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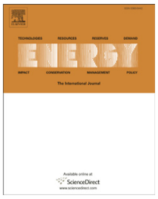

Power system steady-state analysis with large-scale electric vehicle integration

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ABSTRACT

It is projected that the electric vehicle will become a dominant method of transportation within future road infrastructure. Moreover, the electric vehicle is expected to form an additional role in power systems in terms of electrical storage and load balancing. This paper considers the latter role of the electric vehicle and its impact on the steady-state stability of power systems, particularly in the context of large-scale electric vehicle integration. The paper establishes a model framework which examines four major issues: electric vehicle capacity forecasting; optimization of an object function; electric vehicle station siting and sizing; and steady-state stability. A numerical study has been included which uses projected United Kingdom 2020 power system data with results which indicate that the electric vehicle capacity forecasting model proposed in this paper is effective to describe electric vehicle charging and discharging profiles. The proposed model is used to establish criteria for electric vehicle station siting and sizing and to determine steady-state stability using a real model of a small-scale city power system.

1. Introduction

The integration of renewable energy sources (RES) and electric vehicles (EVs) has been promoted significantly due to fossil fuel shortage and environment concerns as well as smart grid. The manufacturing and marketing of EVs has developed significantly in recent decades. It has been estimated that approximately 1.2 million BEVs and 0.35 million PHEVs will be on road in the UK by 2020 [1]. It has also been determined that there will be a total installation of 53.2 GW of RES including planning projects with a total power demand of 51.8 GW in winter-max scenario in the UK by the same year [2]. Similar statistics are apparent in other developed nations. Thus, it can be concluded that conventional generation and extensive integration of RES are required in future power systems to support normal electric demands, such as domestic, commercial and industrial loads, as well as stochastic loads, especially EVs.

Traditional power system analysis includes developing models of components, network calculations, power flow solutions, fault analysis and stability analysis. Analyses operate mainly in the time domain and involve steady-state analysis, transient state analysis and dynamic state analysis – where steady-state analysis is the basis of the other two [3]. This paper focuses on future power system with large-scale EV integration and examines pertinent technical issues in steady-state analysis, which are regarded as fundamental to both transient and dynamic state analysis. Such issues include EV capacity forecasting, development of an optimization object function, EV station siting and sizing and steady-state stability.

There have been numerous publications to date which consider EV capacity forecasting. Liu et al. [4] discuss the opportunities and challenges of Vehicle-to-Home (V2H), Vehicle-to-Vehicle (V2V), and Vehicle-to-Grid (V2G) technologies. An EV aggregator model and the optimal EV demand calculation flowchart based on the Genetic Algorithm (GA) are introduced. EVs are assumed to be fully charged or discharged in the examples. Shaaban et al. [5] and Liu et al. [6] use Monte Carlo simulation for normally distributed virtual trips and EV initial state-of-charge (SOC). The trip model [5] is applied in the EV energy consumption model. Rolink and Rehtanz [7] use the homogeneous semi-Markov process to determine the probability of EV resting at a defined location and at a given time: the total EV capacity is calculated based on this probability and the rated charging power and EV numbers. Other methods, such as

