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Decentralised dispatch of distributed energy resources in smart grids via multi-agent coalition formation

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HIGHLIGHTS

- We propose a multi-agent coalition formation-based mechanism for efficient energy dispatch in power distribution networks.
- This mechanism is decentralised and does not need global information.
- The network structure has influence on the performance of the mechanism.

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ABSTRACT

The energy dispatch problem is a fundamental research issue in power distribution networks. With the growing complexity and dimensions of current distribution networks, there is an increasing need for intelligent and scalable mechanisms to facilitate energy dispatch in these networks. To this end, in this paper, we propose a multi-agent coalition formation-based energy dispatch mechanism. This mechanism is decentralised without requiring a central controller or any global information. As this mechanism does not need a central controller, the single point of failure can be avoided and since this mechanism does not require any global information, good scalability can be expected. In addition, this mechanism enables each node in a distribution network to make decisions autonomously about energy dispatch through a negotiation protocol. Simulation results demonstrate the effectiveness of this mechanism in comparison with three recently developed representative mechanisms.

1. Introduction

Due to recent improvements in power grid technology, electrical energy systems are undergoing radical transformations in functionality to increase efficiency and reliability. These transformations are not only in the bulk power transmission systems but also in the distribution networks [12]. A distribution network is the final stage in the delivery of electricity to end users [6]. Typically, bulk generation is the only energy resource to a distribution network and the direction of power flow is strictly from the central generation to downstream electric components [30]. Recently, there has been an increasing number of renewable generators embedded in distribution networks [22]. This poses two challenges for distribution network operators [25]. First, electricity networks are already highly capacity constrained, so adding additional generation, which is not managed effectively, may overload the networks. Second, it is very difficult to balance electricity demand with generation from intermittent renewable resources. If the operator of the distribution network fails to balance supply and demand, the network can potentially become unstable and this may result in brownouts and in the worst case, cascading blackouts. Therefore, efficient energy dispatch mechanisms are necessary.

Recently, many energy dispatch mechanisms have been proposed. These mechanisms can be roughly classified into two categories: centralised mechanisms such as [34] and decentralised mechanisms such as [25]. A centralised mechanism relies on a centralised control architecture, where each generator is directly coordinated by and communicates with a central decision-maker. A decentralised mechanism eliminates the need for a central decision-maker by distributing the decision making to the generators themselves. Centralised mechanisms are easy to implement and control but have a potential single point of failure,

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because failure of the central decision-maker can cause the whole network to suffer brownouts or even cascading blackouts. Decentralised mechanisms can avoid such risks because there is no central decision-maker. Some of the current decentralised mechanisms, e.g., [25], however, rely on a leader that knows the number of resources which must be collectively provided in the network. In other words, these decentralised mechanisms require global information to achieve decentralised decision making. Requiring global information is a drawback, because such information acquisition is time-consuming and this situation is even worse in large distribution networks. Other decentralised mechanisms, e.g., [9], are based on decomposition techniques. They solve the energy dispatch problem by decomposing the main problem into multiple sub-problems which can be solved efficiently and in parallel by different local controllers. These decentralised mechanisms, however, have two drawbacks. First, in these decentralised mechanisms, it is not clear who divides the main problem into sub-problems and who partitions the power transmission network into areas, where each area has a local controller. If there is a manager or a control centre which executes the division and partition tasks, these mechanisms become centralised in nature, such as the mechanism proposed in [4]. The second drawback is that because each area is controlled by a local controller, each sub-problem for an area is still solved in a centralised manner by the local controller, which implies that the size of each area cannot be too large, as, otherwise, these large areas will suffer the common drawbacks of centralised mechanisms: the single point of failure and the high computational complexity of local controllers to solve local optimisation sub-problems. Therefore, if the size of the power transmission network is large, there will be a large number of areas. Because the local controller of each area can exchange information only with its neighbouring local controllers, the overhead of communication and coordination among these local controllers to achieve a globally optimal solution is very heavy in methods like the one proposed in [9]. In other words, the scalability of these decentralised mechanisms may not be very good.

