Electrical Power and Energy Systems 98 (2018) 474–487

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Optimal decentralized coordination of electric vehicles and renewable generators in a distribution network using A* search

Lu Wang[a,b,*], Suleiman Sharkh[a], Andy Chipperfield[a]

[a] *Faculty of Engineering and the Environment, University of Southampton, SO17 1BJ, UK*
[b] *Global Energy Interconnection Development and Cooperation Organization, Beijing 100031, PR China*

ARTICLE INFO

Keywords:
Vehicle-to-grid
Renewable energy
A* search
Decentralized dispatch

ABSTRACT

The increasing integration of Electric vehicles (EVs) and renewable generators (RGs) is an inevitable trend of power grid concerning the global control of greenhouse gas release. This will challenge constrained distribution networks due to the intrinsic intermittency of renewable power and additional charging load demand of EVs. However, appropriate dispatch of EVs via vehicle-to-grid (V2G) operation in coordination with RGs can solve the stability issues, provide operational support for the power grid, reduce the reliance on fossil fuels and benefit both the environment and EV users. This paper develops a novel algorithm to solve the optimal decentralized coordinated dispatch problem of RGs and EVs based on multi-agent and the A* search procedure. This optimal dispatch problem is formulated as a distributed multi-objective constraint optimisation problem using the Analytic Hierarchy Process taking into account both power grid and EV users' concerns and priorities. The inherent uncertainty of EV driving activities and RG output power are considered in this work, of which the stochastic modelling is established using copulas. The proposed algorithm is tested on a radial distribution network, a modified UK generic distribution system. The simulation results demonstrate the feasibility and stability of the proposed A*-based optimal coordinated dispatch strategy.

1. Introduction

In order to achieve the International Energy Agency's target of CO_2 emission reduction, clean generation and transport are the essential parts that all countries need to work on [1–4]. In Spain and Denmark, wind power supplies more than 20% of their national electricity demands [5]. Large-scale integration of the RGs could also cause serious problems of instability of a power system, due to the intermittence and uncertainty of renewable power [6]. As EVs electrify the transport consumption of energy and thus help to reduce CO_2 emission, the integration of a great number of EVs is inevitable [7]. Hence, a colossal additional charging load of EVs will be imposed on the network causing serious issues such as overloads. The coordination of RGs and EVs can solve the potential issues of instability caused by RGs and EVs, in addition to realizing clean transport and the sustainable development of the energy supply. In order to realize a stable performance, RGs and EVs should be dispatched in a smart way such that synchronous charging of EVs is avoided and EVs are charged from renewable energy when it is available and discharged to feed the electricity back into the grid via V2G when the supply is deficient [8,9]. The optimal coordination of EVs and RGs may even be capable of providing operational support to the power grid, decreasing the total electric power production and EV users' costs [10–13].

Many papers have discussed strategies for dispatch of EV batteries when they are connected to the grid [14–21]. However, as demonstrated in [22], in order to effectively reduce the CO_2 emissions and reap desired environmental benefits, RGs should provide at least a part of EVs' charging energy.

Studies on the dispatch of EVs in coordination with RGs have been presented in many publications [23,5,8,24–26] using different methods, such as hierarchical framework, virtual power plant concept and many different optimization algorithms. However, [23,5,25,26] focus on the day-ahead dispatch of EVs and RGs instead of real-time operation. Network constraints were not considered in [5,8,26,24] did not take V2G operation into account.

Most of the publications mentioned above, as well as [27–30], focus on the centralized dispatch of a power network. It collects and analyses data from the entire network at a central control centre, which could be problematic when dealing with a large network. As it connects with a great number of uncertain elements, such as EVs and RGs and their behaviours are likely to change at any time; the frequency and volume of data collection are supposed to be considerable. Moreover, when

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* Corresponding author.
E-mail address: lw5g13@soton.ac.uk (L. Wang).

https://doi.org/10.1016/j.ijepes.2017.11.036
Received 29 June 2017; Received in revised form 23 October 2017; Accepted 28 November 2017

formulating the optimization problem for a centralized dispatch, the number of constraints increases exponentially with network size [31]. Hence, it will eventually be nearly impossible to solve this problem in a centralized way using available computers. In order to address these shortcomings, decentralized approaches have been developed, which share the computational and data collection effort amongst several small control centres (agents) distributed across the network. This decentralized dispatch system can be readily expanded when the network expands by employing additional small control centres to manage the add-on parts of the network while leaving the original part of the dispatch system largely unchanged.

Some researchers have developed several distributed dispatch approaches [26,32–34]. But they either neglected the capacity constraints or used a recursive strategy where the number of recursion increases exponentially with the increasing penetration of distributed generators. Wang et al. [35] utilized a dynamic-programming-based algorithm to solve the optimal coordination problem of RGs and EVs, however, the computational cost could greatly increase with the growing number of RGs and EVs. There is therefore a clear gap in the research with regards to the application of decentralized system to solving the optimal coordinated dispatch of RGs and EV batteries, including V2G.

This paper developed a novel algorithm based on the A* search procedure to solve the optimal coordinated dispatch problem of RGs and EVs, formulated as a distributed multi-objective constraint optimization problem (DMOCOP) in [35]. The objectives of the optimal coordination of EVs and RGs are satisfying both EV users and grids' concerns and requirements, including EV charging cost saving, providing sufficient energy throughout a day to support any necessary journey, ensuring the stability of the network without overloading any cable and contributing to network's load levelling. As a decentralized algorithm, each node of the network is represented by an agent, which is responsible for the computation of objective function and communication with agents of directly-connected nodes. An agent is only aware of the elements that are locally connected and their status information and manages the dispatch of locally-connected EVs and RGs so that the stability of the network is ensured and all the objectives of dispatch are best achieved.

