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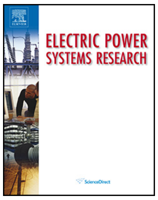

Smart distribution system operational scheduling considering electric vehicle parking lot and demand response programs

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ABSTRACT

Electric vehicle (EV) technology with a vehicle to grid (V2G) property is used in power systems to mitigate greenhouse gas emissions, reduce peak load of the distribution system, provide ancillary service, etc. In addition, demand response (DR) programs as an effective strategy can provide an opportunity for consumers to play a significant role in the planning and operation of a smart distribution company (SDISCO) by reducing or shifting their demand, especially during the on-peak period. In this paper, the optimal operation of a SDISCO is evaluated, including renewable energy resources (RERs) along with EV parking lots (PLs). RER and PL uncertainties and a suitable charging/discharging schedule of EVs are also considered. Furthermore, price-based DR programs and incentive-based DR programs are used for operational scheduling. To achieve this aim, a techno-economic formulation is developed in which the SDISCO acts as the owner of RERs and PLs. Moreover, DR programs are prioritized by using the technique for order preference by similarity to ideal solution method. In addition, a sensitivity analysis is carried out to investigate different factors that affect the operational scheduling of the SDISCO. The proposed model is tested on the IEEE 15-bus distribution system over a 24-h period, and the results prove the effectiveness of the model.

1. Introduction

1.1. Motivation and aims

The penetration of electric vehicles (EVs) considering different types of charging can bring advantages and disadvantages to the owner of a smart distribution company (SDISCO). The operation of EVs can be classified into uncontrolled charging mode, controlled charging mode, and smart charging/discharging mode. If EVs are charged in an uncontrolled charging mode, improper results may occur such as increase in loss [1,2], high demand [3,4], unbalancing of the load [5,6], voltage drop [7], and decrease in the cable and transformer life [8,9]. EVs also offer a unique advantage in terms of a technology known as vehicle to grid (V2G) [10]. The V2G concept is essentially the ability of EVs to inject the electrical power to the SDISCO. Therefore, by using the controlled charging mode or smart charging/discharging mode, i.e., charging during the mid-peak or off-peak periods and discharging during the on-peak period, the performance of SDISCO is improved. This mode has many benefits for the SDISCO, such as ancillary service-spinning reserve [11,12], load leveling and peak load shaving [13,14], voltage regulation [15], and decreasing in CO_2 gas emissions [16].

Moreover, demand response (DR) programs are a key element in the sustainable development of the SDISCO, which can be enabled by the SDISCO. DR is a set of actions for reducing the consumer's demand that is implemented by changing the price of electricity or paying an incentive or receiving a penalty. These programs are implemented when interruptions occur in the conventional power plant or renewable energy resource (RER) generations. DR programs are also designed to improve the reliability of the SDISCO and reduce the electricity consumption during on-peak hours [17].

Because the number of EVs may increase in the future, the management and operation of the SDISCO at present are more

