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Operational scheduling of a smart distribution system considering electric vehicles parking lot: A bi-level approach

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ABSTRACT

In this paper, a new bi-level framework is presented for operational scheduling of a smart distribution company (SDISCO) with electric vehicle (EV) parking lot (PL) and renewable energy sources (RES), i.e., wind and photovoltaic (PV) units. In the proposed bi-level model, maximization of the profit of SDISCO is obtained in the upper-level (leader) problem by minimizing the cost of power purchased from the wholesale market due to the EV PL unique capability, i.e., PL-to-grid. The lower-level (follower) problem aims to maximize the profit of the PL owner. This model is converted to a non-linear single-level problem by using Karush–Kuhn–Tucker (KKT) conditions. Fortuny-Amat and McCarl method is used for linearization based on auxiliary binary variables and sufficiently large constants. Moreover, uncertainties such as duration of the presence of EVs in PL, the initial state of the charge (SOC) of EVs and output power generation of wind and PV units are simultaneously considered through a set of scenarios. The SDISCO's profit is investigated in four modes: (1) without RES and with the controlled charging of EVs; (2) without RES and with smart charging/discharging of EVs; (3) with RES and with the controlled charging of EVs; (4) with RES and with smart charging/discharging of EVs. In all these modes, a price-based demand response (DR) program is considered, as well as incentive-based DR, and combined price-based DR and incentive-based DR. The presented model is tested on the IEEE 15-bus distribution system over a 24-h period. The results show that SDISCO gains more profit by using a suitable charging/discharging schedule and employing a critical peak pricing (CPP) program. Furthermore, by comparing this bi-level model with the centralized model, the effectiveness of the bi-level model is demonstrated. Also, sensitivity analyses on the number of EVs, size of RES and the percentage of customer participation in the DR program are evaluated on the optimal operation of the SDISCO.

1. Introduction

1.1. Motivation

Among various energy consumers in the world, the transportation sector is one of the largest users of fossil fuels and the largest contributor to greenhouse gas emissions and pollutants. According to the report of the international energy agency (IEA), the transportation sector consumed 45% of the worlds' oil in 1973, and this value was reached to 62.3% in 2011. In terms of greenhouse gas emissions, the transportation sector accounts for more than 20% of the carbon dioxide [1]. On the other word, the global demands for fossil fuels due to the continuous growth of human activities are incrementing which leads to an increase in greenhouse gas emissions and pollutants. With regard to benefits, e.g., reducing the fuel consumption and greenhouse gas emissions and improving the energy efficiency, electric vehicles (EVs) have recently gained much attention and will be widely used in the transportation system in the future [2]. For example, 62% of the total fleet in the United States of America is estimated to be hybrid EVs in 2050 [3].

The power system has limited storage capacity, therefore vehicle-to-grid (V2G) concept, that has emerged with the EVs, has attracted the

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Nomenclature

Indices

b, b′	index for branch or bus
F	index for linear partitions in linearization
n, N	index for EV number
S, s	index for scenarios
Sb	index for slack bus
t, t′	index for time (h)

