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Coordinated control of distribution grid and electric vehicle loads

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ABSTRACT

Electric vehicle (EV) charging results in unusual power peaks during low energy prices, which can have adverse impacts on distribution grid operation. Therefore, coordinated dispatch of EV loads including the operational constraints of distribution grid is essential. However, a centralized approach to solve this problem is computationally challenging task. This work proposes a bi-level hierarchical vehicle-grid (VG) optimization framework. In the hierarchy, optimal operation of the distribution grid is considered in one level, while the optimal operation of EVs is carried out in another level. The proposed framework consists of comprehensive mathematical modelling of distribution system components, EVs, and operational constraints. The proposed framework is applied to coordinate charging of hundreds of EVs in the IEEE 34-node three-phase unbalanced distribution system. Case studies demonstrate that the hierarchical VG optimization framework provides benefits to the distribution grid operations as well as to the EV owners.

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1. Introduction

Smart grid technology at distribution grid level, energy management systems, and smart appliances at customers' premises facilitate demand dispatch process [4,2,25]. Electric vehicles (EVs) are flexible loads which are suitable for demand dispatch. Penetration of EVs in distribution grids is increasing due to the environmental concerns and incentives from regulators. Studies show that EVs provide economic benefits to the customers [23,13]. Aggregation of EVs can provide grid level applications, such as ramping, frequency regulation, and reliability improvement [12,27,1]. EVs also provide benefits to distribution utilities by facilitating demand dispatch [4,6,18,10,7,26,9,19]. Thus, in this context, coordinated dispatch of EVs can benefit utilities as well as EV customers.

In system-wide demand dispatch applications, it is essential to consider operational constraints of distribution grid while dispatching EV loads. In [10,7,26], grid constraints are included while scheduling multiple EVs. In [9,19], coordinated charging of EVs is proposed with objectives to minimize power losses and improve the voltage profile. Artificial immune system has been used in [19] to reschedule the electrical vehicles in the distribution feeder. Similarly, [28] utilizes aggregator EV concept to optimally manage the active distribution network. However, the study is focused on distribution side and benefit of the demand dispatch to EV owners is not considered. A large scale demand dispatch process requires solution to practical sized three-phase unbalanced distribution grid with thousands of EVs, which is a computationally challenging task as the resulting model is mixed integer non-linear programming problem (MINLP) [17,11]. In order to reduce the computational complexity, the mathematical model of distribution grid with EVs in [8] is simplified to a linear programming (LP) problem. However, the resulting LP problem does not guarantee feasibility of the original non-linear model. A centralized approach to solve the MINLP problem is computationally involving in a practical sized distribution system. To reduce the computational complexity, distributed and hierarchical computing approaches can be used with information exchange among various levels in the hierarchy. In this demand dispatch application, these levels refer to distribution grid operator and the EV aggregators (EVAs) [6,11].

In [13], EV dispatch problem is solved using centralized and distributed approaches. It is shown that computational complexity can be reduced by using distributed approach, which leads to small manageable problems. In [11], it is pointed out that with the large number of EVs, the computational complexity increases and decentralized approach could be potentially suitable for application that require real-time performance. The proposed models [13,17,11] are demonstrated to be beneficial to EV customers. However, the models in [11,13] do not account the distribution grid model. Inclusion of distribution grid model in [13,17,11] leads to challenging computational issues.

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Nomenclature

Subscripts
i nodes
j branch connecting nodes i and $i+1$
k load tap changers, $k \in j$
m nodes where base (non-EV) loads are connected, $m \in i$
n nodes where capacitors are connected, $n \in i$
p phases, $p = a, b, c$
q electric vehicle number
r receiving end
s sending end
t time
$t1$ time when electric vehicle is available for grid connection
$t2$ time when electric vehicle is off the grid
tr transformer, $tr \in j$

Superscripts
cl capacitor loads
ev electric vehicles
max maximum value
min minimum value
vr variable load
zl constant impedance load