In this paper, a multi-agent coalition formation mechanism is proposed to address the energy dispatch problem. Unlike centralised mechanisms, the proposed mechanism is decentralised and has no central controller, so the single point of failure, inherently associated with centralised mechanisms, can be avoided. Unlike some decentralised mechanisms which need global information before a solution can be obtained, the proposed mechanism does not require global information but only needs local information. Unlike other decentralised mechanisms which need to partition the network into several areas and assign a local controller to each area to solve a sub-problem, the proposed mechanism needs neither such a partition process nor any local controllers for management and supervision. In the proposed mechanism, each component, e.g., a load, a generator and a distribution line, in the network makes decisions independently based only on its local information without management and supervision of local or central controllers. Each component is modelled as an agent and the network is modelled as a multi-agent system which consists of several components. Here, an intelligent agent is an entity which is able to make rational decisions autonomously in a dynamic environment, namely blending pro-activeness and reactiveness, showing rational commitments to decision making and exhibiting flexibility when facing an uncertain and changing environment [46]. A multi-agent system is composed of several intelligent agents and individual agents may perform different roles. The agents in a multi-agent system can work autonomously, make decisions independently and interact with each other to achieve global goals. Multi-agent systems, as a new paradigm which can facilitate distributed control [31], have been adopted in power systems for various purposes, such as voltage support [5], power restoration [48] and system management [32].

The rest of the paper is organised as follows. Section 2 reviews current related studies. Section 3 introduces our multi-agent coalition formation-based energy dispatch mechanism. Section 4 presents the properties of the proposed mechanism. Section 5 investigates the performance of the proposed mechanism in comparison with other energy dispatch mechanisms via simulation. Finally, Section 6 concludes the paper and outlines future work.

2. Related work

Many energy dispatch mechanisms have been presented over past decades. As described above, these mechanisms can be roughly classified into two categories: centralised mechanisms and decentralised mechanisms. Most of the current centralised energy dispatch mechanisms are based on computational intelligence techniques, such as genetic algorithms, particle swarm optimisation and differential evolution, etc. [10,26,47]. These mechanisms can obtain optimal results of energy dispatch but the calculation process is centralised. Such centralisation has a potential single point of failure.

Zhao et al. [50] developed a multi-agent based particle swarm optimisation mechanism for optimal energy dispatch. Their mechanism integrates a multi-agent system and a particle swarm optimisation algorithm, where each agent represents a particle in the particle swarm optimisation algorithm. In their mechanism, the environment is organised as a lattice-like structure and each agent is fixed on a lattice point. Such a lattice-like structure is distributed and this means that each agent can compete and cooperate only with its neighbours. However, in order to accelerate the diffusion of information and then obtain the optimal solution, each agent has to use not only its own experience but also the experience of the 'best agent' among all the agents in the environment. Although the best agent is not a central controller, it is a special entity in the environment. If the best agent is out of order or is difficult to find, their mechanism may not work properly.

Abido [1] investigated and evaluated the effectiveness of Pareto-based multi-objective evolutionary algorithms for solving the power dispatch problem. He first designed a procedure for quality measurement of different techniques. Then, he developed a feasibility check procedure to restrict the search of multi-objective evolutionary algorithms to a feasible region of the problem space and used a hierarchical clustering algorithm to provide the power system operator with a representative and manageable Pareto-optimal set. Finally, he presented a fuzzy set theory-based approach to extract one of the Pareto-optimal solutions as the best compromise one. His methods, however, are centralised in nature, as these methods are based on the assumption that all the necessary information are already known.

Dai et al. [8] proposed a seeker optimisation algorithm-based method for power dispatch, where the search direction is based on the empirical gradient by evaluating the response to the position changes and the step length is based on uncertainty reasoning using a simple fuzzy rule. The search process of their method is decentralised. However, their method operates on a set of solutions and these solutions are obtained in a centralised manner. Shaw et al. [34,35] proposed improved seeker optimisation algorithm-based methods for power dispatch but the methods still have the same drawback as Dai et al.'s method has.

Dominguez-Garcia and Hadjicostis [12,13] developed a set of distributed algorithms for the control and coordination of loads and distributed energy resources in distribution networks. Their algorithms are relevant for load curtailment control in demand response programs and also for coordination of distributed energy resources for the provision of ancillary services. Their algorithms assume that the total number of resources that need to be