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Coordination and control for energy distribution in distributed grid networks: Theory and application to power dispatch problem

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ABSTRACT

This paper presents a new framework considering decentralized energy coordination and generation, and flow control for supply–demand balance in distributed grid networks. Consensus schemes using only local information are employed to produce energy coordination, generation, and flow control signals. For the supply–demand balance, it is required to determine the amount of energy needed at each distributed resource. Also, due to the different generation capacities of each energy resource, coordination of energy flows among distributed energy resources is essentially required. Thus, this paper proposes a new framework which gives decentralized energy coordination scheme, generation, and flow control method considering these constraints based on distributed consensus algorithms. The proposed framework in this paper can be nicely utilized in energy dispatch or energy flow scheduling. Furthermore, it can be applied to various engineering problems including water irrigation systems, traffic networks, and building automation systems since it deals with attributed distribution and resource allocation in large scale distributed systems. Through illustrative examples, the effectiveness of the proposed approaches is illustrated. A possible application to power dispatch problem in the IEEE-14bus is also addressed for more detailed and realistic evaluation.

1. Introduction

In recent years, a smart grid has attracted a tremendous amount of research interest due to its potential benefit to modern civilization. The remarkable development of computer and communication technology has enabled a realization of smart grid. A key feature of a smart grid is the change of the energy distribution characteristics from a centralized energy system to a distributed energy system.

The distributed energy system consists of distributed resources such as renewable energies including photovoltaic (PV), hydro-electric, solar thermal, water, and wind powers (Del Real, Galus, Bordons, & Andersson, 2009; Geidl & Andersson, 2005). Though centralized energy plants still cover the major portion of energy demand, the amount of demand covered by distributed resources has been increasing steadily (Moslehi & Kumar, 2010).

In distributed energy systems, achieving the supply–demand balance, which is one of the fundamental requirements, is a key challenging issue due to its decentralized characteristics. The supply–demand balance problem has been traditionally considered as the economic dispatch (Chen & Chen, 2001; Edlund, Bendtsen, & Jórgensen, 2011; Xia, Zhang, & Elaiw, 2011; Zhang, Ying, & Chow, 2011) which minimizes the total cost of operation of generation systems. However, the traditional dispatch problem is a highly nonlinear optimization problem and thus it has been addressed usually in a centralized manner.

Distributed control of distributed energy systems has been considered in Yasuda and Ishii (2003), Xin, Qu, Seuss, and Maknouninejad (2011), and Dominguez-Garcia and Hadjicostis (2010). In the distributed energy system, individual resources are interconnected with each other through communication layer for information exchange which is called cyber-layer and physical connection for energy exchange which is called physical layer.[1] Also, considering different generation capacity and storage capacity, a coordination of energy flow among distributed res-

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[1] The energy exchange occurs at the physical-layer which is infrastructure such as pipe and power line for physical energy flow. On the other hand, the information exchange occurs at the cyber-layer which is infrastructure such as communication line or wireless communication network for information flow. In this paper, the structures of physical-layer do not necessarily need to be coincided with that of cyber-layer. The only assumption for the structure is connectedness of those networks.

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ources to achieve supply–demand balance is required. Thus, for the coordination of generation and flow, sharing information is essential. It is more realistic and economic to use only local information. This kind of problem has been solved in consensus (Gao, Ma, Zuo, Jiang, & Du, 2012; Hui & Haddad, 2008; Jadbabaie, Lin, & Morse, 2003; Olfati-Saber & Murray, 2004; Ren, Beard, & Atkins, 2007; Zhu & Martnez, 2010). Distributed resource allocation method named "center-free algorithm" has been considered in Servi (1980). In this algorithm, since the amount of resource for each node is determined by the sum of weighted difference with its neighbors, we can easily see the equivalence of the algorithm to the consensus (see Appendix A). Thus, we can consider that the idea of consensus had been already used in the distributed resource allocation problems.

In this paper, energy distribution among distributed resources is studied. The problem is classified into three subproblems. First, for supply–demand balance, it is required to determine the amount of energy needed at each resource. Thus, in the first subproblem, which is called *energy coordination*, the desired net energy[2] for supply–demand balance is determined within the generation capacity of each resource[3]. The unit commitment problem (Ongsakul & Petcharaks, 2004; Senjyu, Shimabukuro, Uezato, & Funabashi, 2004; Snyder, Powell, & Rayburn, 1987) which economically schedules available generating units can be considered as a previous step of the energy coordination problem. Second, for the given desired net energy from the energy coordination, it is required to determine the generation control input at each distributed resource. Thus, in the second subproblem, we consider generation control *with energy coordination*. Third, for the given desired net energy without energy coordination, the desired net energy may not satisfy the generation capacity of some resources. Thus, it is required to transmit energy to the resources because of insufficiency of generation due to limited capacity. Thus, in the third subproblem, we consider flow control as well as generation control *without energy coordination*. In this problem, consensus schemes are employed to produce energy coordination, generation, and flow control signals in a distributed manner. On the other hand, load flow algorithms (Bhujel, Adhikary, & Mishra, 2012; Hubbi & Refsum, 1983; Rese, Simoes Costa, & Silva, 2013) are to determine the magnitudes and phase angle of voltages at each bus and active and reactive power flow in each line. However, the load flow algorithms require a model described by Jacobian matrices, which gives linearized relationship between small changes in voltage angle and magnitude with the small changes in real and reactive power. Thus, the load flow algorithms are valid under the assumption that global information is available and there exists a centralized coordinator for solving load flow problem using the algorithms. Whereas the proposed methods in this paper do not require global information, it can be utilized for large scale systems and it is robust to change of network structure.

