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Stochastic assessment of the impact of photovoltaic distributed generation on the power quality indices of distribution networks

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ABSTRACT

This paper aims to assess the impact of photovoltaic distributed generation (PVDG) connection on the power quality indices (PQI) of distribution networks, such as: long term voltage variations (voltage conformity issues) and voltage unbalance. The stochastic nature of PVDG and loads were considered in the study using probabilistic techniques. The impact of PVDG on the number of tap changes of the voltage regulators was investigated. The tests results in a real life large scale distribution network demonstrated that the PVDG can cause around 31% of improvements in the voltage conformity indices. This impact is less beneficial than the one associated with the connection of conventional distributed generation due to the variability in the primary energy resource. Furthermore, it was demonstrated that the connection of PVDG increases the lifespan of the voltage regulators as a result of a reduction about 20% in the number of tap changes.

1. Introduction

One of the most prominent renewable distributed generation (DG) is the solar based on photovoltaic conversion. In Brazil, the photovoltaic DG (PVDG) has been stimulated due to the high levels of solar irradiation thanks to favorable geographical conditions and reduction in the photovoltaic panel's costs.

The technical assessment of PVDG installation in the distribution network must consider its impact on the performance indices associated with: resistive losses, feeder loading and power quality. Power quality disturbances may cause tripping or inadequate operation of customer's equipment. Furthermore, regulatory agencies establish penalties for distribution utilities that do not meet power quality targets. Consequently, several studies have been carried out to assess the impact of PVDG in power quality indices, such as: voltage unbalance [1] and harmonics [2,3]. Other important power quality disturbance is the long-term voltage variations. Namely, deviations in the voltage RMS value, at the nominal frequency of the network, with durations greater than 1 min. In Brazil, the problems of power quality related to long-term voltage variations are denominated as voltage conformity problems [4]. The regulatory agencies [4] and international standards [5] define voltage conformity indices based on the cumulative duration associated with a nodal voltage. That is, the total duration, in percentage terms of the monitoring period, in which a nodal voltage has been outside of a specified interval.

The PVDG introduces uncertainties in the planning and operation of distribution networks due to large variations in its output power caused by the stochastic behavior of the solar irradiation. Several papers have proposed methodologies to model uncertainties associated with PVDG in the performance assessment of distribution networks [6–12]. In these references, the preferred approach to model uncertainties in PVDG is the probabilistic load flow (PLF). The PLF methods used for this purpose can be classified in accordance with the representation of the uncertainties in three categories:

(i) Non-Sequential [6,7]: the performance indices are evaluated for a single time interval, such as the peak load. Therefore, the temporal dependence in the uncertainties is ignored.
(ii) Pseudo-Stochastic [8–10]: the evaluation of the performance indices is carried out for a study period (daily or weekly). Usually, the study period is divided into intervals with durations from 1 s up to 1 h. This representation recognizes the temporal dependence of the uncertainties related to PVDG and load, but the serial correlation of the uncertainties among the time intervals is not completely represented. The most used techniques to solve the PLF in the pseudo-stochastic representation

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are: the Monte Carlo Simulation (MCS) [8] and the analytical [9,10].

(iii) Stochastic [11,12]: in this representation the serial correlation in the uncertainties is accurately modeled using the time series theory. Due to the temporal correlation among the time intervals of the study period, the most suitable technique to solve the PLF problem in the stochastic representation is the MCS with sequential sampling.

Some algorithms used in the non-sequential and pseudo-stochastic representations to solve the PLF are based on elegant mathematical methods such as: Nataf Transformation and Latin Hypercube Sampling [6], Cornish–Fisher expansion [7,10] and Point-Estimate [9]. These algorithms have low computational cost regarding to the MCS because the probability distributions of the voltages are obtained using analytical formulas. However, these algorithms have limited practical application since they cannot estimate cumulative duration indices used in voltage conformity assessment. This limitation is due to the fact that the analytical solution of the PLF generates the probabilities distributions of the nodal voltages, but not a cumulative duration indices, since they are associated with a chronological test function of the nodal voltages. In other words, the cumulative duration indices are not directly associated with nodal voltages, but with the summation of the time intervals in which a nodal voltage stayed in a specified interval. This summation is dependent of the chronological state transition processes of the system due to the uncertainties in the stochastic behavior.

