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Operation of renewable-dominated power systems with a significant penetration of plug-in electric vehicles

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ABSTRACT

This paper aims to study the operational consequences of the integration of a large number of plug-in electric vehicles in a renewable-dominated power system. The coordination between the power system operator and the charging process of plug-in electric vehicles under a smart-grid environment is modeled using several approaches. The operation of the power system is modeled by means of a network-constrained stochastic economic dispatch. This problem is formulated using a two-stage stochastic programming model in which the uncertainties associated with the charging process of plug-in electric vehicles and with the availability of the renewable sources are characterized as stochastic processes. Numerical results on a realistic case based on the Iberian Peninsula power system are provided and analyzed.

1. Introduction

PEVs (plug-in electric vehicles) are becoming an actual option to replace traditional combustion-engine cars. This fact is a consequence of several reasons; firstly, PEVs are widely considered as an effective means of reducing the carbon emissions resulting from the extensive usage of combustion-engine vehicles. The reduction of carbon emissions might result in a positive impact against the global climate change and an improvement of the air quality in our cities. Secondly, the usage of PEVs can be considered as a tool for reducing the dependency on fossil fuels and, therefore, for increasing energy supply security. This fact is particularly relevant for those countries without fossil fuel reserves. This argument is reinforced thanks to the high increase of the usage of renewable technologies for electric energy production that may be used to charge PEVs.

In a scenario in which the general usage of PEVs is promoted, it is necessary to carefully analyze the impact caused by the additional demand which results from charging PEVs (hereinafter referred to as PEV demand) on the operation of power systems. That is, the operation of a power system could be at risk if an excessive demand is added in inadequate periods, especially during peak demand hours. In this situation, demand-side management actions could help to place this additional demand in more convenient periods.

Special attention should be paid to renewable-dominated power systems, in which an important portion of the demand procurement is obtained by means of non-dispatchable generating units. For these power systems, an adequate selection of the energy and reserve schedules is vital for ensuring a safe procurement of the demand at a reasonable cost.

The evolution of the communication capabilities between energy suppliers and domestic consumers will facilitate the incorporation of novel PEV charging control schemes. Moreover, the demand associated with the charging process of PEVs is suitable for demand-side management since the usage of PEVs does not coincide in time with the consumption of power from the electrical grid. In this regard, smart grids provide an adequate framework for implementing an effective communication between the ISO (Independent System Operator) and PEV users in order to manage PEV demand effectively [1]. Therefore, considering a smart grid environment, the ISO may control the charging process of PEVs to allocate the PEV demand in adequate periods from the standpoint of the system operation. The so-called G2V (Grid-to-Vehicle) and V2G (Vehicle-to-Grid) capabilities allow the ISO to exercise control over the charging process of PEVs. The G2V capability enables the ISO to decide in which periods PEVs are charged, whereas the V2G

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capability additionally allows the ISO to use the energy stored in the batteries of PEVs to supply part of the demand, if it is necessary.

Since the publication of the pioneering work of Kempton and Letendre [2] in the late nineties analyzing the economical advantages of using vehicle-to-grid approaches, the study of the impact of PEVs and PHEVs in the power system operation has been an active research topic, especially in recent years. For example, reference [3] analyzes the usage of an electric-vehicle fleet for providing regulation services. The coordination of an electric vehicles aggregator with the system operator considering a tertiary regulation control is formulated in Ref. [4]. In Ref. [5], the usage of vehicle-to-grid approaches in power systems with high wind power penetration is studied. Ref. [6] proposes a probabilistic constrained load flow considering both wind power generation and electric vehicles. In Ref. [7] a demand side management procedure is applied to optimize the charging cycles of electric vehicles. In Ref. [8] the battery degradation is explicitly considered in the energy management performed by the grid operator. In Ref. [9], an algorithm is proposed to control the charge of electric vehicles in deregulated electricity markets, whereas the price-responsiveness of plug-in electric vehicles is considered in Ref. [10]. Reference [11] analyzes the cost savings obtained if smart charging of PEVs is implemented. In Ref. [12] the impact of charging electric vehicles in the distribution grid is analyzed. The power consumption of electric vehicles is estimated in Ref. [13]. A robust optimization model to analyze the effect of including vehicle-to-grid facilities in small electric energy systems is presented in Ref. [14]. Finally, Ref. [15] presents a mid-term operation model to analyze the impact of PEVs in the Spanish power system. For an extensive and detailed review concerning the integration of electric vehicles, power grids, and renewable energies, the reader is referred to Ref. [16].