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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)
$P^{L,DR}$	Customers' demand after DR (kW)
$P^{L,max}$	Maximum customers' demand before DR (kW)
P^{PV}	Output power of PV unit (kW)
$P^{PV\text{-}Rated}$	Rated output of PV unit (kW)
$P^{PV,max}$	Maximum output power of PV unit (kW)
P^{W}	Output power of wind unit (kW)
$P^{W\text{-}Rated}$	Rated 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)
Pr^{ch}	Charging tariff of EVs ($/kWh)
Pr^{dch}	Discharging tariff of EVs ($/kWh)
$Pr^{L,DR}$	Electricity price after DR ($/kWh)
Pr^{Wh2G}	Price of purchased electricity from the wholesale market by the SDISCO ($/kWh)
P(v)	Probability of the wind speed
$Q^{L,DR}$	Customers' reactive power after DR (kVAR)
$R_{b,b'}$	Resistance between branches b and b′ (Ω)
R^{ch}	Charging rate (kWh)
R^{dch}	Discharging rate (kWh)
SOE^{arv}	Initial SOE of EVs at the arrival time to the PLs (kWh)
S^{b}	Apparent power in bus b (kVA)
$S^{b,max}$	Maximum apparent power in bus b (kVA)
SOE^{dep}	Desired SOE of EVs at the departure time from PLs (kWh)
$SOE^{ini,min/max}$	Truncation region for the initial SOE of EVs
SOE^{max}	Maximum rate of SOE (kWh)
SOE^{min}	Minimum rate of SOE (kWh)
t^{arv}	Arrival time of EVs to the PLs
$t^{arv,max}$	Upper bound of the arrival time
$t^{arv,min}$	Lower bound of the arrival time
t^{dep}	Departure time of EVs from the PLs
$t^{dep,max}$	Upper bound of the departure time
$t^{dep,min}$	Lower bound of the departure time
V_a, V_b	Wind speed limit
V_{ci}	Cut-in speed of wind turbine (m/s)
V_{co}	Cut-off speed of wind turbine (m/s)
V_r	Rated speed of wind turbine (m/s)
V^{Rated}	Nominal voltage (V)
V^{max}	Maximum allowable voltage (V)
V^{min}	Minimum allowable voltage (V)
$X_{b,b'}$	Reactance between branches b and b′ (Ω)
Z	Impedance (Ω)
ΔS	Upper limit in the discretization of quadratic flow terms (kVA)
η^{ch}	Charging efficiency (%)
η^{dch}	Discharging efficiency (%)
θ	Illumination intensity (w/m^2)
θ_r	Rated illumination intensity (w/m^2)
μ	Mean value
ρ^{s}	Probability of each scenario
σ	Standard deviation

Variables

I,I2	Current flow (A), squared current flow (A2)
P^{ch}	Transferred power for charging EVs (kW)
P^{dch}	Discharging power of EVs (kW)
$P^{G2L,DR}$	Power purchased from the SDISCO by customer after DR programs (kW)
P^{G2PL}	Power purchased from the SDISCO by PL (kW)
P^{Loss}	Power loss of the SDISCO (kW)
P^{PL2G}	Power purchased from PLs by the SDISCO (kW)
$P^{PV2L,DR}$	Power purchased from PV unit by customer after DR programs (kW)
P^{PV2PL}	Power purchased from PV unit by PL (kW)
P^{Wh2G}	Power purchased from the wholesale market by the SDISCO (kW)
$P^{W2L,DR}$	Power purchased from wind unit by customer after DR programs (kW)
P^{W2PL}	Power purchased from wind unit by PL (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^{ch}	Binary variable that shows the charge status of EVs (0 or 1)
X^{dch}	Binary variable that shows the discharge status of EVs (0 or 1)

Others

m	Alternative quantity
o	Attribute quantity
SS	Distance between each alternative and the ideal solution/nonideal solution
V	Ideal-solution/nonideal solution
W	Weight of attributes
λ	Decision maker's importance factor

complicated than that in the past. One of the important solutions in this context is an efficient use of parking lots (PLs). EV owners do not use the EVs: 93–96% of daytime. The high numbers of EVs having V2G capability can provide a good opportunity for the operation and planning of the SDISCO, if an optimal management of charging/discharging the EVs is implemented. Furthermore, uncertainty is one of the most important and inherent features of RERs and PLs. In the presence of uncertainty in the SDISCO, the operation and planning are also uncertain. Therefore, using DR programs is considered as a tool for reducing the amount of energy not-supplied (ENS).

This paper aims at the operational scheduling of the SDISCO considering RERs and PLs and their uncertainties. To achieve this goal, a techno-economic formulation is developed to maximize the profit of the SDISCO. However, the uncertain nature of different RESs and PLs may have considerable effects on the optimal operation of the SDISCO. Therefore, uncertainties are modeled using the probability distribution function (PDF). Furthermore, the impact of