



Cooperative secondary frequency control of distributed generation: The role of data communication network topology



Nozhatalzaman Gaeini, Ali Moradi Amani, Mahdi Jalili *, Xinghuo Yu

School of Engineering, RMIT University, Melbourne, VIC 3001, Australia

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ABSTRACT

This paper studies the role of the topology of data communication network on the stability of cooperative secondary frequency control in distributed generation power systems. In order to implement a distributed control approach, local controllers should share their data over a data communication network whose structure is not necessarily the same as the physical power network. Although the parameters of generation units are often fixed and set by the manufacturing process, the structure of data communication network is flexible and can be considered as a tunable design variable. In this work, we first derive stability condition for the distributed secondary frequency control that is composed of two parts; one part coming from dynamics of the individual generation units, and the other part from the structure of data communication network. We then introduce a metric that shows the contribution of the network on the stability of secondary frequency control system. This metric is independent of the individual generation units, and depends only on the structure of the data communication network. Using this metric, the stabilization effect of synthetic networks (with scale-free and small world structures) on the secondary frequency control system is studied. Simulations verify the acceptable performance of the proposed metric.

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1. Introduction

Power grids are one of the most critical infrastructures in the modern world, attracting attention of many scholars. Daily lives will be disrupted under improper functioning of power grids. With increasing demand for energy and limited non-renewable resources, there has been much investment in renewable energy production. The appearance of renewable energy resources pushes the structure of power networks towards distributed generations and smart grids. Modern power grids are large-scale composed of many (distributed) generation units. Complex dynamical behavior of these grids makes them considerably difficult to control [1]. In general, an interconnected power system consists of number of main areas each of which includes a number of generation units and consumers. Current distributed generation grids include multi-areas each consists of many micro grids. This architecture leads to further complexity in the stability analysis and control of modern power grids [2].

The first step in the stability analysis of a power grid is to model it properly. Katiraei et al. introduced a small-signal model of a

micro grid in autonomous mode comprising both conventional and renewable sources [3]. The proposed model is precise, but too complex to be extended to micro grids and multi-area power systems. Power grids can be modeled as complex networked structures whose nodes (or vertices) are generators and consumers and whose links (or edges) are the physical wirings connecting them [4]. Recently efficient graph theory tools have been developed in this field that can be readily used to engineer many real-world complex networks such as modern power grids as well as corresponding data communication networks. Nishikawa et al. introduced a complex network approach to model different combinations of generators, transmission lines and consumers [4]. They modeled the power grids as a complex network of coupled second-order phase oscillators. Similar model based on Kuramoto oscillator was also considered to study stability and synchronization in interconnected generators [5].

With increasing appearance of distributed generation and renewable energy resources, the structure of power networks has shifted from high-capacity power units towards a lot of distributed generation units with massive physical interconnections over low voltage power lines. Following this evolution, the structure of the control systems have been also converted from centralized scheme to distributed fashion [6–9], leading to better robustness, lower costs because of low-bandwidth communication links, scalability

* Corresponding author.

E-mail address: mahdi.jalili@rmit.edu.au (M. Jalili).

and flexibility as compared to centralized control [10]. In distributed control scheme, each subset of power units can share their data over a data communication network which is not necessarily the mirror of the physical power network between them. Therefore, each Distributed Generation (DG) requires only self-information and that of some nearest neighbors' to achieve synchronization. This considerably reduces the communication costs.

The data communication network plays a crucial role by providing appropriate interactions among DGs to synchronize their activity. In the islanded operation mode of a microgrid, there is no reference bus and also inertia is lacking. Therefore, the units can sense one another based on the data receiving from the data communication network, and thus coordinate their frequency and voltage levels. A number of research works have studied the impact of inherent network deficiencies on the performance of secondary control. For example, [11,12] studied the role of time-variant and time-invariant time delay on the distributed secondary control. Lu et al. [13] studies the effect of communication link uncertainty in the distributed control of microgrid. The structure of the data communication network which carries data between control systems can be independent from the physical network which transfers electrical power between generation and consumption units [14]. Unlike physical power network whose structure is difficult (if not impossible) to be modified in practice, the topology of the data communication network can be easily modified with no (or small) cost. Therefore, one can optimize the performance by modifying the topology of the data communication network. This is the main motivation for this research work.

To study the frequency control, we use a comprehensive model that includes three parts: (i) the internal dynamics of the load and generation units, (ii) the structure of the physical power lines connecting them, and (iii) the topology of the data communication network between controllers employed to implement the distributed control and has independent identity of physical power network (see Fig. 1 for an example of physical power network and data communication network with different topologies). One can control the stabilization properties of the whole system by only changing the topology of the data communication network, which can easily be done. It has been shown that the network

topology has a critical role in its dynamical properties [15–18] and collective behaviors such as synchronization [19] and controllability [20].

