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Technical impact of photovoltaic-distributed generation on radial distribution systems: Stochastic simulations for a feeder in Spain

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ABSTRACT

The assessment of the technical impact of photovoltaic-distributed generation (PV-DG) units on radial distribution systems (RDSs) is complex because of the probabilistic nature of their output power and the diversity of potential sites where they can be installed. This type of evaluation thus requires a multivariate probabilistic analysis involving non-Gaussian correlated random variables.

In a previous study, we applied an analytical technique to assess this technical impact for a single 10-min period. In the research presented in this paper, this technique was improved so that it could be applied during a full year, assuming 10-min intervals for PV and load profiles. This is the time period required to accurately assess the effects of stochastic PV inputs, and to determine the improvement of power quality (PQ) parameters, based on current regulations.

This article describes a case study for a rural RDS located in the region of Andalusia in the south of Spain with spatially correlated PV-DG units. Our objective was to improve the analytical technique and also the accuracy of probabilistic methods. In our opinion, this can enhance the operation and planning of PV-DG in RDSs and provides a better understanding of the effects of spatial PV dependence structures.

1. Introduction

Although the integration of DG in radial or meshed systems is a source of technical and economic benefits [1–8], it can also lead to safety problems [1]. The main technical benefits are the following: (i) improvement of voltage stability and voltage profile; (ii) power loss reduction; (iii) enhanced system reliability and security; and (iv) improved power quality (PQ) and support of ancillary services. Various individual or multi-objective indices have been proposed to quantitatively evaluate some of these technical benefits [2–5].

One of the DG technologies is PV. Therefore, PV-DG provides RDSs with a number of technical benefits [9–15]. In order to maximize benefits and minimize problems, various technical specifications have been adopted in countries throughout the world for the interconnection of DG [16] and particularly for PV-DG units [17,18].

Numerous researchers have studied how to optimize the penetration and siting of DG in distribution systems. A detailed description of research on the topic is given in [11,12,19]. Generally, such studies propose a multi-objective optimization approach in order to ensure technical benefits, such as maximum loss reduction, improvement of voltage profile, and minimum costs. Focusing on PV-DG units, we [9,10] developed an automatic algorithm to obtain the optimal allocation and sizing of PV-DG units in RDSs, based on a multi-objective optimization approach. For this purpose, we took into account technical aspects to improve the voltage profile, branch load levels, and voltage stability. Also taken into account were cost-effective measures for both PV generation and the reduction of feeder loss.

Since the proliferation of PV-DG in RDSs may alter their behavior, effective assessment tools are needed. The deterministic modelling of RDSs with stochastic PV-DG units is not advisable for the following reasons: (i) PV power outputs are spatially correlated random variables; (ii) the load profiles of an RDS are random variables. Therefore, Probabilistic Load Flow (PLF) techniques [20,21] (e.g. analytical techniques or Monte-Carlo Simulations [MCSs]) are tools that can more accurately assess the uncertain impact of PV-DG in combination with deterministic methods [9,10,22].

We proposed an analytical technique in [21] to account for multi-correlated input data uncertainties. In this case, it was specifically conceived for an RDS with PV-DG. This technique, which involved a Probabilistic Radial Load Flow (PRLF) based on the Cumulant method, reconstructed the solution by using the Cornish-Fisher expansion. We demonstrated the accuracy of this method by comparing its results with the MCS with 10,000 trials, which was the reference. The low value of the (average) individual relative errors was evidence of the accuracy of the technique. A rank correlation matrix

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was used to represent the dependence of the PV-DG units. This type of matrix has also been successfully applied to the simulation of wind power injections [23,24].

However, the analytical technique in [21] was only able to evaluate the technical impact of PV-DG on RDSs for a single 10-min interval and did not take into account longer time simulations. Therefore, this paper presents a generalized analytical technique that can be used to evaluate the technical impact for both series of loads and PV generation for any period of time. Nonetheless, the results of this study are for a one-year time period, which is the necessary duration to accurately assess the effects of stochastic PV inputs and to determine the actual improvement of PQ parameters.

For example, distribution network operators must keep customer voltages within the limits stipulated in the regulations [25–28] (e.g. ±6% Australia, ±7 Spain, ±7.5% Hungary, and ±10%, EN 50160). This assessment must be performed for any week of the year [28] and is based on the measurement of the voltage magnitude averaged at 10-min intervals. The voltage values measured during this one-week period are statistically characterized (Cumulate Distribution and Probability Density Functions CDFs, PDFs). Finally, the index used to characterize the voltage magnitude is typically the 95th weekly percentile of the 10-min averaged values [28], which must not be higher than the highest limit in the regulations. Accordingly, the 5th weekly percentile should not be lower than the lowest limit in the regulations.

The paper is structured as follows. Section 2 explains the main objective of this study. Section 3 outlines the generalized analytical technique proposed. Section 4 describes the RDS data that were assessed from the rural feeder [ENDE 100 RDS] in [10], its load, and the PV generation data. Section 5 discusses how the generalized analytical technique was applied to the ENDE 100 RDS with PV-DG units. This section thus shows the PDFs and CDFs of certain RDS variables (e.g. the most critical node voltage and line power flow as well as the total losses). Finally, the conclusions that can be derived from this study are presented in Section 6.