Parameters

A(t)	incentive of DR programs at t-th hour ($/kWh)
C^{cd}	cost of equipment depreciation ($/kWh)
E(t,t)	self-elasticity
E(t,t′)	cross-elasticity
$I^{max,\ b,\ b'}$	maximum current of branch b, b′ (A)
P(t)	customers' demand at t-th hour after DR (kW)
$P^0(t)$	initial demand at t-th hour (kW)
P^{con}	contracted power in DR programs (kW)
P^L	customers' demand before DR (kW)
$P^{L,DR}$	customers' demand after DR (kW)
P^{max}	charging or discharging rate (kWh)
P^{PV}	output power of PV unit (kW)
$P^{PV,max}$	maximum output power of PV unit (kW)
P^W	output power of wind unit (kW)
$P^{W,max}$	maximum output power of wind unit (kW)
PEN(t)	penalty of DR programs at t-th hour ($/kWh)
$Pr^0(t)$	initial electricity price at t-th hour ($/kWh)
Pr(t)	electricity price at t-th hour after DR ($/kWh)
$\rho^{L,DR}$	electricity price after DR ($/kWh)
ρ^{ch}	charging tariff of EVs ($/kWh)
ρ^{PL2EV}	price of power purchased of PL by EVs ($/kWh)
ρ^{dch}	discharging tariff of EVs ($/kWh)
ρ^{Wh2G}	price of buying electricity from the wholesale market by SDISCO ($/kWh)
$Q^{L,DR}$	customers' reactive power after DR (kVAR)
$R_{b,\ b'}$	resistance between branch b, b′ (Ω)
SOC^{arv}	initial SOC of EVs at the arrival time to the PL (kWh)
t^{dep}	departure time of EVs from the PL
V^{Rated}	nominal voltage (V)
V^{max}	maximum allowable voltage (V)
V^{min}	minimum allowable voltage (V)
$X_{b,\ b'}$	reactance between branch b, b′ (Ω)
Z	impedance (Ω)
ΔS	upper limit in the discretization of quadratic flow terms (kVA)
η^{ch}	charging efficiency (%)
η^{dch}	discharging efficiency (%)
SOC^{dep}	desired SOC of EVs at the departure time from PL (kWh)
SOC^{max}	maximum rate of SOC (kWh)
SOC^{min}	minimum rate of SOC (kWh)
t^{arv}	arrival time of EVs to the PL
π_s	probability of each scenario

Variables

I,I2	current flow (A), Squared current flow (A2)
P^{ch}	transferred power for EVs charging (kW)
P^{dch}	discharging power of EVs (kW)
P^{Loss}	power loss of SDISCO (kW)
P^{Wh2G}	power purchased from wholesale market by SDISCO (kW)
P^+	active power flows in downstream directions (kW)
P^-	active power flows in upstream directions (kW)
Q^{Wh2G}	SDISCO's reactive power (kvar)
Q^+	reactive power flows in downstream directions (kVAR)
Q^-	reactive power flows in upstream directions (kVAR)
V,V2	voltage (V), squared voltage (V2)
x	binary variable for linearization of the complementary conditions
λ	dual variable ($/kWh)

Others

C	greater than or equal to zero constraint
L	Lagrangian function
M	sufficiently large constants

attention of many operators and planners, and it has created new hopes for providing the storage requirements of the power system. It is noted a large number of EVs that is imposed on smart distribution company (SDISCO) in the future, resulting in high energy consumption demands. In this situation, coordination of PLs in the operation modes consist of PL-to-Grid (PL2G) and Grid-to-PL (G2PL) is a challenging issue of the SDISCO. In the PL-to-Grid mode, the PL's power is injected into the SDISCO, that is resulting from discharging the EVs. In the Grid-to-PL mode, the power is drawn from the SDISCO by PL for charging the EVs. Also, the high penetrations of EVs to SDISCO increase the production of the traditional power plant. So, the fossil fuel consumption and greenhouse gas emission increase. Therefore, the use of renewable energy sources (RES) is also inevitable alongside traditional power plants for supplying this part of the energy. Studies show that EV owners do not use the vehicles more than 93–96% of day-time [4,5]. Thus, it is clear that by increasing the penetration of EVs in the transportation sector, the battery storage capacity of these vehicles while they are parked can be used for improving the performance of SDISCO.

Moreover, demand response (DR) is one of the most cost-effective and efficient methods for smoothing the load profile. By participating in DR programs, customers are able to change their energy consumption in response to energy price changes and get incentives in return.

This paper aims at the operational scheduling of SDISCO considering RES and PL along with their uncertainty. Since the PL owner is private, a new bi-level model is developed. In the upper-level, maximization of the profit of SDISCO has performed, while in the lower-level, maximization of the profit of PL owner has conducted. However, the uncertain nature of RESs and PL may have a considerable effect on the optimal operation of SDISCO. So, uncertainties are modeled by the probability distribution function (PDF). Furthermore, the effect of charging methods, i.e., controlled charging, smart charging/discharging, and also a price-based and an incentive-based DR program are considered on the operational scheduling of SDISCO. In addition, the effect of the size of wind and photovoltaic (PV) units and the number of EVs are evaluated on the operations of SDISCO. Since the model involves uncertainties, stochastic programming is used for solving the objective function. In fact, this paper aims at answering the following questions:

– What is the appropriate model with the aim of maximization of the