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Integrated operation of electric vehicles and renewable generation in a smart distribution system

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ABSTRACT

Distribution system complexity is increasing mainly due to technological innovation, renewable Distributed Generation (DG) and responsive loads. This complexity makes difficult the monitoring, control and operation of distribution networks for Distribution System Operators (DSOs). In order to cope with this complexity, a novel method for the integrated operational planning of a distribution system is presented in this paper. The method introduces the figure of the aggregator, conceived as an intermediate agent between end-users and DSOs. In the proposed method, energy and reserve scheduling is carried out by both aggregators and DSO. Moreover, Electric Vehicles (EVs) are considered as responsive loads that can participate in ancillary service programs by providing reserve to the system. The efficiency of the proposed method is evaluated on an 84-bus distribution test system. Simulation results show that the integrated scheduling of EVs and renewable generators can mitigate the negative effects related to the uncertainty of renewable generation.

1. Introduction

The ability to influence electricity demand profile by controlling Electric Vehicles (EVs) in order to cope with intermittent renewable generation and distribution network constraints is a primary capability required to a smart grid. Moreover, an EV, due to its charging/discharging flexibility is a good candidate for supplying ancillary services [1,2]. The energy stored in batteries of EVs can be, indeed, used as a flexible reserve capacity in order to integrate intermittent renewable generation. By using combined on/off charging signals, the system operator can manage a fleet of EVs in order to provide reserve for compensating renewable power generation variability.

1.1. Renewable generation uncertainty

Some of the main limits related to wind and solar power generation are represented by the dispatchability and reliability problems associated with its operation since the output power is determined by the weather conditions. This intermittent generation makes network balance and reserve planning more complex than before and other dispatchable compensating resources are required in order to follow the electrical load demand profile. So, the operator can just provide some reserve capacity in day-ahead scheduling in order to have enough backup resources for making corrective decisions in real-time.

In day-ahead energy and reserve scheduling, renewable generation is mainly modeled as a negative demand [3] and the forecast error of the power generated by renewable units may be modeled by using stochastic or deterministic methods [4–6]. In the deterministic approach, a predefined value for the forecast error for wind and solar generation at each period is taken into account in order to estimate the range of changes for the renewable power generation. The amount of the reserve that is required to counterbalance the variation of renewable generation is calculated based on the values of the forecast error and is usually presented as a percentage of renewable forecasted power in each period. The forecast error value is calculated by weather forecast institutes considering various parameters and historical data.

On the other hand, in most stochastic methods, the amount of reserve requirement for each period is not determined before the energy scheduling [3,6]. In the first step, plausible scenarios of wind and solar generation, with a given probability of occurrence, are created by using a probability distribution function (PDF) of wind or solar generation. The energy and reserve scheduling is carried out for each scenario while the comparison with a base scenario allows assessing all generation variations in order to determine the reserve requirement. Also, in stochastic methods [3,6],

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Nomenclature

Sets

t	index of optimization periods, $t = 1, 2, \ldots, 24$
v	index of electric vehicles, $v = 1, 2, \ldots, N_{a,v}$
a	index of aggregators, $a = 1, 2, \ldots, A$
w	index of wind turbines, $w = 1, 2, \ldots, W_a$
pv	index of Photovoltaic (PV) units, $pv = 1, \ldots, pv_a$
n, m	index of buses, $n, m = 1, 2, \ldots, N$

Variables: (1) Binary variables

$X(v,t)$	binary variable of EV v related to discharge state in period t
$Y(v,t)$	binary variable of EV v related to charge state in period t

(2) Continuous variables

OF	total operation cost of an aggregator ($)
$P_S^a(t)$	scheduled power from the main grid in period t (kW)
$P_{EV}^{Dch}(v,t)$	power discharge of EV v in period t (kW)
$P_{EV}^{Ch}(v,t)$	power charge of EV v in period t (kW)
$R_{EV}(v,t)$	scheduled reserve provided by EV v in period t (kW)
$E_s(v,t)$	state of charge related to EV v in period t (kW h)
$SR(a,t)$	accepted reserve capacity of aggregator a in period t (kW)