Moreover, the inherent uncertainty of EV travel patterns and renewable power generation is considered in this work, which are stochastically modelled and simulated using Gaussian copulas, so that the correlation between each pair of random variables are taken into account.

The proposed A*-based optimal dispatch algorithm is tested on a radial distribution network, a modified UK Generic Distribution System (UKGDS), for its stability, feasibility and efficacy at satisfying the requirements of both EV users and the grid. It is important to note that the algorithm is developed for the application in radial network, while its application in the loop network hasn't been investigated yet and will require future research. In practice, the aggregator or the distribution network operator (DNO) can be in charge of this optimal dispatch problem.

The main contributions of this paper are as follows:

1. The paper proposes a novel decentralized dispatch algorithm for EVs and RGs using A* search procedure.
2. The stochastic simulation of EV travel patterns and RG power outputs based on Gaussian Copulae is utilized to test the proposed algorithm.
3. The stability of the A*-based algorithm is demonstrated. Charging cost saving and sufficient battery energy are ensured for EV users, while wind power curtailment is minimized and load levelling is realized for grid.

The rest of this paper is organized as follows. In Section 2, a general model of electricity network and agents are presented, followed by a detailed introduction of DMOCOP that were proposed in our previous work [35] in Section 3. In Section 4, a novel A*-based optimal dispatch procedure is presented. The stochastic modelling of EV travel patterns and renewable power generation is discussed in Section 5. The results of simulations using MATLAB to verify the feasibility and efficacy of the proposed dispatch approach, are presented and discussed in Section 6. Finally, the conclusions of the work are presented in Section 7.

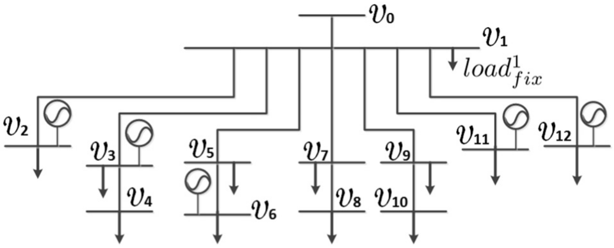

Fig. 1. Diagram of a modified generic radial distribution network.

2. A general model of the electricity network and agents

Fig. 1 shows a radial distribution network, which is derived from a UKGDS [36]. It includes RGs and EVs. The node, v_0 is the slack bus, which is connected to the rest of the power grid. Detailed description of the network model can be found in [35]; a summary is given in this section.

A set of RGs integrated within the network are denoted by $\mathbf{G} = \{g_1,...,g_n\}$, with each RG $g_i$generating electric power $p_i \in RG_i$ MW. $RG_i = \{0,...,P_i^{max}\}$ is a range of electric power that $g_i$can produce, where discretization is applied to simplify the computation. Let $\mathbf{p} = \{p_1,...,p_n\}$ denote a set of power output variables for the renewable generators in $\mathbf{G}$.

The network also connects with a set of EVs which are denoted by $\mathbf{EV} = \{ev_1,...,ev_m\}$. Each EV ev_i can be dispatched in one of the 7 modes available: charge $(+)$ or discharge $(-)$ at high (3), medium (2) or low (1) current, OR idle (0), hence, $\delta_i \in DM_i = \{-3,-2,-1,0,1,2,3\}$. Let $\delta = \{\delta_1,...,\delta_m\}$ denote a set of dispatch modes for EVs in $\mathbf{EV}$.

$V = \{v_1,...,v_k\}$ denotes the set of nodes within the network. A node v_i could have several children nodes $chi(v_i)$ and a parent node $\widehat{v_i}$. $adj(v_i)$ represents a set of nodes that are adjacent and directly connected via distribution cables to v_i. The fixed load at v_i is denoted by $load^i_{fix}$. $\mathbf{EV}(v_i)$ and $\mathbf{G}(v_i)$ denote the sets of EVs and RGs connected at v_i, respectively.

The set of distribution cables in the network is denoted by $\mathbf{T}$ and t_{ij} refers to the distribution cable between nodes i and j. The power flow along the cable t_{ij} is denoted by f_{ij}, and cannot exceed the thermal capacity of the cable C_{ij}.

The network is managed by agents in a decentralized way, with each node mapping to an agent, which is only aware of the elements, including RGs and EVs, locally connected with the associated node. Each agent conducts a part of the computation and communication required to solve the optimal dispatch problem.

3. Distributed Multi-Objective Constraint Optimization Problem (DMOCOP)

The DMOCOP extends the Distributed Constraint Optimization Problem (DCOP) described in [37] to multi-objective optimization problems, as demonstrated in [35]. It contains three main elements:

1. Variables X: In this work, a variable can be a renewable generator's power output or an EV's battery dispatch mode $X = \{\mathbf{p},\delta\}$.
2. Domains D: D include all possible values of variables X. In this work, a variable x_i's domain d_i can be denoted by:

$$d_i = \begin{cases} RG_i & \text{when } x_i \text{ is a renewable generator} \\ DM_i & \text{when } x_i \text{ is an EV battery} \end{cases} \tag{1}$$