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More accurate sizing of renewable energy sources under high levels of electric vehicle integration

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ABSTRACT

Electric vehicles (EVs) and distributed generation are expected to play a major role in modern power systems. Although many studies have introduced novel models to integrate distributed generation into high levels of EV-adoption scenarios, none has considered EV-embedded battery performance degradation and its economic effect on system planning. Based on well-established models and data to emulate the capacity fading of lithium-ion batteries, the current work presents a mixed-integer linear programming optimization framework with decision variables to size renewable energy resources (RESs) in modern microgrids. The objective function aims to minimize the total cost of the system while guaranteeing a profitable operation level of vehicle-to-grid (V2G) application, narrowing the gap between design stage and real-life daily operation patterns. Stochastic modeling is used to incorporate the effect of different uncertainties involved in the issue. A case study on a residential system in Okinawa, Japan, is introduced to quantitatively illustrate how a profitable V2G operation can affect RES sizing. The results reveal that accounting for the economic operation of EVs leads to the integration of significantly higher capacities of RESs compared with a sizing model that excessively relies on V2G and does not recognize battery-fading economics.

1. Introduction

Although renewable energy resources (RESs) are promising solutions to depart from the dependence on fossil fuels, extending their share is a great challenge because of their varying generation nature. Plug-in EVs require significant amount of electric energy to meet their daily transportation needs; however, by implementing smart charging plans that are supported by smart grid infrastructure, EVs can absorb surplus generated renewable energy and expand the utilization of base-load power plants. Furthermore, vehicle-to-grid (V2G) application can reduce demand peaks. Therefore, future large integration of EVs is expected to positively affect the electric power system, although it will increase power transmission and distribution losses.

The effect of large-scale EV adoption on RES expansion has been thoroughly studied [1–13]. For example [5], concluded that the national grid of Denmark can potentially reduce excess generation of a 50% wind-share scenario by one-half using smart charging and V2G applications if the entire vehicle fleet switches to EV. In another study in Western Denmark region with a 25% wind generation share scenario, different EV control strategies were simulated, which affirmed how smart strategies can reduce the rejected wind generation and improve energy efficiency compared with non-smart strategies that would passively affect the power system [3]. An additional study confirming the potential role of EV applications in the Danish high wind-share future is found in Ref. [6]. In Ref. [10], EV control strategies to accommodate the stochastic behavior of wind generation and attenuate its unbalanced prices in deregulated power markets were investigated. Regarding the EV integration into a high photovoltaic (PV) penetration scenario in a study conducted in the Kansai area in Japan, it was estimated to reduce the annual excess generation by 3 TW h using a 13% EV integration level coupled with a similar percentage of smart-controlled domestic water heat pump [4]. The conjugate use of PVs and V2G for demand peak shaving in urban regions in Brazil and the potential EV revenues were analyzed in Ref. [8]. Some studies focused on the role of EVs in creating more ecofriendly power systems by reducing harmful emissions of thermal power plants [3,14]. An excellent review on the other effects of EVs can be found in Ref. [15].

