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Development of a probabilistic tool using Monte Carlo simulation and smart meters measurements for the long term analysis of low voltage distribution grids with photovoltaic generation

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ABSTRACT

Connections of distributed generation (DG) units based on the use of photovoltaic cells are highly increasing in low voltage distribution grids. In that way, one of the major problems met by the Distribution System Operators (DSOs) comes from overvoltage in the neighbourhood of dispersed units. Consequently, it is important for them to have an analysis tool that computes statistical voltage profiles and allows to assess maximal penetration rates of photovoltaic generation (PV) on low voltage (LV) distribution feeders. In previous studies, it has been shown that such a tool could be obtained by using a Probabilistic Load Flow based on analytical techniques or Monte Carlo methods.

In this paper, given its simplicity of implementation, a pseudo-chronological Monte Carlo simulation is used and the statistical behaviour of prosumers (consumers with PV units) is directly based on smart meters measurements. Thanks to this tool, and using collected measurements from smart meters that are expected to be massively deployed in the future, it will be possible for the DSO to directly assess voltage profiles at all the nodes of the LV grid. Moreover, in the context of alleviating the impact of photovoltaic generation on the recorded voltage profiles, smart meters data will also be used in order to not only quantify the influence of reactive power flows on the collected results but also to estimate the auto-consumption potential over some critical nodes of the grid.

1. Introduction

Following the Kyoto agreements and in the context of a liberalised energy market, decentralized generation often based on renewable energy sources is emerging in medium (MV) and low voltage (LV) grids. Those networks are becoming more and more active systems with power flows and voltage profiles influenced by both generation and consumption. In the future, given the "20–20–20" objectives of the European Union and the more ambitious objectives in Wallonia (Belgian region), the expected penetration of decentralized generation in distribution grids could lead to a critical behaviour of a system that has not been initially designed and sized to face power injections coming from dispersed units.

In LV grids, one of the major problems that could be met by the Distribution System Operators (DSOs) comes from overvoltage in the neighbourhood of a decentralized generation unit. Such a situation could happen during periods of low consumption and high production of the dispersed units, especially on long circuits. Reverse power flows going up towards the MV/LV transformer can then degrade the network stability [1–3].

The DSO is responsible for the security of its system and power quality. For example, Distribution Networks Operators must keep steady-state voltages within the limits stipulated in the regulations [4,5] (e.g. +10/−6% during 98% of the week in Australia, ±10% during 95% of the week in the European standard EN 50160, etc.). It is therefore important to estimate critical penetration rates of decentralized generation in LV grids, to associate a probability to the simulated risky states and to precisely locate the "hot" nodes of the network. This long term analysis is necessary to define tailored solutions to the massive integration of DGs, considering technical and economical constraints.

In order to estimate investments, some early developments have been proposed in [3]. If the analytical method introduced in the referenced paper allows the computation of a maximal penetration rate of photovoltaic generation on a given LV feeder, this method is based on restrictive hypotheses like the assumption of a purely resistive network or a linear distribution of loads along the LV connections, etc. Consequently, this analytical approach can lead

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to overestimated reinforcements and can be insufficient for the accurate quantification of critical overvoltage situations. Practically, the deterministic modelling of radial distribution grids with PV generation units is not advisable given their random behaviour and their spatial correlation [6]. Therefore, Probabilistic Load Flow techniques [2,7] represent tools that are better suited in order to accurately assess the uncertainty associated to fluctuating PV generation. In that way, a planning tool based on a Probabilistic Load Flow developed in a pseudo-chronological Monte Carlo environment [2,8] was proposed in contribution [2]. In that paper, a deterministic approach based on mean hourly generation and consumption was compared with another one that takes into account the random behaviour of both the load and the photovoltaic generation during each hour of the simulated pseudo-chronological Monte Carlo process. It was so concluded that, thanks to the consideration of the hourly probabilistic behaviour of PV generation, this approach was leading to critical photovoltaic penetration rates much more restrictive than the ones computed with a deterministic load flow. Nevertheless, this paper was only considering entire correlation scenarios between load and PV generation. In that context, Refs. [6,7] evaluate different scenarios of spatial correlation for PV generation and load. Moreover, Ref. [7] introduces an analytical method that combines the cumulant method with the Cornish–Fisher expansion to solve the voltage regulation problem in radial distribution networks. This analytical approach is then compared with a traditional Monte Carlo method and is proved to have better performances in terms of rapidity of convergence and computational cost. Finally, it is interesting to note that, until now, references found in the literature [2,6,7,9–11] were all built on solar irradiance measurements, which are not necessarily available for the DSO and do not take into account the efficiency of the cells.