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Nomenclature

BTTR	Beijing-Tianjin-Tangshan Region
BEV	batter electric vehicle
DG	distributed generation
DR	demand-response
EV	electric vehicle
FCV	fuel cell vehicle
GA	genetic algorithm
G2V	grid-to-vehicle
GBP	GB pound sterling
HEV	hybrid electric vehicle
LV	low-voltage
MV	medium-voltage
NI	Northern Ireland
PDF	probabilistic density function
PSO	particle swarm optimization
PHEV	plug-in hybrid electric vehicle
RES	renewable energy source
SOC	state-of-charge
SQP	sequence quadratic programming
UC	unit commitment
UK	United Kingdom
USA	United States of America
V2G	vehicle-to-grid
V2H	vehicle-to-home
V2V	vehicle-to-vehicle
C_I^{SS}	investment cost
$C_{I\_\mathrm{C}}^{SS}$	charger cost
$C_{I\_i}^{SS}$	investment cost of the *i* th EV station
$C_{I\_i\mathrm{max}}^{SS}$	maximum investment limit of the *i* th EV station
$C_{I\_\mathrm{lp}}^{SS}$	land price
$C_{I\_\mathrm{oe}}^{SS}$	other equipment cost
$C_{I\_\mathrm{T}}^{SS}$	transformer cost
C_M^{SS}	maintenance cost
$C_{M\_\mathrm{C}}^{SS}$	charger maintenance cost
$C_{M\_\mathrm{F}}^{SS}$	feeder maintenance cost
$C_{M\_i}^{SS}$	maintenance cost of the *i* th EV station
$C_{M\_i\mathrm{max}}^{SS}$	maximum maintenance cost limit of the *i* th EV station
$C_{M\_\mathrm{oe}}^{SS}$	other equipment maintenance cost
$C_{M\_\mathrm{T}}^{SS}$	transformer maintenance cost
C_O^{SS}	operation cost
$C_{O\_\mathrm{char}}^{SS}$	charging cost
$C_{O\_\mathrm{dis}}^{SS}$	discharging cost
$C_{O\_\mathrm{hs}}^{SS}$	human service cost
$C_{O\_i}^{SS}$	operation cost of the *i* th EV station
$C_{O\_i\mathrm{max}}^{SS}$	maximum operation cost limit of the *i* th EV station
$C_{O\_\mathrm{power}}^{SS}$	power consumption cost of electric devices
CT_p	charging cycle of charging-only EVs
d	daily travel distance
d_R	maximum range of EV
E,E^{SS}	SOC
E_a	available SOC
E_B	capacity of EV battery packs
E_{cj}	discrete SOC before charging starts from each time interval
E_{c_set}	setting value of start SOC for charging-only EVs
E_{dj}	discrete SOC before discharging starts from each time interval
E_k	SOC at start time
E_l	SOC at a later time *l* after *m* intervals charging and *n* intervals discharging
E_{start},E_{end}	start point SOC and end point SOC
$f(l)$,$g(l)$	decision variables
h,h^{SS}	PDF of initial SOC after one day travel
$I_{line}(l)$	current of each line at time *l*
K_P	power steady-state stability reserve
K_U	voltage steady-state stability reserve
L_{ik}^{SS}	distance between the *i* th EV station and the *k* th main parking lot
$L_{k\mathrm{max}}^{SS}$	range limit of the*k* th main parking lot
M_{char}, M_{dis}	cost per unit power in the economic calculation and carbon emission reduction amount per unit power in environmental application
N	total EV number
N_a	number of flexible charging EVs
N_B	number of BEVs
N_c	number of the time intervals of the charging and discharging process
N_{char}	number of EVs at charging
N_d	number of discrete time intervals
N_{dis}	number of EVs at discharging
N_{FC}	number of FCVs
N_H	number of PHEVs
N_l	total number of transmission lines in the system
N_p	number of charging-only EVs
N^{SS}	total number of EV stations planned in a specific area
N_α, N_β, N_γ, N_ϕ	number of flexible EVs under different scenarios
$P_a(l)$	charging power of flexible EVs at time *l*
P_{Bd}	battery rated discharging power
P_c	rated charging power
P_{c_total}	total charging power
$P_{c\_total}^M$	total charging cost
P_{char}	charging power
P_d	rated discharging power
P_{d_total}	total discharging power
$P_{c\_total}^M$	total discharging cost
P_{dis}	discharging power
$P_{EV}(l)$	EV charging power at time *l*
$P_{EV}^M(l)$	EV charging cost at time *l*
P_{EV}^{SS}	EV power demand at EV stations
$P_{EV\_i}^{SS}$	EV power demand at the *i* th EV station
$P_{F\_i\mathrm{max}}^{SS}$	maximum load limit in feeders
P_j	discrete charging/discharging power for the *j* th period
$P_L(l)$	gross load power at time *l*
P_{max}	maximum power of steady-state stability
$P_{\mathrm{max}node}$	maximum power limit of each node
$P_{node}(l)$	power of each node at time *l*
$P_p(l)$	charging power of charging-only EVs at time *l*
$P_{RES}(l)$	RES generation power at time *l*
P_S	sending power from the infinite bus
$P_S(l)$	object power at time *l*
$\overline{P}_S$	mean level of the object power
$P_{T\_i\mathrm{max}}^{SS}$	maximum load limit in transformers
R_{line}	resistance of each line
$(R+jX)_{ik}^{SS}$	impendence between the *i* th EV station and the *k* th main load node
$(R+jX)_{k\mathrm{max}}^{SS}$	maximum impendence limit of the*k* th main load node
T_1, T_2	setting time for EV charging curve
t_3	discharging end time
T	time interval
T_a	available time duration
T_{amin}, T_{amax}	minimum and maximum value forT_a
U_0	actual operating voltage
U_{cr}	critical voltage of load buses
x_n	sign to identify the existence of EVs
y,z	objective function
α, β, γ, ϕ, φ	probabilities
μ	log_e mean in SOC PDF
σ	standard deviation in SOC PDF
η	transmission loss percentage