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Probabilistic congestion management using EVs in a smart grid with intermittent renewable generation

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ABSTRACT

This paper presents a probabilistic model to reduce the probability of line congestions and voltage violations in a smart grid located in a radial distribution network. Renewable distributed resources and a high penetration of Electric Vehicles (EVs) are considered. The uncertain parameters taken into account are: power demand, power generated by wind and solar photovoltaic generators, and the behavior of the EVs that do not participate in the congestion procedure. A probabilistic power flow based on the point estimate method is firstly used to compute the distribution functions of the line flows and node voltages. Next, a congestion management strategy is proposed in order to keep the line flows and node voltages within the appropriate range at a given confidence level. The strategy is based on the sensitivity distribution factors: Power Transfer Distribution Factors (PTDFs) and Voltage Distribution Factors (VDFs). The control variables to carry out the corrective actions are the active and reactive power injections from a subset of EVs or their charging points. It is assumed that these controlled EVs are able to inject power into the network using Vehicle to Grid (V2G) capabilities. To illustrate the method, a distribution grid based on a modified version of the IEEE-37 Node Test Feeder is tested.

1. Introduction

Electric power systems are facing some major challenges due to the incorporation of new generation sources to the generation mix. These are mostly Distributed Renewable (DR) resources, with a smaller environmental impact and a lower rated power than traditional ones. On the other hand, they are usually non-dispatchable units that introduce sources of uncertainty and that may be scattered throughout the system; moreover, they are usually connected to weakly meshed or even radial distribution networks. An overview of the main issues concerning the integration of DR into electric power systems may be found in [1].

Likewise, due to the growing interest in plug-in Electric Vehicles (EVs), new challenges in the operation and regulation of power systems are arising [2]. Several authors analyze the impact of these new loads on distribution networks, mainly focusing on the demand increase [3–5]. Also in this context, an optimization model to determine the EVs charging profile is presented in [6].

On the other hand, on the bright side of this incoming reality, these generation and demand sources may be also part of the solution as is the case of the capability of EVs to inject power in the system, the so called Vehicle to Grid (V2G) procedure. In [7], a framework to analyze the integration of EVs both as a load with different charging profiles and as a generator, the V2G, is described. In [8], the optimal charging and discharging profile of EVs is determined with the objective of minimizing the overall operational cost. A qualitative study on the potential use of EVs for network services related to active power or power quality may be found in [9]. In [10], the adequacy of the services that V2G may provide in different markets is evaluated. A review on the current status and implementation of battery chargers, charging power levels and infrastructure for EVs is presented in [11]. The research conducted in [12] shows how the jointly consideration of EVs and DR may be beneficial in demand-side management programs.

The last relevant issue to be taken into account is the uncertainty all these players introduce in the operation of the power system: DR are, by nature, intermittent and the EVs, both in their demand or generator facets, are subject to the availability and driving patterns. Several probabilistic models are developed to adequately incorporate this uncertainty sources in the study of the power systems.

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A robust optimization model to minimize the expected operation cost of demand supply that takes into account the uncertainty in DR generation and the behavior of EVs is proposed in [13] considering different levels of EVs and distributed generation. The authors in [14] presents a mid-term model to evaluate the impact of V2G on the power system operation cost.

All this complexity results in an environment in which the electric power, as well as the information to adequately control the power system, must flow in both directions. This perspective, already used in the transmission system, it is not so widely extended in the distribution system, where these new players and their uncertainty are merging. The concept of smart grid arises as a consequence of the need of managing a wider conceptual model to operate the distribution system. The goal of these smart grids is to handle the whole system by integrating the actions of consumers, producers and those with both roles ("prosumers") to get a sustainable, clean, economic and reliable electricity supply. A large number of research studies facing this new environment have been developed. A review of smart grid projects that are being, or have been, developed in the European Union may be found in [15]. In [16], a literature review on the integration of EVs in the smart grids, with special attention to smart metering, communications, V2G, and the integration of renewable distributed generation is presented.

Among these goals of the smart grids, one of the major tasks is the congestion management problem that could be caused, among other sources, by those clean and sustainable sources, because of their uncertain behavior. It is worth mentioning that the aforementioned changes are going faster than the actual power network capacity expansion. Many studies have been published focusing on the congestion management problem, as the literature reviews [17–20] show. An optimization model based on real transmission distribution factors to solve the congestion management is proposed in [21], and that model is extended in [22] to incorporate a reactive control. However, these models are intended for transmission systems and, hence, control variables as generation operation or Flexible AC Transmission System, are not available in a smart grid located in a radial distribution network. Besides, they do not usually take into account any uncertainty source. A recent paper [23] focuses on the congestion problem in micro-grids. It presents an optimization model that maximizes the profit, in which EVs with V2G capability are used to manage congestion, and the uncertainty of DR generation is modeled by means of scenarios.