Based on this review of the bibliography, a probabilistic tool using a pseudo-chronological Monte Carlo approach is developed in this paper. The choice of the Monte Carlo method is justified by its simplicity of implementation. The developed tool presents the originality to lie on energy data measured thanks to smart meters that have been installed, jointly to PV installations, in the city of Flobecq (Belgium). This approach allows the definition of the statistical behaviour of PV generation directly on basis of data measured by the DSO. Moreover, several correlation scenarios between customers and the potential of auto-consumption (PV power directly consumed by the prosumer) can be computed thanks to the proposed approach. Finally, the influence of reactive power as well as on the recorded voltage profiles as on the current flown in the lines can also be investigated with the proposed probabilistic tool.

The current paper is structured as follows. Firstly, the main objectives of the study are described in Section 2. Then, in Sections 3 and 4, the approach used in order to define the statistical behaviour of each prosumer (a prosumer is a customer with its own PV) on basis of smart meters measurements is detailed.

Based on [12], Section 5 describes a simple analytical approach in order to calculate the voltage profile along a radial LV feeder. In a sixth part, to assess probabilities of overvoltage (or undervoltage) in a distribution network, a software tool using pseudo-chronological Monte Carlo simulation is presented. Practically, this tool computes (quarter of an hour by quarter of an hour) voltages along the studied feeder throughout the specified period of time (specified number of system states to be simulated in order to have a convergence of the calculated probabilities and voltage profiles). Finally, the application to a practical case study is discussed to show the results of the proposed tool, to demonstrate its interest for DSOs and to introduce the impact of some eventual solutions (reactive power control, load shifting, etc.) in order to alleviate the influence of PV generation on the voltage in LV grids.

2. Aim of the study

Given the massive deployment of PV generation combined with the apparition of new electrical loads (like electric vehicles, storage with batteries, etc.), the long term planning of LV grids is a real need. For example, in 2012, around 300 PV installations with a peak power set between 3 and 5 kW have been installed in the city of Flobecq (Belgium) on citizens' roofs. This amount of PV generation is quite important at the city scale as it represents a penetration rate of about 25%. This rate is defined, in fact, as the ratio between the number of PV connections and the total number of connections at the city scale. As this LV network is an example of what could be LV grids in a mid-term future, the DSO has installed smart meters to measure, on a "quarter of an hour" basis, consumed and injected energy, as well as other electrical values interesting for grid sizing and operation. In this paper, a probabilistic tool is developed on the direct basis of the data provided by the smart meters and no more on irradiance measurements like it was the case in [2,6,7,9–11]. In order to implement this tool, a typical day of a given month is statistically defined using the smart meters measurements. Here, the month August is chosen because it is typically a month with an increased PV generation (normally, days are sunny) and a low load level (some people can be on holiday). However, note that this approach could be extended to larger periods (on seasonal or annual basis). For each customer, each quarter of an hour of the "typical day" is characterised by a Cumulative Distribution Function (CDF) [13] associated to the mean quarter-hourly power injected towards the grid and a CDF associated to the mean quarter-hourly power consumed from the grid. This approach allows the definition of the statistical behaviour of PV generation directly on basis of data measured by the DSO. Moreover, with the developed tool, it is possible not only to access the reactive power consumed by each prosumer but also to model the influence of a reactive power control on the PV inverter [14]. Finally, thanks to the comparison of different contexts of PV dependence, Ref. [6] clearly demonstrated that, when there are different locations for PV installations in a given area, an important factor to take into account was the spatial correlation between those PV generation units. In the proposed study, the importance of this factor is confirmed thanks to the simulation of several correlation scenarios between customers.

3. Definition of a monthly "typical day" for a prosumer on basis of smart meters data

In this section, the idea is to define quarter of an hour by quarter of an hour two CDF representing the statistical behaviour of a prosumer for the injection towards the grid and for the consumption from the grid, respectively. For a "typical day", $(2 * 96)$ CDF must thus be computed. In the current case, those CDF are based on a monthly approach. Indeed, only measurements of a given month (the same month taken into account over several years of measurements) are considered for the definition of our "typical day". Note that only August 2012 measurements have been taken into account for the definition of the typical day, as the meters started to be installed in end 2011. Measurements over coming years will improve the quality of the CDF that will be so defined from an extended amount of data. August has been chosen as it can be considered as a critical month in terms of high PV injection (days are normally sunny during the summer) and low load level (holiday time).

In order to implement the CDF computation, measurements from the smart meters installed in Flobecq have been used. Each prosumer is equipped with two smart meters (see Fig. 1). Note