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A new model based on optimal scheduling of combined energy exchange modes for aggregation of electric vehicles in a residential complex

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A B S T R A C T

As electric vehicles offer a promising choice to deal with the growing air pollution and the global consumption of fossil fuels in the future smart grids, integrating their full benefit in the power system should be of a high priority. Numerous studies surveyed the possibility of charging/discharging modes of vehicles such as vehicle-to-grid, grid-to vehicle and vehicle-to-building and one introduced a new mode as vehicle-to-vehicle. However, none of them considered all available modes in a study. In the future smart grids, electric vehicles will be integrated with other generation or consumption parts such as distributed energy resources, smart homes and the external grid. As a result, a comprehensive perspective toward the simultaneous scheduling of combined energy exchange modes should be established. In this paper, advantages of 18 energy exchange modes are integrated. The presented model facilitates the participation of sub-aggregators in the aggregation of electric vehicles in a residential complex. The complex consists of a smart building and a smart parking lot. The proposed model promises higher income for sub-aggregators and less energy not charged for vehicles while ensuring the convenience for residents. This will result in more incentive for both sub-aggregators and residents to cooperate.

1. Introduction

Recently, PEVs (plug-in electric vehicles) which include PHEVs (plug-in hybrid electric vehicles) and EVs (electric vehicles), have received growing attention. This is mainly due to their aggregated advantages over other types of transportation technologies. These advantages include environmental compatibility, low noise level, high energy efficiency, lower operating costs, the potential to run on locally produced renewable energy and ancillary services provision through V2G (vehicle-to-grid) energy exchange mode [1–5]. The EPRI (Electric Power Research Institute) projects that 62% of the entire U.S. vehicle fleet will consist of PHEVs by 2050 using a moderate penetration scenario [1].

Integration of DERs (distributed energy resources) in future smart grids is a key solution of the increasing electric power demand supply. Application of renewable energy sources or renewables in residential scale accompanied by energy storage will be viable in future smart grids. This will be viable through participation of local aggregators in small distribution grids called sub-aggregators in this paper. In addition to electric vehicles, the contribution of renewables and residential demand response to emission decrease is inevitable [6–10].

As the use of electric vehicles is growing, the adverse impact of these vehicles on smart grids must be resolved. Uncontrolled application of electric vehicles will bring about problems such as overloading, voltage drop, power loss, etc. In particular, stochastic charging/discharging behavior of electric vehicles may cause interference with smart grid operator's scheduling [11–16]. However, the capability of PEVs to exchange energy with other generation or consumption sectors and their proven benefits for the power system should not be neglected.

Several studies have addressed the impact of PEVs on distribution networks and some have proposed the solution. In Ref. [17], an investigation has been done to evaluate three scheduling methods for electric vehicles in distribution networks. Uncontrolled charging/discharging, minimum charging cost and minimum power loss strategies have been compared to show the beneficiary of the managed application of electric vehicles. Authors in Ref. [18] have investigated a single smart home and attempted to improve the variance of the household load using two personal PHEVs driven by the residents. Reference [1] has applied the EDA (Estimation of Distribution Algorithm) to schedule a smart parking lot

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Nomenclature

Indices
- i vehicle indicator
- j hour indicator
- r solar scenario indicator
- s wind scenario indicator
- $S_{i,j,s,r}$ value of the sample symbol S for vehicle i, at hour j, in scenario s of the wind power and scenario r of the solar radiation

Continuous variables
- $\mathrm{E2B}_{j,s,r}$ power flow from energy storage to the building
- $\mathrm{E2G}_{j,s,r}$ power flow from energy storage to grid
- $\mathrm{ENS}_{i,s,r}$ ENS (energy not-supplied) at departure
- $\mathrm{E2V}_{i,j,s,r}$ power flow from energy storage to a vehicle
- $\mathrm{G2B}_{j,s,r}$ power flow from the grid to the building
- $\mathrm{G2E}_{j,s,r}$ power flow from the grid to energy storage
- $\mathrm{G2V}_{i,j,s,r}$ power flow from the grid to a vehicle
- $\mathrm{PV2B}_{j,s,r}$ power flow from solar cells to the building
- $\mathrm{PV2E}_{j,s,r}$ power flow from solar cells to energy storage
- $\mathrm{PV2V}_{i,j,s,r}$ power flow from solar cells to a vehicle
- $\mathrm{SOC}_{i,j,s,r}$ vehicle battery's SOC (state of charge)
- $\Delta\mathrm{SOC}_{i,s,r}$ vehicle battery's SOC change at departure
- $\mathrm{SOCE}_{j,s,r}$ energy storage's SOC
- $\mathrm{V2B}_{i,j,s,r}$ power flow from a vehicle to the building
- $\mathrm{V2E}_{i,j,s,r}$ power flow from a vehicle to energy storage
- $\mathrm{V2G}_{i,j,s,r}$ power flow from a vehicle to the grid
- $\mathrm{V2V}n_{i,j,s,r}$ power sent by a vehicle to another vehicle
- $\mathrm{V2V}p_{i,j,s,r}$ power received by a vehicle from another vehicle
- $\mathrm{W2B}_{j,s,r}$ power flow from the wind turbine to building
- $\mathrm{W2E}_{j,s,r}$ power flow from the wind turbine to energy storage
- $\mathrm{W2G}_{j,s,r}$ power flow from the wind turbine to the grid
- $\mathrm{W2V}_{i,j,s,r}$ power flow from the wind turbine to a vehicle
- z objective function