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Nomenclature

BVL annual loss value of the total electric vehicle (EV)-embedded battery
C_B battery replacement cost ($/kWh)
C_P^t, C_S^t power purchasing and selling prices through the tth time step (abbreviated as “at t”) ($/kWh)
E_{ave} average electric energy consumed by an EV per one-way trip (kWh)
E_{EV} average nominal capacity of an EV battery (kWh)
E_{Tran}^t total energy required for EV transportation at t (kWh)
L_{Exp} life expectancy of the aggregated battery under operating conditions other than the reference condition (year)
L_{Ref} life expectancy of the aggregated battery under the reference operating condition (year)
NPV installed capacity of a PV array (kW)
NWT installed capacity of wind turbines (WTs) (kW)
N_{EV} total number of EVs
N_{Con}^t total number of grid-connected (within the design location) EVs at the beginning of the tth time step
N_{Dcon}^t total number of grid-disconnected EVs at the beginning of the tth time step
N_{in}^t number of EVs arriving at the microgrid at t
N_{Out}^t number of EVs leaving the microgrid at t
PV_{Aq}, $PV_{O\&M}$ annualized acquisition and operating costs of PVs ($/kW)
P_{Ch}^t, P_{Dch}^t battery charge and discharge power at t (kW)
$\overline{P}_{Ch}$, $\overline{P}_{Dch}$ maximum charge/discharge power per EV (kW)
$\overline{P_G}$ maximum grid power that can be purchased or sold (kW)
P_L^t power consumption at t (kW)
P_{PG}^t grid purchased power at t (kW)
P_{PV}^t generated power by installed PVs at t (kW)
$P_{PV_1}^t$ generated power by an equivalent 1-kW PV at t (kW)
P_{SG}^t power sold to the grid at t (kW)
P_{WT}^t generated power by installed WTs at t (kW)
$P_{WT_1}^t$ generated power by an equivalent 1-kW WT at t (kW)
Q_{Con}^t energy stored in the grid-connected EVs at the beginning of t (kWh)
Q_{Dcon}^t energy stored in the grid-disconnected EVs at the beginning of t (kWh)
Q_{in}^t energy stored in the arriving EVs at t (kWh)
Q_{Out}^t energy stored in the departing EVs at t (kWh)
R_{th} thermal resistance of EV battery (°C/kW)
SOC^t aggregated state of charge (SOC) of EVs at t
$\underline{SOC}$ minimum allowed SOC for the battery
$\overline{SOC}$ maximum allowed SOC
Sw^d aggregated SOC swing at day d in the optimization horizon
T_{Amp}^t ambient temperature at t (°C)
T_{th}^t battery temperature of the grid-connected EVs (°C)
TH optimization time horizon
u^t binary variable that expresses the grid power flow state (one for purchasing and zero for selling) at t
WT_{Aq}, $WT_{O\&M}$ annualized acquisition and operating costs of WTs ($/kW)
β_{th}^t degradation factor due to thermal effect (year^{-1})
β_{SOC}^t degradation factor due to SOC effect (year^{-1})
β_{Sw}^t degradation factor due to SOC swing effect (year^{-1})
$\eta_{\frac{DC}{AC}}$ DC to AC energy conversion efficiency
η_r battery round-trip efficiency

The aforementioned studies did not consider EV-embedded battery fading and their economic effect on power system planning with few of them considering only the cyclic-fading effect. Accounting for the complex performance of embedded batteries is the main reason for this deficiency. Ref. [16] introduced an aggregated model that accounted for the battery performance degradation in analyzing the effectiveness of V2G application of different battery technologies. It showed that in addition to the electricity time-of-use rates, V2G profitability is highly dependent on the ambient temperature and depth of discharge. Thus, V2G application might be inappropriate. In Refs. [17] and [18], battery capacity fading due to driving and V2G usage was analyzed, and an economic feasibility study for such applications in three U.S. cities was conducted. In Ref. [19], different charging strategies for EVs in a distribution system based on real-world driving pattern in Germany were analyzed using a model that depicted the calendric and cyclic stress factor effects on battery pack. The results confirmed the significant effect of non-cyclic stress factors on battery depreciation. With regard to the short-term scheduling of EV applications [20], and [21] presented efficient optimization models that considered different battery life stress factors.

Because EV owners will not participate in the V2G application unless it is profitable, profound consideration should be extended during power system planning. In this respect, the current paper presents an optimization model for RES sizing, such as PVs and WTs, in residential microgrids under high EV integration levels, where the performance degradation of EVs is thoroughly considered. This study directly aims to narrow the gap between real short-term scheduling and long-term RES planning. It is worth noting that RES sizing for microgrid scale has received little attention in the literature. Furthermore, the literature did not report any direct optimization method, i.e., running a certain algorithm or model to obtain the optimal penetration or size of RES.

In the current work, well-established models and data were employed to emulate the battery capacity fading of EVs. A detailed battery-fading model is integrated into a general power management framework that represents an intelligent operation of EVs to balance the RES generation, grid power, and electric demand, which are formulated and solved in a mixed-integer linear programming (MILP) fashion. Power management and RES sizing are optimized from the economic point of view, and thus, a profitable EV interaction with the grid and RESs is guaranteed, resulting in a more realistic planning. The inherit stochastic nature of the problem due to the involvement of RESs, EV operation, and electric consumption patterns is modeled using appropriate probability distribution functions (PDFs) to generate scenarios for several years and is then solved as deterministic problem using the CPLEX optimization engine. A comparative case study on a residential microgrid in Okinawa, Japan, is presented to explain the effect of EV economic operation on RES sizing under different levels of EV integration. Furthermore, the battery replacement cost and uncertainty levels involved in predicting the EV operation and electric consumption patterns were investigated.