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A multi-agent based integrated volt-var optimization engine for fast vehicle-to-grid reactive power dispatch and electric vehicle coordination

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HIGHLIGHTS

- Integrated volt-var optimization engine is proposed for distributed grid control.
- The proposed method reduces up to 92% computational time.
- The benefits and charging demands of electric vehicle owners can be guaranteed.
- Costly diesel generator usage can be reduced by adopting more vehicle-to-grid var.
- The computation time of optimization decreases even when more energy sources added.

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ABSTRACT

Electric Vehicles have been receiving increasing attention. As the number of electric vehicles increases, uncoordinated charging of electric vehicles can lead to voltage and frequency instability in microgrids. Various methods have been proposed for electrical vehicle coordination, where most of them focused on controlling active power. Vehicle-to-grid var has been recently included in volt-var optimization approaches, which aim at improving voltage stability using var sources. However, most of these approaches are based on computationally inefficient heuristic methods, which are not applicable to handle fast-changing vehicle-to-grid var. Furthermore, the uncertainties and charging demands of electric vehicles have not been considered thoroughly. In this paper, an integrated volt-var optimization engine is proposed for distributed electric vehicle charging coordination and fast vehicle-to-grid var dispatch, considering the uncertainties and charging demands of electric vehicles. The proposed method is based on a multi-agent system, which distributes complex optimization processes to enhance computational efficiency. Case studies show that the proposed distributed method reduces up to 92% computational time without economic losses, compared with the central coordination. It is also observed that the costly usage of diesel generators can be reduced by employing more vehicle-to-grid var due to their similar functionality in voltage regulation. Surprisingly, it is found that when utilizing the power support from electric vehicles and diesel generators, the computational time decreases even when more decision variables are added.

1. Introduction

Electric vehicles (EVs) are considered as a promising option for reducing carbon footprint in populated areas as the energy industry transitions towards decarbonization. The International Energy Agency estimates that the sales of passenger light-duty EVs/plug-in hybrid EVs (PHEVs) will increase significantly from 2020 onwards and might reach more than 100 million EVs/PHEVs sold per year worldwide by 2050 [1]. With a considerably large population of EVs and an improvement in battery performance, EVs can function as large-scale distributed energy storage systems (ESSs) in grid-to-vehicle (G2V) and vehicle-to-grid (V2G) manners. G2V and V2G refer to two scenarios, which are using EVs as ESSs to store energy from power systems, and to release energy to power systems, respectively. Research about employing EVs

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Nomenclature

Abbreviations

BEV	Battery electric vehicle
CB	Capacitor bank
DG	Diesel generator
DGA	Diesel generator agent
ESS	Energy storage system
EV	Electric vehicle
EVA	Electric vehicle agent
G2V	Grid-to-vehicle
GA	Genetic algorithm
ISO	Independent system operator
ISOA	Independent system operator agent
IVVO	Integrated volt-var optimization
LA	Load agent
LMP	Locational marginal price
OPF	Optimal power flow
PHEV	Plug-in electric vehicle
PLC	Parking lot charging facility
PLCA	Parking lot charging agent
RPD	Reactive power dispatch
SCADA	Supervisory control and data acquisition
V2G	Vehicle-to-grid
VPP	Virtual power plant
VPPA	Virtual power plant agent
VVO	Volt-var optimization