2. Aim of the study

Increasing the value of PV-DG through the accurate assessment of its performance in RDSs will doubtlessly be one of the priorities in PV energy research in the coming years. When there are different locations for PV-DG units in an area, an important factor to take into account is the dependence of stochastic PV infeeds, induced by the inertia of meteorological systems. When independence is assumed, this considerably reduces the accuracy of the technical impact assessment [29,30] since spatial PV dependence has a significant impact on the overall prediction of uncertainty for the whole area.

This paper focuses on the assessment of the technical impact of PV-DG units on a RDS within the context of the spatial PV dependence structure. New contributions with respect to previous research in [21] are the following: (i) the proposal of a generalized analytical technique that uses stochastic time-series of load and PV generation for a one-year period; (ii) the comparison of different contexts of PV dependence that highlights the importance of the modelling of spatially correlated PV-DG units in RDSs and affords a better understanding of this type of dependence structure.

It was not easy to choose an RDS for our study since RDSs can have a variety of potential load profiles and design characteristics. Nevertheless, for our purposes, we selected an ENDE 100 RDS [10] because it had a suitable mix of consumer classes as well as design characteristics that were typical of feeders in Andalusia (southern Spain). Furthermore, a large set of 10-min load data was available from the local electric utility company.

An important concern for technical impact assessment is simulation time resolution. For example, in an annual simulation, the 1-min resolution has a high computational cost [31] whereas the 1-h resolution provides sufficient accuracy for estimating the distributions of RDS variables (e.g. voltage profiles) [32]. However, our study required a10-min assessment since its objective was to compare the node voltage improvement of the RDS to the voltage limits in the regulations [25,26,28].

3. Computational procedure

Fig. 1 shows a flowchart of the generalized analytical technique, which is explained in the following sections. Succinctly put, in this technique, two meteorological random variables are used to obtain the output PV power for each ith 10-min interval at any jth location, which has a correlated spatial PV dependence structure. Taking as input the cumulants of the PV-DG and the loads, a PRLF provides CDFs and PDFs of voltages at the nodes, the power flows in the lines, and the total real losses for each ith 10-min interval. This process is repeated until the total number of simulations throughout the year is reached. When all simulations are run, a finite mixture provides the results for the annual distribution functions.

3.1. Load modelling

The stochastic load model used in our research is described in [20,21]. In this model, load consumption profiles for each kth node are generated from Typical Daily Profiles (TDPs) for different consumer classes. This approach treats the TDPs of each jth consumer class $\boldsymbol{L}_j(m, 10\text{-min}_i)$ as a normally distributed random variable, which changes from month to month (m) and during each ith 10-min interval. For each jth consumer class, seven TDPs were specified per month: two for weekends $\boldsymbol{L}_j^{we}(m, 10\text{-min}_i)$ and five for working days $\boldsymbol{L}_j^{wo}(m, 10\text{-min}_i)$.

The random variable, 10-min real power consumed by the kth node of an RDS in the mth month and during the ith 10-min interval was obtained by adding the random variables $\boldsymbol{L}_j(m, 10\text{-min}_i)$. For example, for working days (Fig. 1):

$$\boldsymbol{P}_{\boldsymbol{Lk}}^{\boldsymbol{wo}}(m, 10\text{-min}_i) = \sum_{j=1}^{n_{cc}} cn_{j,k} \cdot \boldsymbol{L}_{\boldsymbol{j}}^{\boldsymbol{wo}}(m, 10\text{-min}_i) \tag{1}$$

where n_{cc} is the number of consumer classes and $c_{nj,k}$ is the number of consumers who belong to the jth consumer class at the kth node of the RDS. The reactive power consumed is determined by assuming a power factor. Although this method can be used to study the effect of load dependence, the explanation of such an analysis is beyond the scope of this paper.

3.2. PV system modelling

The probabilistic PV system model in [21] was specified for a 10-min interval (Fig. 1). Thus, for each jth location, the meteorological random variables involved were the 10-min global and diffuse irradiation ($\boldsymbol{H}^j_{g,10\text{-min}_i}, \boldsymbol{H}^j_{d,10\text{-min}_i}$). The 10-min global irradiation was obtained from the random variable, daily clearness index $\boldsymbol{K}^j_T$, whereas the 10-min diffuse irradiation was obtained from the random variable, hourly diffuse fraction $\boldsymbol{k}^j_d$. Both irradiations were used to build the random variable, 10-min tilt global irradiance, for each ith 10-min interval at the jth location $\boldsymbol{G}^j_{g,10\text{-min}\_\beta_i}$. Subsequently, the random variable, 10-min PV electrical power for each ith 10-min interval at the jth location, $\boldsymbol{P}^j_{pv,10\text{-min}_i}$, was obtained from the 10-min tilt global irradiance and the 10-min electrical efficiency of the PV cell, which depended on the tilt global irradiance. The probabilistic PV system model also took into accout the stochastic relationship between distributions, corresponding to different locations depending on a spatial PV dependence structure. This dependence was modelled separately from marginal distributions with a rank correlation matrix.