In this paper, we study how the topology of the data communication network transferring state information for distributed secondary controllers affects the stability performance of a distributed generation system. The paper is organized as follows. In Section 2, a frequency control model of an interconnected microgrid is considered while focusing is on using of complex network in modeling of interchange power among distributed generation units. In Section 3, providing a consensus protocol, the state space model of a set of distributed interconnected generation units is attained. Using eigenvalue decomposition, a stability measure will be derived. The measure is directly related to the structure of data communication network configuration. Then in “simulation result” section, using the metric, we will study the stabilization degree of a data communication network by its spectral analysis. The Section 5 concludes the paper.

Preliminaries: Let's consider graph G as a non-empty finite set of N nodes denoted by set $V = \{\vartheta_1, \vartheta_2, \dots, \vartheta_N\}$ and edges denoted by set $E \subset V \times V$. If there is a directed edge from ϑ_i to ϑ_j , ϑ_i is defined as parent and ϑ_j as child. A digraph is called strongly connected if there is a directed path from every node to every other. An undirected graph is connected if there is a path between any distinct pair of nodes. A directed tree is a digraph, where every node has a specific parent except one, and a directed graph has a spanning tree if there exists a directed tree of the graph edges that connect all the nodes of the graph. The adjacency matrix $A = [a_{ij}]$ of a weighted graph is defined as $a_{ii} = 0$ and $a_{ij} > 0$ if $(i, j) \in E$ where $i \neq j$. Let matrix $L = [l_{ij}]$ be defined as $l_{ii} = \sum_{i \neq j} a_{ij}$ and $l_{ij} = -a_{ij}$, where $i \neq j$. Matrix L satisfies the following conditions:

$$l_{ij} \leq 0, \quad i \neq j$$

$$\sum_{j=1}^n l_{ij} = 0, \quad i = 1, \dots, n$$

Matrix L is called the Laplacian matrix, which is a symmetric zero row-sum matrix for undirected networks. This matrix is a positive semi-definite matrix with all eigenvalues larger than or equal to zero (the number of its zero eigenvalues is equal to the number of connected components).

2. Modeling of microgrids

A microgrid, as the main building block of modern power networks, includes a number of generators, loads, transmission and distribution lines and transformers which are connected to one other over a low or medium voltage busbars. It is designed in isolated operation mode to supply local consumers such as hospitals, university campuses and houses reliably. Distributed generation units (DGs) in a microgrid can be either traditional synchronous machines or renewable energy sources. Those of DGs contribute in frequency control are referred as active nodes (or dispatchable sources), i.e. they can exchange their data with other active nodes to make control signal [8]. This study assumes only synchronous machines are active nodes contributing to the frequency control. Renewable sources with uncertain and stochastic output can be included in the consuming load [21].

The difference between the generated power, ΔP_{mech} and the electrical load affects the frequency of the microgrid. Dynamics of this effect is shown as first-order transfer function in Fig. 2 containing the inertia of the generation unit (M) and damping factor of loads (D). Electrical load, which is shown by ΔP_L , comprises of a variety of electrical devices which motor loads are a dominant part of them [22]. Each generating building block in the microgrid

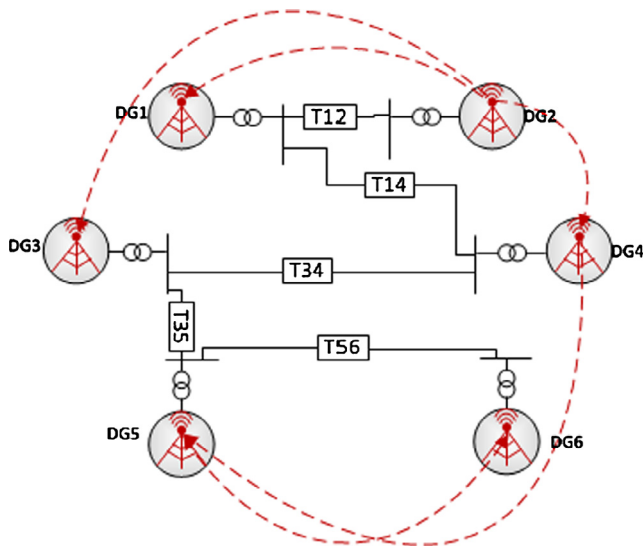


Fig. 1. An example of microgrid with two independent networks: black lines show the physical power network and red dashed lines show the data communication network. Note that the data communication network is completely independent of the physical power network. T_{ij} represents the physical line impedance between DG_i and DG_j of a microgrid. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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