The objective of this paper is to analyze the impact of the integration of a large number of plug-in electric vehicles on the operation of a renewable-dominated power system. For that, it is assumed that the ISO, as responsible for the system operation, solves a network-constrained stochastic economic dispatch problem that optimizes energy and reserve deployment simultaneously. This type of economic dispatch is especially tailored for power systems with significant renewable capacity. The stochastic economic dispatch is formulated as a two-stage stochastic programming problem [17]. The first stage represents the day-ahead scheduling whereas the second stage models the real-time dispatch for different realizations of the uncertain parameters. The transmission network is modeled using a dc model. The coordination between the ISO and the PEVs is characterized using three different approaches: i) the ISO does not have control over the charging process of PEVs, ii) the ISO decides the periods in which PEVs are charged, and iii) in addition to controlling the charging of PEVs, the ISO disposes of the energy stored in PEVs for supplying part of the demand if necessary. The last two approaches correspond to the so-called G2V (Grid-to-Vehicle) and V2G (Vehicle-to-Grid) configurations, respectively [18]. The resulting problem is a linear programming problem that is solved by means of commercial software [19].

The structure of the rest of the paper is as follows. Section 2 describes the proposed decision-making process. Section 3 presents the modeling of the demand associated with the charging process of PEVs. The mathematical formulation of the problem is provided in Section 4. A realistic case study is discussed in detail in Section 5. Relevant conclusions are provided in Section 6.

2. Decision-making process

The operation of a power system is a complex problem which is divided into several stages. Firstly, a market-clearing procedure is performed. The market-clearing is usually a day-ahead market which is realized the day prior to the actual energy delivery on an hourly basis. The objective of the market-clearing is to determine for each hour of the next day: i) the energy produced by each power unit, ii) the energy consumed by each load and, iii) the market-clearing prices. Next, short-time markets (spanning from minutes to hours) as adjustment and ancillary service markets are cleared in order to adjust the power production to the actual consumption needs in each instant, while the technical constraints of the production units, loads and transmission lines are satisfied. These markets are of high interest in power systems with either numerous uncertain production units or with uncertain loads. Finally, when the energy delivery is physically provided, a real-time dispatch is performed to ensure the energy balance if fluctuations in demand and power outputs occur. However, it is important to note that the most part of traded energy is negotiated in the day-ahead market.

The market-clearing procedure used in this paper to represent the day-ahead market corresponds to a network-constrained stochastic economic dispatch. The classical economic dispatch is a mathematical programming problem consisting in allocating the total demand among available generating units so that the production cost is minimized [20]. The network-constrained stochastic economic dispatch is an economic dispatch model that explicitly considers the transmission network and the uncertainty associated with both the power production and demand. This model is appropriate for those power systems with high penetration of non-dispatchable power units. These units are those whose power output depends on the randomness of the natural sources involved in their power production processes. For instance, the power outputs of solar PV (photovoltaic) and wind power plants are subjected to the randomness associated with the solar irradiation and the wind speed, respectively. Specifically, the uncertain parameters considered in this paper are twofold: a) the power production of non-dispatchable generation units, namely, photovoltaic and wind power plants, and b) the system demand, which is considered as a combination of PEVs demand and conventional demand. Observe that the demand associated with PEVs is uncertain for the ISO when the day-ahead market is cleared the day prior to the physical energy delivery.

In order to explicitly consider the uncertainty faced in the operation of the power system, the network-constrained stochastic economic dispatch co-optimizes simultaneously energy and reserve deployment accounting for different realizations of the uncertain parameters, [17] and [21]. Traditionally, the reserve deployments are the changes over the energy scheduled in the day-ahead market, which are performed by the dispatchable units (thermal and hydro units). These reserve deployments are made in order to maintain the energy balance in each bus of the system if a deviation between electricity production and consumption occurs. In this paper, it is considered an additional reserve deployment that is procured by those PEVs controlled by the ISO. Then, the ISO may use the energy stored in the PEV batteries to compensate generation deficits and it may also decide to charge the PEV batteries in those hours with generation surplus. The expected demand of those PEVs that are not controlled by the ISO is procured in the day-ahead market, whereas its deviations with respect to the expected value are satisfied with the reserve deployments described above.

If energy and reserve deployment are simultaneously optimized it is possible to determine a day-ahead schedule that is flexible enough to accommodate effectively the different realizations of the uncertain parameters. This problem is formulated as a classical two-stage stochastic programming problem in which the first-stage represents the day-ahead market, while the second-stage represents the actual energy deployment in which uncertain parameters are revealed and reserves are deployed. This second stage is usually named as real-time dispatch.