This paper presents a probabilistic model to reduce the probability of congestion of lines, or the probability of under/over voltages in nodes, in a smart grid located in a radial distribution network, by means of a sequential approach that makes use of the capability of power injection provided by the EVs or their corresponding charger. A probabilistic power flow, initially introduced in [24], is employed to take into account parameters with uncertainty. In this model, the Point Estimate Method (PEM) [25,26] with a scheme $2m+1$ is used. This method is adequate to handle the stochastic input information in the probabilistic analysis of the congestion management because: (i) it uses a deterministic routine to solve the AC power flow, (ii) it keeps the computational burden low, and (iii) it only requires the first four moments of the distributions of the uncertain input parameters. In this study, a Newton-based routine [27] is used to solve the AC power flow; however, it could be easily replaced by a backward/forward algorithm if the AC power flow does not converge properly. Regarding uncertainty, this paper considers the following uncertainty sources: power demand, wind generation, photo-voltaic generation and uncontrolled EVs. It should be remarked the capability of the PEM to handle the uncertainty of differently distributed parameters.

The method proposed is a predictive-type method, which can be implemented with a small number of simple actions, power injections, performed by the controlled EVs and the charging points. After solving the PEM, the Cumulative Distribution Functions (CDF) of the output variables, line flows and voltage magnitudes, are computed by means of the Cornish–Fisher expansion [28]. These curves are used to check the probability of congestion, and then, a sequential procedure, based on distribution factors [29] determines the actions to be taken to meet the probability of congestion, if that can be achieved with the available resources. A key point behind this procedure is the capability of the power injections to shift those CDF curves until the target probability is met.

The main contribution of this paper is the definition of a probabilistic framework, able to handle all the aforementioned uncertainty sources, to define the probability of line congestion and/or voltage violation, and the actions to be taken to reduce it, in a smart grid located in a radial distribution network. In addition, a practical algorithm to exploit the capability of controlled EVs, and their charging points, to keep those probabilities within a given confidence level is presented.

The rest of the paper is organized as follows. In Section 2, the proposed model, the overall methodology and the assumptions are described. Section 3 includes the mathematical approach for the uncertainty modeling, the probabilistic power flow and CDFs evaluation, the details of the corrective actions and the sequential procedure. In Section 4, two case studies based on a modified version of the IEEE-37 Node Test Feeder [30] are described and discussed to illustrate the proposed methodology. And finally, conclusions are drawn in Section 5.

2. Problem statement and methodology

In this section, a probabilistic framework to address distribution line congestions and over/under voltage violations is presented. The objective is to keep the probability of occurrence of any violation within a given confidence level. The approach is based on a sequential algorithm that takes advantage of Electric Vehicle V2G capabilities.

Several sources of uncertainty are considered. Specifically, power demand, wind and PV power outputs as well as the behavior of EVs are modeled by means of probability density functions. Moreover, EVs are grouped into two categories: (i) uncontrolled EVs: EVs with a probabilistic behavior for charging/discharging and (ii) controlled EVs: EVs with V2G capabilities, which are eligible to perform the corrective actions. The overall procedure is described in the flowchart in Fig. 1.

The probability density functions are the input data for a Probabilistic Power Flow (PPF) problem, which is solved using a PEM [26]. Once the PPF is solved, the Cornish–Fisher expansion [28] is used to calculate the CDFs of the output variables (power flows and voltage magnitudes). Moreover, mean values for Power Transmission Distribution Factors (PTDFs) and Voltage Distribution Factors (VDFs) are also computed. More details are provided in Section 3.1.

Then, two sets are built: the Set of Congested Lines (SCL) and the Set of Nodes with Voltage Violations (SNVV). The SCL contains all distribution lines whose probability of congestion is greater than a certain confidence level $Pr[P_{ij} \geq \overline{P}_{ij}] \geq \theta_{ij}$, while the SNVV contains all nodes whose probability of over or under voltage violation is greater than a given confidence level $Pr[V_i \geq \overline{V}_i] \geq \overline{\alpha}_i$ or $Pr[V_i \leq \underline{V}_i] \geq \underline{\alpha}_i$, respectively. The confidence levels θ_{ij}, $\overline{\alpha}_i$, and $\underline{\alpha}_i$ are exogenous parameters set by the user, and $Pr[\,]$ is the associated probability.

If both sets (the SCL and the SNVV) are empty, the procedure ends (all line and nodes meet the required probabilities); if not, proceed with the congestion management algorithm.

The congestion management procedure is a sequential algorithm that initially considers all lines included in the SCL and then all nodes in the SNVV. Taking into account the sensitivity factors