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Demand-side management in smart grid operation considering electric vehicles load shifting and vehicle-to-grid support

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Demand fluctuation in electric power systems is undesirable from many points of view; this has sparked an interest in demand-side strategies that try to establish mechanisms that allow for a flatter demand curve. Particularly interesting is load shifting, a strategy that considers the shifting of certain amounts of energy demand from some time periods to other time periods with lower expected demand, typically in response to price signals.

In this paper, an optimization-based model is proposed to perform load shifting in the context of smart grids. In our model, we define agents that are responsible for load, generation and storage management; in particular, some of them are electric vehicle aggregators. An important feature of the proposed approach is the inclusion of electric vehicles with vehicle-to-grid capabilities; with this possibility, electric vehicles can provide certain services to the power grid, including load shifting and congestion management. Results are reported for a test system based on the IEEE 37-bus distribution grid; the effectiveness of the approach and the effect of the hourly energy prices on flattening the load curve are shown.

Introduction

The transition towards the Smart Grid (SG) requires to incorporate new functionalities and capabilities to the existing electricity grid. Among some identifiable features, distributed generation is a common characteristic of the SG and, in addition, the nature of these generators is varied since they can be non-dispatchable renewable, such as wind turbines or photovoltaic panels, combined heat and power, fuel cells, microturbines or diesel-powered plants. Devices which are able to store energy, like electric fixed batteries, can help the system to smooth the intermittent behavior of renewable sources enabling an easier integration. The next generation of the electricity grid will also pave the way to electrified transportation [1]. SGs comprise different entities that can interact with each other bidirectionally, giving the possibility to establish commercial relationships to serve and request electric energy or to solve technical problems that could arise, thus empowering the consumer. These entities within the SG can respond to changes in the prices at which the energy is bought and sold to the main grid with the objective of minimizing the costs of the energy they need or maximizing the income from the energy they sell. Among the many features that make a grid smart, the essential aspect is the integration of power system engineering with information and communication technologies. In turn, this integration can allow for advances in reliability, efficiency and operational capability [2].

Among other interesting characteristics of SGs, the concept of Demand-Side Management (DSM) has attracted the attention of many researchers and, among DSM strategies, demand response has been widely considered [3–5]. Demand response can be understood as voluntary changes by end-consumers of their usual consumption patterns in response to price signals [6]. Along with the savings regarding electricity bills, this kind of schemes can be used to avoid undesirable peaks in the demand curve that take place in some time periods along the day, resulting in a more beneficial rearrangement [7–10]. Through the use of DSM, several benefits are expected, like the improvement in the efficiency of the system, the security of supply, the reduction in the flexibility requirements for generators or the mitigation of environmental damage, although some challenges have to be overcome starting from the lack of the necessary infrastructure [11]. In addition, the introduction of DSM has to be conceived taking into account other distributed energy resources technologies that could be present in SGs [12,13]. In regard to this, several SG projects worldwide are underway or have been completed [14,15].

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Nomenclature

Indexes and sets

t, T index and set for time periods, $t \in T$
e, E index and set for the scenarios used to model the uncertainty, $e \in E$
i, R index and set for renewable generators belonging to the agent, $i \in R$
j, G index and set for non-renewable generators belonging the agent, $j \in G$
b, B index and set for batteries belonging to the agent, $b \in B$
v, H index and set for electric vehicles belonging to the agent, $v \in H$
n, A index and set for demand nodes of the agent, $n \in A$
t_m, T_M index and set of transitions periods for the electric vehicles belonging to the agent, $t_m \in T_M$
$|\alpha|$ the cardinality of a set α