Mathematical symbols and operators

$\circ$	the operator of the entrywise product
$\alpha(i)$	the set of buses that are directly connected to bus i
$\check{V}$ and $\hat{V}$	the lower and upper voltage magnitude constraints
$\theta_{ij}^t = \theta_i^t - \theta_j^t$	the voltage angle difference between bus i and j
A_i, B_i and C_i	the generation cost coefficient factors of diesel generators
AM	the auxiliary matrix for computing charging power variations
B_{ij}	the susceptance of a line ij
C_d	the battery degradation cost
C_t	the cost at time interval t
and C_Q^t	the active power and reactive power price cost at time interval t
$Cost_k$	the charging cost of k^{th} EV
Cpc_k^{batt}	the battery capacity of k^{th} EV
DoD_{lim}	the maximum depth of discharge
end_k	the index of the last charging interval of k^{th} EV
G_{ij}	the conductance of a line ij
I_τ	the charging time interval τ
I_{kt}	the charging interval of the k^{th} EV at time index t
N	the number of EVs that are connected to chargers
n	the number of remaining time intervals for making decisions
N_{DG}	the set of diesel generators
N_{node}	the number of buses except for the feeder bus
N_{PL}	the set of parking lots
P_τ	the charging power at time interval τ
$P_{average}$	the constant charging power of the average strategy
P_{cap}^{high} and P_{cap}^{low}	the maximum and minimum total active charging power
$P_{i,ramp}^{DG}$	the maximum ramping up/down rate of i^{th} diesel generator
P_{kt}	the charging active power of the k^{th} EV at time interval t
P_{ramp}^{low} and P_{ramp}^{high}	the maximum and minimum variation of the total charging power
PC_i^t and QC_i^t	the active/reactive power from DGs or parking lots at time t
PD_i^t and QD_i^t	the active/reactive power consumption at bus i at time t
Q_{kt}	the charging reactive power of the k^{th} EV at time interval t
Ra_k	the EV charger rating of the k^{th} EV
s_τ	the state variable at time interval τ
SOC_k^{ini}	the initial state of charge of k^{th} EV
SOC_k^{target}	the targeted state of charge of k^{th} EV
u_τ	the decision variable at time τ
UTM	the upper unitriangular matrix
V	the evaluating function
V_j^t	the voltage magnitude at bus j
Y_{ij}	the complex admittance of a line ij
Z	the augmented decision variable set
Ra_i^{DG}	the power rating of i^{th} DG
SOC_τ	the state of charge at time interval τ

Subscripts and superscripts

k	EV index
τ	the current time interval index
i and j	bus index or device index
t	the iterative time interval index

as ESSs to provide active power has been successfully established for a long time from different perspectives. From the perspective of EVs, the economic benefits of EV charging have been investigated in [2] while optimizing the energy management of EVs has been the focus in [3]. From the perspective of microgrids, researchers have also explored the usage of EVs as distributed energy sources for frequency regulation [4,5], voltage control [6], and demand peak shaving in power grid [7]. The upgrade of grid components to accommodate the EV charging has also been considered in [8]. Moreover, EVs can also serve as energy buffers for intermittent energy sources such as solar and wind energy [9]. However, using EVs as active power based ESSs causes degradation in considerably expensive EV batteries [10].

Besides having the role of active power based ESSs, EVs can also serve as var sources as the technology of EV chargers advances. Var compensation through EV chargers has been implemented in [11,12]. Different from using EVs to provide active power to the grid, no degradation of batteries happens in V2G var compensation [13]. A recent study [14] has built a volt-var optimization (VVO) engine to manage V2G var. VVO is a reactive power dispatch (RPD) method, which is able to optimize voltage and/or reactive power[1] of a distribution network using volt-var components such as EVs. Nevertheless, the proposed VVO engine in [14] and other similar methods [15,16] ignore the uncertainties of EV availability, which further leads to the neglect of various and fast-changing charging scenarios. If the rapidly changing nature of the charging scenarios is taken into consideration, the proposed method in [14] is not sufficiently fast to handle the uncertain var sources from EVs. This is because the proposed method in [14] is based on an evolutionary algorithm – genetic algorithm (GA) – and requires multiple runs of power flow to generate candidate solutions and evolve, which is very time-consuming. Similarly, other evolutionary algorithm-based RPD methods [17,18] are not applicable to

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[1] Throughout this paper we use the term ‘var’ to denote ‘reactive power’ and the two terms are interchangeable.