Parameters

D_t	total hourly demand in period t (kW)
$P_{w,t}$	forecasted wind power of turbine w in period t (kW)
$P_{pv,t}$	forecasted solar power of unit pv in period t (kW)
Δt	coefficient related to period duration
$C_{Dch}^{v,t}$	discharge price of EV v in period t ($/kW h)
Ω_t	hourly electricity price of open market ($/kW h)
ψ_t	price of the reserve provided by EV v in period t ($/kW h)
η_v^C	grid-to-vehicle charging efficiency coefficient for EV v
η_v^D	vehicle-to-grid discharging efficiency coefficient for EV v
$E_{trip}^{v,t}$	required energy for traveling of EV v in period t (kW h)
$P_{Dch,v}^{Max}$	maximum power discharge of EV v (kW)
$P_{Ch,v}^{Max}$	maximum power charge of EV v (kW)
Ψ_v^{max}	Maximum level of state of charge for EV v (kW h)
Ψ_v^{min}	minimum level of state of charge for EV v (kW h)
$E_{BatCap,v}$	capacity of battery of EV v (kW h)
$Res_{a,t}$	total reserve requirement of aggregator a in period t (kW)
$PR_{a,t}$	purchased reserve from other aggregators for aggregator a in period t (kW)
$SR_{a,t}$	sold reserve to other aggregators by aggregator a in period t (kW)
α_t	wind power forecast errors in period t
β_t	solar power forecast errors in period t
$O_{a,t}$	price offer for providing reserve in period t submitted by aggregator a ($/kW h)
$R_{a,t}^{max}$	available reserve capacity of aggregator a to sell in period t (kW)

when the probability of scenarios is very low and the cost for providing reserve is very high, an expected load not served term is also considered in order to use involuntary load shedding as a variable in the day-ahead energy resource scheduling optimization. However, it is obvious that in the distribution system operation, it is not acceptable to force some customers to shed their demand due to renewable generation unexpected variation.

Although many forecasting approaches and stochastic scheduling methods exist, there is no guarantee that forecasting values of renewable generation are exactly equal to their actual output power in the real-time [7,8]. So, the day-ahead scheduled quantities may not satisfy all the system constraints in the real-time operation and, in some cases, need to be re-dispatched. For this reason, the real-time scheduling is essential in distribution systems with high penetration of intermittent renewable generation sources. For example, a very short-term wind forecasting for a real world application using data provided by Hydro Tasmania has been presented in [8]. A 2.5 min horizon is proposed in a neuro-fuzzy methodology with less than 4% error. This methodology can be used in real-time operation in order to update the input data of the energy and reserve scheduling optimization in real-time (e.g. 5 min ahead).

Endowing distribution systems with real-time network monitoring and control capabilities [9] offers the opportunity to involve EVs in the provision of the reserve service, thus alleviating the problems determined by renewable energy production variability [10] and also contributing to air pollutant emissions reduction. In [11], for example, a stochastic linear optimization algorithm considering several uncertainties related with the participation of EVs in the day-ahead energy and regulation reserve market has been presented.

However, the compensation of an unexpected decrease in the renewable generation by reserve provided by EVs has not been considered within the distribution energy and reserve scheduling problem in the literature. In this paper, EVs can provide two types of reserve service in order to compensate the wind and solar power variability.

1.2. Electric vehicles and roles of aggregators

Smart grids require a new management philosophy and new operation methods to adequately schedule renewable based generation and Distributed Energy Resources (DER), including EVs as controllable loads [12,13]. On the other end, the large number of EVs significantly increases the number of decision variables that must be considered in the energy resource scheduling problem. Due to the high number of EVs and DERs available in the distribution network, the complexity of the energy resource scheduling problem also increases.

Therefore, the large numbers of players requires new management methodologies based on a hierarchical and distributed philosophy. It is also necessary to develop decentralized control and operation of distribution systems in order to improve the efficiency of energy resource scheduling methods aiming at obtaining fast response for optimization problems with many variables.

This challenge motivates the introduction of one or more aggregators as intermediary entities between the DSO and the EVs or DERs owners. Thus, an entity called "aggregator" is considered in this paper that can use the communication and information system provided by the smart grid in order to aggregate the generation/consumption profile of a large number of EVs and renewable generators. Moreover, aggregators can also contribute to ancillary service provision. The concept of EV aggregator using bidirectional