Parameters

W^e probability of scenario e
$\hat{\lambda}_t^b$ main grid hourly forecasted buying price in time period t (cents €/kWh)
$\hat{\lambda}_t^s$ main grid hourly forecasted selling price in time period t (cents €/kWh)
$P_{i,t}^{R,e}$ renewable power output for generator i in time period t for scenario e (kW)
X parameter related to capacity constraints of the agents
$\Theta_{n,t}$ total demand prior to load shifting for bus n in time period t (kW)
f_e fraction of the total demand that can be shifted
$\phi_{n,t}$ fixed demand for bus n in time period t (kW)
$\gamma_{n,t}$ maximum shiftable demand for bus n in time period t (kW)
k maximum number of periods that demand can be shifted (hours)
k_ϵ rate between maximum shiftable demand and fixed demand, constant for all periods and nodes
k_δ upper bound for the change in the value of shiftable demand between two consecutive periods, constant for all the periods and nodes (kW)
μ_j variable cost for non-renewable generator j (cents €/kW)
ι_j fixed cost for non-renewable generator j (cents €)
ζ_j start-up cost for non-renewable generator j (cents €)
ς_j shut-down cost for non-renewable generator j (cents €)
$P_{g,j}^{min}$ minimum power output for non-renewable generator j (kW)
$P_{g,j}^{max}$ maximum power output for non-renewable generator j (kW)
$P_b^{d,max}$ maximum discharging power for battery b (kW)
$P_b^{c,max}$ maximum charging power for battery b (kW)
S_b^{max} maximum state of charge for battery b (kWh)
η_C charging efficiency for batteries
η_D discharging efficiency for batteries
P_v^{min} minimum charging or discharging power allowed for electric vehicles (kW)
P_v^{max} maximum charging or discharging power allowed for electric vehicles (kW)
S_v^{max} battery capacity of electric vehicle v (kWh)
κ_v^t kilometers covered by electric vehicle v in time period t (km)
ϑ average battery consumption (kWh/km)

Variables

$P_t^{S,e}$ power sold in time period t for scenario e (kW)
$P_t^{B,e}$ power bought in time period t for scenario e (kW)
$C_{t,j}^{G,e}$ non-renewable generation cost for generator j in time period t for scenario e (cents €)
$P_{j,t}^{G,e}$ r power output for non-renewable generator j in time period t for scenario e (kW)
$P_{b,t}^{d,e}$ discharging power for battery b in time period t for scenario e (kW)
$P_{b,t}^{c,e}$ charging power for battery b in time period t for scenario e (kW)
$P_{v,t}^{d,e}$ discharging power for electric vehicle v in time period t for scenario e (kW)
$P_{v,t}^{c,e}$ charging power for electric vehicle v in time period t for scenario e (kW)
$\Phi_{n,t}^e$ optimal demand for bus n in time period t for scenario e (kW)
$\Gamma_{n,t}^e$ optimal shiftable demand for bus n in time period t for scenario e (kW)
$M_{n,t,t'}^e$ amount of demand that goes from time period t to time period t' for bus n and scenario e (kW)
$S_{b,t}^e$ state of charge for battery b in time period t for scenario e (kWh)
$S_{v,t}^e$ state of charge for electric vehicle v in time period t for scenario e (kWh)

Binary variables

β_t^e binary variable that takes the value "1" if the agent is buying in time period t for scenario e, and "0" otherwise
$v_{t,j}^{G,e}$ binary variable that takes the value "1" if generator j is running in time period t for scenario e, and "0" otherwise
$y_{t,j}^{G,e}$ binary variable that takes the value "1" if generator j starts up in time period t for scenario e, and "0" otherwise
$s_{t,j}^{G,e}$ binary variable that takes the value "1" if generator j shuts down in time period t for scenario e, and "0" otherwise
$y_{v,t}^{d,e}$ binary variable that takes the value "1" if electric vehicle v is discharging in time period t for scenario e, and "0" otherwise
$y_{v,t}^{c,e}$ binary variable that takes the value "1" if electric vehicle v is charging in time period t for scenario e, and "0" otherwise

In order to simplify the implementation of the proposed approach in real systems, most of the actions in the SG are taken by the agents. In order to take these actions, the agents act on their own interest; sometimes, however, they make use of additional information provided by the SG operator. The individual decisions of the agents can only be slightly corrected by the SG operator (centralized correction) in order to correct the violation of technical constraints in the SG, in case they arise.

To make decisions each agent poses an optimization problem to maximize its profit over a set of periods, they can perform DSM strategies and Vehicle-to-Grid (V2G). As energy prices are usually higher for high demand periods, the optimization problems result in a flattened load curve. Following the regulatory trends in many countries, in particular in countries in Europe [16], the renewable generation in the model is also prioritized over the conventional generation. The framework considers market and technical