Decision variables
- $F_{i,j,s,r}$ binary indicator for EVs charging
- $G_{i,j,s,r}$ binary indicator for EVs discharging
- $K_{j,s,r}$ binary variable for energy storage charging
- $L_{j,s,r}$ binary variable for energy storage discharging
- $T_{i,j,s,r}$ binary indicator for battery lifecycle preserving strategy (direct load control)

Parameters
- c_i capacity of each vehicle battery
- d_i estimated driving distance before the arrival
- $g_{j,r}$ solar radiation
- h_i^{arr} arrival time of the vehicle
- h_i^{dep} departure time of the vehicle
- h_i^{presence} set of hours when the vehicle is parked in the smart parking lot
- N_i number of hours in which the vehicle is parked in the smart parking lot
- N_{rs} number of combined solar and wind scenarios
- P_{rs} simultaneous occurrence probability of solar scenario r and wind scenario s
- p_i^{min} minimum rate of charging/discharging power for vehicles
- p_i^{max} maximum rate of charging/discharging power for vehicles
- $p_{j,r}^{v}$ solar cells' output power
- $p_{j,s}^{w}$ wind turbine's output power
- $p2p_j$ electricity purchasing price
- $p2s_j$ electricity selling price
- pen_j penalization of ENS for a vehicle with departure at hour j
- $SOC_{i,h_i^{arr}}$ initial SOC of vehicles at arrival
- $SOC_{i,h_i^{dep},s,r}$ final SOC of vehicles at departure
- $v_{j,s}^{wind}$ wind speed
- η_i vehicle mobility efficiency

Constants
- α allowable ratio to discharge vehicles in the battery lifecycle preserving strategy
- ce nominal capacity of energy storage
- ce_{min} minimum allowed SOC for energy storage
- p_{ce}^{min} minimum rate of charging/discharging power for the energy storage
- p_{ce}^{max} maximum rate of charging/discharging power for the energy storage
- pc power limitation on the complex
- pl power limitation on the parking lot
- s_{PV} total solar cells surface
- η_{PV} solar radiation efficiency
- η_{X2Y} efficiency of power flow from X to Y

and has confirmed the rapid convergence of the algorithm in comparison with other methods. A comparison between local and global optimal scheduling strategies for electric vehicles has been done in Ref. [19]. In Ref. [20], authors have proposed a new method to consider power and voltage limitations for optimal scheduling of electric vehicles in distribution networks. The results have been compared with that of scheduling without limitation consideration in the model. Researchers in Ref. [21] compared controlled and uncontrolled charging/discharging strategies from different points of view. Authors in Ref. [22] present an assessment of the impact of PEVs on distribution networks considering different portions of penetration of PEVs. In Ref. [8], the unit commitment of power generation units including wind and solar resources has been surveyed in the presence of PEVs. Using defined scenarios to take the uncertainty of intermittent resources into consideration, the expected emissions and cost of the unit commitment schedule has been minimized for the set of scenarios. A similar study has been presented in Ref. [6] to compare unconstrained charging, 3-h delayed constrained charging, smart charging and smart charging with demand response. References [23–26] investigate the integration of electric vehicles application and demand response implementation. Results indicate that residential demand response programs which include smart household appliances and electric vehicles decreases the operation cost of the system while maintaining the convenience of the customers.

Since the study by Kempton and Letendre [27], EV does not mean only an electric load but a power source to sustain peak energy and storage capacity to electric power grids. Energy exchange between PEVs and other parts of the system is addressed by some researchers. V2G and G2V (grid-to-vehicle) modes have been at the center of attraction in the literature. Reference [28] studied the resource scheduling in a smart distribution network considering V2G. It took the technical constraints of the distribution network into consideration and established a mechanism

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