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ScienceDirect

Energy Procedia 110 (2017) 334 – 339

Energy Procedia

1st International Conference on Energy and Power, ICEP2016, 14-16 December 2016, RMIT University, Melbourne, Australia

Voltage control in distributed generation systems based on complex network approach

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Abstract

In this paper, a new approach for modeling of voltage control problem in distributed generation systems based on the complex network theory is proposed. Distributed generation systems (DGS) including renewable energy sources are highly complex nonlinear dynamical systems by nature. There are many theoretical and practical challenges to apply the existing control technologies to them. The novel approach, introduced in this paper, embeds the complex network theory into the voltage control problem of DGS; i.e. the voltage control of DGS is introduced as a synchronization problem in complex networks. Complex network methodology shows a promising simplification in the analysis as well as timely response in large-scale systems. Thanks to the well-developed graph theory as well as advancements in control of multi-agent systems, the model presented in this paper, can deal with real-time hierarchical multi-objective requirements of control problems in DGS. Finally, the pinning control approach is applied to the model in order to solve the voltage synchronization problem of the microgrid.

Peer-review under responsibility of the organizing committee of the 1st International Conference on Energy and Power.

Keywords: Distributed generation; Voltage control; Complex networks

1. Introduction

Sustainable energy production for highly distributed consumers in future power grids is a perplexing problem in electrical engineering society. Fossil fuels are still the main energy resources worldwide; however, finite resources as

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1876-6102
Peer-review under responsibility of the organizing committee of the 1st International Conference on Energy and Power.
doi:10.1016/j.egypro.2017.03.149

well as their environmental impacts push the mankind into using more renewables. Modern power grids are expected to intelligently integrate distributed generation systems including renewable generation units [1].

The concept of microgrid, as the building block of large-scale distributed power generation systems, has been developed in last decades to make the management of DGS easier and more flexible. A microgrid is an autonomous subsystem consisting generation and storage units which reliably supplies local loads such as hospitals, university campuses and suburbs [2]. All units in a microgrid are connected to a medium or low voltage distribution bus [3] either directly or through power converters [4, 5]. The microgrid normally works in the grid-connected mode, in which its AC bus is connected to the main power grid. However, in the case of disturbance or fault, the microgrid will be isolated from the main grid and starts working in islanded mode.

Each microgrid has a dedicated control system which manages the balance of local generations and consumptions in the islanded mode as well as power transfer with the main grid or other microgrids in the grid-connected condition. It has a hierarchical architecture including three levels which are normally called primary, secondary and tertiary [6]. The nature of microgrids makes them really difficult to control: each microgrid consists of multiple small generation units with different capabilities and characteristics where normally none of them can play the role of a dominant generator. On the other hand, penetration of renewable energy resources causes lack of inertia in the power system especially in the island mode [7, 8]. Therefore, a control system with response faster than traditional interconnected grids considering constrained control signals is necessary for sound operation of the network [9]. Considering nonlinear dynamical behaviors of renewable generation units, the control problem becomes a large-scale multi-objective constrained nonlinear one, which is not easy to tackle using existing control technologies [1].

Complex Networks (CN) theory is one of the tools which has shown promising results in handling computational cost and real-time constraints of large-scale algorithms. This methodology, which is originated from graph theory, essentially models large-scale systems as a set of nodes connected to each other through a number of links [10]. CN in combination with other available tools allow us designing large-scale control systems in a timely manner [11]. Nodes may have dynamics themselves and links may be either directed or undirected. Although CN provides a fast and reliable approach to model, analyze and control of large-scale systems [12, 13], the way one can embed it into the problem is still a hot research topic [14, 15]. The main contribution of this paper is to represent the voltage control in DGS as a pinning control problem of a complex network. The most important task of the control system of a microgrid in the island mode is to regulate frequency and voltage as well as sharing the load between DGS properly [2-4]. It can be done either by controlling generation units [16] or by demand-side management [17].

In section 2 of this paper, a model for voltage control of a microgrid is presented. Pinning control, which is a well-known synchronization methodology in complex networks, is briefly introduced in section 3 and applied to regulate the voltage of the microgrid in sections 4 and 5. The paper is concluded on section 6.

2. Control structure of distributed generation systems

In order to guaranty satisfactory performance of microgrids, a hierarchical control structure including primary, secondary and tertiary control systems, is proposed in [6]. There are many research articles which contribute to each of these control levels [3]. Primary control is a fast-acting local control system usually embedded inside the DGS. It maintains voltage and frequency of the islanded microgrid during load/generation changes [5, 16, 18, 19]. Voltage and frequency are then compensated by secondary control which can be implemented either in centralized or distributed schemes [2]. The higher level tertiary control optimizes the power flow between each microgrid and the main grid or between microgrids themselves [20]. Figure 1 shows the general architecture of a microgrid control system. The nonlinear dynamics of i^{th} DG in the d-q frame can be written as [2]:

$$\begin{cases} \dot{x}_i = f_i(x_i) + k_i(x_i)D_i + g_i(x_i)u_i \\ \qquad\quad y_i = h_i(x_i) \end{cases} \tag{1}$$

where u_i and $x_i = [\delta_i \; P_i \; Q_i \; \varphi_{di} \; \varphi_{qi} \; \gamma_{di} \; \gamma_{qi} \; i_{ldi} \; i_{lqi} \; v_{odi} \; v_{oqi} \; i_{odi} \; i_{oqi}]^T$ are control signal and the state vector of i^{th} DG, respectively. $D_i = [\omega_{com} \; v_{bdi} \; v_{bqi}]$ and functions f_i, k_i and g_i are extracted in [2] form internal dynamics of DG. When the voltage droop technique is used in the primary control of each DG, the output voltage magnitude aligns on the d-