Subsequently, the main contribution of this paper can be summarized as follows. First, we propose a new framework which can be applied to various engineering problems such as power dispatch (Saadat, 1999), water irrigation, traffic networks (Kim & Ahn, 2014), smart grid, and building automation (Kim & Ahn, 2015) since the proposed framework deals with physical attribute distribution. Second, the coordination of energy generation and the control of energy flow are precisely defined and formulated. To our knowledge, it is a completely new problem which will surely attract research interest in this field. Third, the proposed approach guarantees convergence to the desired net energy which is not necessarily an average value as in the distributed averaging problem (Baric & Borrelli, 2011; Sun, 2012), and it provides a new mathematical derivation for distributed consensus. Fourth, we further consider the flow control between pairs of distributed energy resources as well as the generation control of each energy resource. Thus, the proposed approach can be applied even if the desired net energy of some energy resources does not satisfy the generation capacity as opposed to those in Dominguez-Garcia and Hadjicostis (2010) and Robbins, Domínguez-García, and Hadjicostis (2011). The solution of this new problem is not directly obtained from existing consensus works. Fifth, we additionally consider the net energy constraint as well as the generation constraint of each energy resource. It is shown that the distributed consensus algorithms ensure energy distribution among distributed nodes that have constraints for both net energy and generation capacity. Sixth, since the energy coordination law is a fully distributed approach, it can be applied even if some resources are locally added to or removed from the grid network under the realizability assumption[4]; thus, it is a practically quite interesting result. Based on the above reasons, we believe that energy coordination, generation, and flow control in the distributed energy systems, which are newly defined in this paper, are helpful in coordinating actual generation and flow among distributed energy plants.

This paper is organized as follows. In Section 2, energy coordination, generation, and flow control problems are formulated. Main results of this paper are presented in Section 3. Illustrative examples are provided in Section 4. A possible application to power dispatch problem is provided in Section 5 and the conclusion is given in Section 6.

2. Problem formulation

Fig. 1 shows a graph representing distributed grid networks. Each node denotes a subsystem, i.e., an area that consists of generators and loads, where generators produce energy with some constraints and loads consume the energy. Thus, energy demand for each node is determined by its loads. Since the generation capacity of each resource are limited, the desired net energy for each node in the system is required to be determined. The energy can be transmitted to its neighboring subsystems since they are interconnected with each other through physical interconnections, which may be called physical network layer. In this paper, we would like to control the energy generation and flow to satisfy supply–demand balance under net energy and generation capacity constraints.

Let p_i^d be the desired net energy at the i-th node; p_{G_i} be the generated energy at the i-th node; and $p_{F_{ij}}$ be the energy flow from the i-th node to the j-th node, where $p_{F_{ij}} = -p_{F_{ji}}$[5] and $i, j = 1, \ldots, n$. The net energy at a node is determined after the exchange of gen-

[2] The definition of "net energy" at a node is sum of generated energy at the node and net energy flows into the node from its neighbor nodes. Detailed explanation about "net energy" can be found in the second paragraph of 'Problem formulation' section.

[3] In this paper, the meaning of resource is generation unit which provides energy such as photovoltaic (PV), hydroelectric, solar thermal, and wind energies. Thus, distributed energy systems consist of these energy resources which have different generation capacity. Thus, it is required to coordinate generation and flow according to demand of network.

[4] The definition of "realizability" can be found in the first paragraph of 'Main result' section.

[5] First, the meaning of $p_{F_{ij}} = -p_{F_{ji}}$ is from the vector notation. Consider a vector $\overrightarrow{AB}$ from point A to point B. Then, a vector with same magnitude but opposite direction $\overrightarrow{BA}$ can also be represented by $-\overrightarrow{AB}$. Now, consider an energy flow $p_{F_{ij}}$ from the ith node to the jth node. Then, the energy flow with same amount of energy but opposite direction can be represented by $p_{F_{ji}} = -p_{F_{ij}}$ in terms of vector notation. Second, energy flow between the ith node and the jth node is determined by energy flow control at every time index k. Thus, there exist only one energy flow between two nodes at every time index k. For example, suppose that there exist $p_{F_{ji}}(k)$ at the kth step. Then, this energy flow can also be represented by $-p_{F_{ij}}(k)$ in terms of vector notation as shown in the above.