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Probabilistic simulation framework for balanced and unbalanced low voltage networks

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ABSTRACT

In Low Voltage (LV) distribution networks, the high volatility of distributed photovoltaic (PV) generation has a severe impact on the variation of operation indices, in steady state conditions. During periods with high PV injection and low demand, LV feeders are more and more subject to overvoltage events and temporary PV units' cut-offs. As a result, the delivered power quality is affected and network operational expenses increase. Moreover, the income of the PV owner is decreased due to the loss of generated energy. For efficiently addressing such operational issues, long term observability analytics of the LV network are required. Distribution System Operators (DSOs) currently deploy such studies in a deterministic manner, focusing on "worst-case" hypothesis, without considering the uncertainty of nodal power injection and consumption. This approach can lead to over restrictive decisions and costly technical solutions. For refining DSO strategies to the variability of network states, probabilistic methods are highly recommended. In this context, this paper presents a Monte-Carlo (MC) framework that simulates the steady operation of the LV network by elaborating user-specific smart metering (SM) measurements. The presented framework integrates a complete three-phase power flow algorithm that can analyse most possible LV network configurations, balanced and unbalanced, considering nodal power injections and consumptions as random variables of each network state. Such unbalanced power flow algorithms had not up to now been linked with probabilistic analysis using network-specific SM readings. For demonstrating the interest of the proposed framework, the latter is used to simulate several configurations in an existing LV feeder with high PV integration and SM deployment.

Introduction

In recent years, the ongoing development of distributed photovoltaic (PV) generation in Low Voltage (LV) networks raises a number of issues that need to be investigated before taking decisions on further developments to come. Which strategy should Distribution System Operators (DSOs) adopt for allowing a lean transition from the "concentrated" to the "distributed" generation model without compromising the network stability, the quality of distributed power and a maximal performance of PV units? Which will be the cost to pay to compensate for PV related problems? Which technical strategies to deploy for fairly allocating distribution costs to all users?

For answering such questions, long term observability analytics of the LV network are necessary. Given the high volatility of distributed generation and consumption loads, new models need to be developed for addressing the induced uncertainties [1]. The understanding of the actual situation in LV distribution has been lately facilitated by the sparsely deployed SM devices while their large deployment is considered as the next important milestone for power distribution. (Pseudo) measurements deployed at several locations over a long period, with updating latencies of 10–15 min, can be exploited for a reliable and information-rich observability of the network, useful to many different systems across distribution utilities. Compared to real-time telemetered data, such long term measurements are more suitable for techno-economic analysis and network development studies. Focusing on long term observability of the LV network, the present paper develops a comprehensive framework that elaborates such metering

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Nomenclature

MV/LV	Medium Voltage/Low Voltage
PV	Photovoltaic
SM	Smart Meter
TDP	Typical Day Profile
$E_{inj,i}$	total quarter-hourly (15-min) injected energy at node i [kW h]
$E_{cons,i}$	total quarter-hourly (15-min) consumed energy at node i [kW h]
$P_{inj,i}$	peak injected power at node i during a 15-min interval [W]
$P_{cons,i}$	peak consumed power at node i during a 15-min interval [W]
f_i	time repartition factor of $E_{inj,i}$ or $E_{cons,i}$
m	iteration index of the Monte-Carlo algorithm
l	iteration index of the power flow algorithm
q	index of the simulated 15-min interval of the day (with $q = 1{:}96$)
E	convergence error of the power flow algorithm [V]
$\left[Y_{012}^{Z}\right]$	sequence components admittance matrix [S]
y_0^z, y_1^z, y_2^z	zero, positive and negative sequence admittance matrix [S]
CDF	Cumulative Distribution Function
MC	Monte-Carlo
DG	distributed generation
%VUF	Voltage Unbalance Factor (%)
V_{nom}	nominal voltage of the MV/LV transformer [V]
$\underline{\boldsymbol{V}}_{initial,abc}$	matrix of initial nodal voltages (phase components) [V]
$\underline{\boldsymbol{V}}_{initial,012}$	matrix of initial nodal voltages (sequence components) [V]
$\underline{\boldsymbol{S}}_{load,abc}$	matrix of initial nodal loads (phase components) [VA]
$\underline{\boldsymbol{S}}_{load,012}$	matrix of initial nodal loads (sequence components) [VA]
$\underline{\boldsymbol{S}}_{\boldsymbol{lateral}}$	total transited power by each unbalanced lateral (per phase) [VA]
$\underline{\boldsymbol{I}}_{load,abc}$	matrix of initial nodal currents (phase components) [A]
$\underline{\boldsymbol{I}}_{load,012}$	matrix of initial nodal currents (sequence components) [A]
$\underline{\boldsymbol{V}}_{abc}$	matrix of computed nodal voltages (phase components) [V]
$\underline{\boldsymbol{V}}_{012}$	matrix of computed nodal voltages (sequence components) [V]

