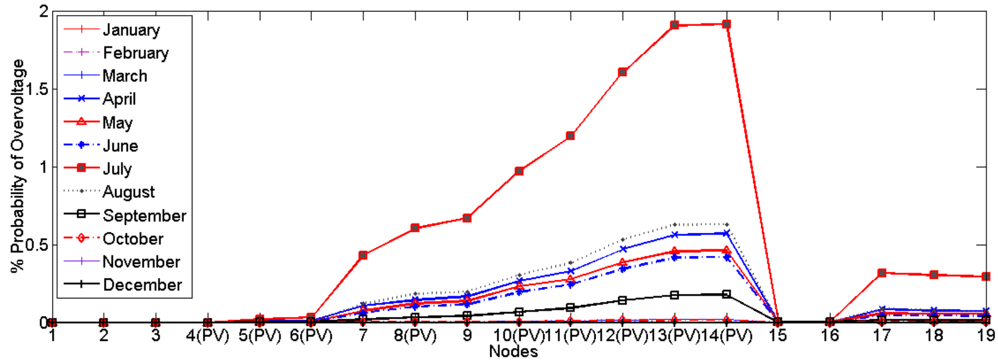

Figure 4

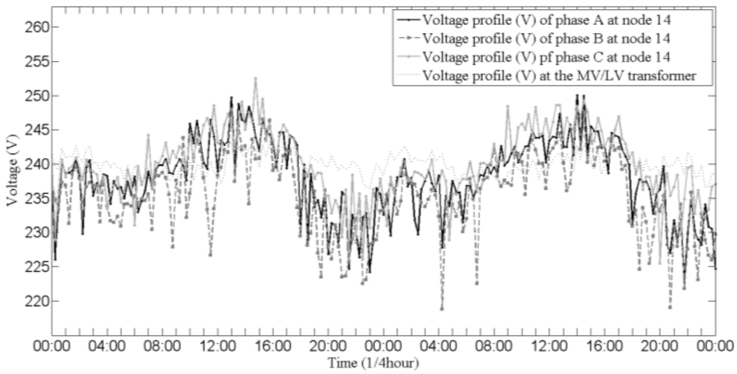

Figure 5

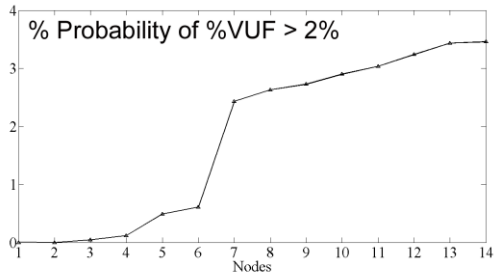

Figure 6

Figure 3. Voltage (V) at PV node 14 during two typical days in April, calculated on a 15-min basis.
Figure 4. Overvoltage risk at the nodes of the simulated feeder for every month of a typical year.
Figure 5. Phase Voltages (V) at PV node 14 during two typical days in July, calculated on a 15-min basis.
Figure 6. The $\%VUF$ for the main line nodes for the month of July

power flows can lead to an instantaneous rise of the voltage profile towards the last nodes. Nodes adjacent to PV units are also affected by rapid voltage variations and oscillations (caused by the on-off control of the units) since these last ones accelerate the degradation of all network components.

In the purpose of studying voltage unbalance caused by unbalanced single-phase PV units and loads connections, the configuration presented in figure (2) was also simulated. To that end, the mutual coupling effects between phases were not taken into account. This means that PV units and loads are considered connected in a single-phase mode, as shown in figure (2), and each phase was separately computed as a single-phase line. The consumption load and the PV unit of each prosumer are both considered to be connected to the same phase. A lateral with 2 loads is connected to phase *a* at node 5 and a lateral with 3 loads is connected to phase *b* at node 7. Every phase was therefore independently computed with its own PV units and loads by applying the forward/backward power flow algorithm used in [6].

Therefore, the voltage profile of each phase at node 14 for two typical days of July is shown in figure (5). As expected the voltage of phases *a* and *c* is higher than the one of phase *b* since the total PV generation connected to this last one is smaller than the one of phases *a* and *c*. The %*VUF* for the nodes of the main line is presented in figure (6). The EN50160 standard suggests that the %*VUF* along the feeder should not exceed the value of 2% for more than 5% of the time. Indeed, for the studied period the %*VUF* does not exceed this value at none of the nodes.

The presented probabilistic framework can calculate such network operation indexes (over voltage risk, under voltage risk, %*VUF,* overloading, captured PV energy,…) along any LV feeder with PV units. LV feeders can either be analysed as perfectly balanced systems or by considering the phase loads' unbalance as long as the configuration allows neglecting mutual coupling effects between phases. Mitigation solutions can also be techno-economically compared based on the network operation indexes obtained of the simulation of each one of them.

4 CONCLUSIONS

The natural evolution of LV networks with high PV integration and random character of consumptions loads, both uncertain and time variable parameters, requires the development of new accurate optimised methodologies for their analysis. To this end, probabilistic approaches are highly recommended since they can simulate LV networks taking into account the time variation of PV injection and consumption loads. This paper presents a probabilistic framework which analyses in a fast optimised way the voltage profile along LV feeders, considering the uncertainty of their loading parameters node by node, based on real SM data. The presented framework can simulate either perfectly balanced systems or unbalanced systems in which the mutual coupling effect between phases can be neglected and each phase can be computed as an independent single-phase line. It can therefore be deployed for the techno-economic evaluation and refinement of solutions to operational problems in LV feeders with high PV penetration. The only prerequisite for its deployment is the availability of SM measurements in the studied LV feeder. This prerequisite goes along with the perspective of a wide rolling out of SM devices in the European LV networks.

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