The stochastic representation is preferable with regarding to pseudo-stochastic and non-sequential representations due to its capacity to recognize serial correlation in the system uncertainties. However, this representation has a high computational cost due to the utilization of MCS to evaluate the performance indices. In spite of that, the stochastic representation is the only available option to evaluate indices associated with the cumulative duration of an event for a study period, such as the voltage conformity. Additionally, the regulatory agencies [4] and international standard [5] for electric energy supply establish targets for the cumulative duration indices related to long term voltage variations. For example, the EN 50160 [5] determines that the voltage magnitude in low and medium voltage distribution networks must stay in the range ±10% for 95% of the time in a week. The estimation of the risk in violating targets for voltage conformity indices requires the probability distributions for these indices. The stochastic representation is the only approach capable to generate these distributions. It is important to emphasize that the setting of a target for voltage conformity indices is well known, but there is no paper that has considered the impact of DG on the risk related to these targets. In this way, the stochastic representation can support distribution utilities planning engineers to identify the DG penetration level that has acceptable risk of violating the target for voltage conformity indices. Additionally, it is possible to estimate the expected loss of revenue of a distribution utility due to penalties as a result of poor voltage conformity indices.

Other important issue related to technical impact of the DG connection is the number of tap changes of voltage regulators. Voltage regulators are installed in conventional distribution networks to maintain the control node voltage in a specified range through the tap changes. When a DG (conventional or photovoltaic) is connected to distribution network the number of tap changes can increase or decrease due to the factors: operation mode of the conventional DG (peak shaving or base load), intermittence of the primary energy resource (wind speed or solar irradiation) and DG failures. The excessive number of tap changes can cause lifetime loss of the voltage regulator due to the presence of impurities caused by arcs and due to the wear owing to movement of mechanical parts [13]. Furthermore, the effects of PVDG integration on the operation of var/volt control devices are currently considered as a great challenge due to the large penetration potential of PVDG in distribution networks [14–16]. Therefore, it is worth to consider the number of tap changes in the technical analysis of DG connection. In the sense to provide more realistic and useful results, it is necessary that the predictive model include uncertainties associated with: solar irradiation, temperature and load fluctuations.

The proposal of this paper is to assess the impact of PVDG insertion on the voltage conformity and unbalance indices. This assessment is carried out using probabilistic approaches to model the stochastic system behavior related to load fluctuations and solar irradiation. Furthermore, the proposed model considered uncertainties associated with temperature variations and DG availability. The selected probabilistic approach to estimate the power quality indices is the PLF with stochastic representation, based on the Quasi-Sequential MCS [17]. The nodal voltages of the system for each scenario generated by the Quasi-Sequential MCS are calculated using a load flow algorithm based on phase-coordinates model [18]. The sample of the system scenarios was used to: compute cumulative duration indices related to voltage conformity, estimate the risks of violating power quality targets and to obtain the chronological variations in the voltage unbalance index. The proposed methodology was tested in a real life primary distribution feeder with 1560 nodes. The results demonstrate that the PVDG connection has a significant impact on the PQI, but its effect is less beneficial than the one associated with conventional DG. Additionally, the impact of DG connection on the number of tap changes of the voltage regulators was investigated.

2. Deterministic and probabilistic models

2.1. Load flow algorithm based on phase-coordinates model

To estimate PQI in a distribution network it is necessary to determine the nodal voltages of the network. These voltages must be calculated considering the unbalanced nature of the power distribution network. This issue can be taken into account using phase-coordinate models for the components [18]. It is possible to combine these models with backward/forward sweep techniques to obtain fast and accurate load flow algorithms for radial distribution networks. In this paper, the backward/forward sweep load flow proposed in [18] is used to evaluate the nodal voltages for each time interval of a system scenario generated by the Quasi-Sequential MCS.

2.2. Time series models for temperature, solar radiation and load

In order to evaluate the cumulative duration indices associated with voltage conformity, it is required to model the temporal dependence of the temperature, solar irradiance and feeder load. In this paper, the autoregressive moving average (ARMA) and Fourier models were used to model these time series. The generic form of the time series model used to represent the stochastic behavior of the temperature and solar irradiation is given by (1):

$$Z_t = S_t + x_t \tag{1}$$

where $S_t = b_0 + \sum_{h=1}^{N_h} [a_h \sin(\omega_h t) + b_h \cos(\omega_h t)]$ is the seasonal component modeled using the Fourier harmonic model. N_h is the number of harmonics. a_h and b_h are the coefficients related to the harmonic component h. ω_h is the frequency associated with the harmonic component h. x_t is the residual which contains a white noise w_t (with zero mean and constant variance σ^2) and perhaps other additional signals.