data for evaluating the most important steady operation indices. The latter are outlined in the following paragraphs.

Regarding steady state conditions, the main concern in LV networks with distributed PV generation is voltage profile. The volatility of PV generation has a severe impact on the variation of voltage profile. During periods of high PV injection and low demand, reverse power flows towards the head of the feeder become more frequent and lead to voltage rise towards the end of the feeder. If the r.m.s. voltage at a certain PV node exceeds the upper limit suggested in the EN 50160 standard, an overvoltage event takes place and the PV inverter must be temporarily cut off [2,3]. A loss of generated PV power is therefore induced which means a loss of income for the PV owner. Besides, this hard curtailment of PV generation deteriorates the delivered power quality, due to significant voltage and current transients, and accelerates the degradation of inverters [4].

Voltage magnitude variation is not the only concern in LV networks with PV units. In three-phase LV networks, unbalanced single-phase loading and generation lead to unequal voltage magnitudes over the three phases. The increased current in the neutral conductor, due to unbalance, results in neutral-point shifting which is disadvantageous for the voltage profile. Voltage unbalance adversely affects network elements and connected equipment [5,6] while the network induces more losses and heating effects. Although restrictions on unbalance of assets are imposed since the 1950s [7], it has always been a challenging issue which nowadays emerges due to the on-going single-phase connection of distributed generation (DG) sources.

In case of urban grids the maximum loading current (and the induced congestion risk) is the main source of power quality issues given that they supply many households in a small area; the transformer capacity and the number of connected users are high and the length of lines is short. At the same time, reverse power flows due to high PV injection can significantly increase line losses and operational expenses (OPEX) that the DSO needs to cover. Finally, other operational indices such as the DG impact on protection failures or network equipment ageing should also be treated with a long term view.

Nowadays, DSOs are called to safeguard a stable and secure power supply in all possible demand conditions while fostering the massive integration of DER generation. As a result, the adoption of a streamlined planning approach for analysing the current energy system becomes urgent and the necessity of leaving behind deterministic worst case design is highlighted. Indeed, it is in the economic interest of the DSO and of the network user that power supply relates to normally expected conditions rather than to extreme cases [3]. A large variety of commercial and non-commercial algorithms are nowadays available for deploying long term analysis of LV networks. The vast majority of them apply a deterministic approach. The software user models the network by deterministically defining the parameters that influence its operation, considering most of the times worst case scenarios. The purpose is to ensure 100% security of the system. For example, the steady state analysis for determining the overvoltage risk in an LV feeder usually considers that each PV unit injects power equal to its rated power and each supply point consumes its lowest expected load. Based on such extremely rare cases, voltage magnitudes near PV nodes result very high compared to the situation that usually occurs. As a result, the DSO determines the maximum acceptable PV power that a feeder can host in a very restrictive manner since this one heavily depends on the feeder's voltage margin. Naturally, this approach may lead DSOs to high initial investments with low amortization rates as well as to very restrictive decisions in terms of DER hosting capacity.

However, if one leaves behind deterministic worst case approach, a new challenge appears. Is there a reliable and accurate way for simulating the most usual operating conditions of LV networks? How can one choose which network states to focus on? The present study investigates whether the above questions regarding LV network modelling could be efficiently answered by applying probabilistic analysis taking advantage of the available SM measurements. For examining this hypothesis, a careful literature review has been initially deployed in Section 'State of the art'.

The main contribution of this paper is presented in Section 'Approach and contributions of this study'. Practically, a novel probabilistic simulation framework is presented. First of all, unlike