Parameters
α, β scalars
Δt time interval
ΔQ reactive power from each unit of capacitor
Δv change in voltage due to one tap position
η efficiency of charging electric vehicle
ρ energy price
A, B, C, D three-phase ABCD parameter matrices
E energy capacity of electric vehicle battery
G energy needed to travel per unit distance
M average driving distance of electric vehicle
R charger rating
$S0$ state of the charge desired by customer
ST transformer VA capacity
$V0$ nominal Phase voltage
X reactance of capacitor
$Z0$ load impedance

Variables
$\Omega 1, \Omega 2, \Psi$ objective functions
cap capacitor position
F fairness index
I three-phase complex current vector
$\bar{I}$ complex conjugate of current
L voltage change due to load tap changer position
P active power consumed by an electric vehicle
PT total active power consumed by electric vehicles
S state of the charge of electric vehicle
tap load tap changer position
V three-phase complex voltage vector

Functions
$\Re$ real part of complex number

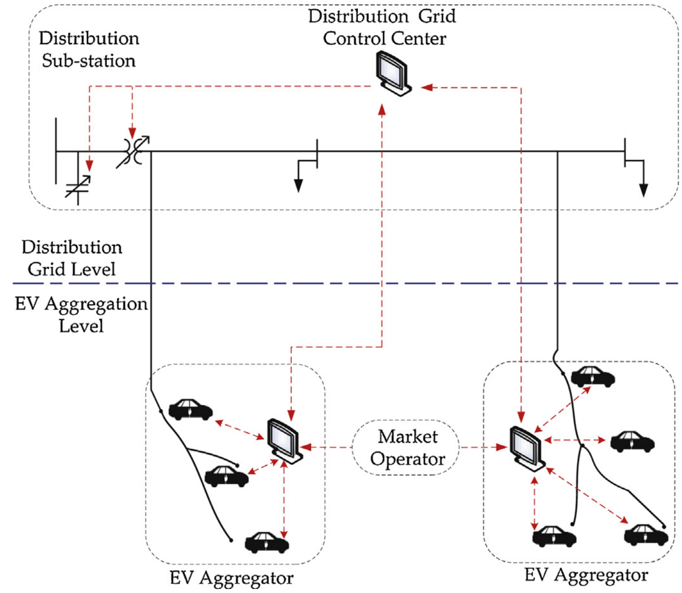

Fig. 1. A bi-level hierarchical V2G optimization framework.

Conceptual hierarchical framework for dispatching EV loads for grid benefits are discussed in [6,18]. Mathematical model required for the bi-level hierarchical optimal dispatch of generators and EVAs is developed in [29]. However, in the hierarchical modeling in [29], the underlying distribution grid model is ignored. Consideration of distribution grid model is important for system-wide demand dispatch as the EVAs can include widely dispersed EVs not connected at the same node in the distribution circuit.

This paper proposes a bi-level hierarchical vehicle-to-grid (V2G) optimization framework, as shown in Fig. 1, to optimally dispatch controllers in distribution grid and EVs. This work builds up on the previous work by the authors in [20] by incorporating comprehensive mathematical models and case studies to demonstrate the coordinated control of distribution grid and EV loads. In the proposed hierarchy, distribution grid and its control/operation form one level, and the operation of EVs form the another level. Smart grid technologies allow information exchange among EVAs, distribution grid control center, individual EVs, and market operator (MO). The EVAs gather individual EV owners' preferences, EV's state of charge (SOC), owners' willingness to participate, and other useful information from the EVs.

The EVAs obtain grid's operating constraints and utility's incentive signals from the distribution grid control center, and energy price from the MO. The mathematical model, which consists of distribution grid, optimizes the operation of the grid based on all the information collected, and dispatch signals can be sent to its control equipment such as load tap changer (LTCs) and capacitor banks. Based on another mathematical model, the EVAs generate optimal charging schedule of EVs, which can be sent to dispatch the EVs. The proposed hierarchical V2G optimization framework benefits the distribution grid as well as individual EV customers. The bi-level modeling framework proposed in this work can be easily integrated to other operational levels (e.g., transmission operation and control) in power systems.

The major contributions of this paper are:

I. Development of detailed and generic mathematical model of underlying three-phase distribution grid that coordinates with EV aggregators to optimize the operation of power grid.

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