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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.

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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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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 daxis of the corresponding reference frame [2]. Therefore, for i^{th} DG we have $v_{odi} = v_{oi}$ and $v_{oqi} = 0$. Using feedback linearization technique, the nonlinear dynamical model of individual i^{th} agent is transformed to:

$$\dot{y}_i = \mathbf{A}y_i + \mathbf{B}u_i + d_i \tag{2}$$

where $y_i = [v_{odi}\ \dot{v}_{odi}]^T$, d_i represents the disturbance on y_i caused by other DG's of the network and **A** and **B** are known matrices. It is assumed that all internal dynamics of each DG are stable and the DG voltage is locally stabilizable. All DG's should follow the reference v_{ref} when they are connected to the network; therefore, the dynamical equation of voltage error of ith DG connected to a microgrid bus becomes:

$$\dot{e}_i = \mathbf{A}e_i + \mathbf{B}u_i + d_i \tag{3}$$

where $e_i = y_i - y_{ref}$ and $y_{ref}=[v_{ref}, 0]$. Since v_{ref} is constant, one has $\dot{v}_{ref} = 0$. The control objective is to design the control signal u_i in such a way that $e_i \to 0$ in the presence of disturbance d_i in a reasonable finite time. To do this, the pinning control approach is used in this paper which is briefly reviewed in the next section.

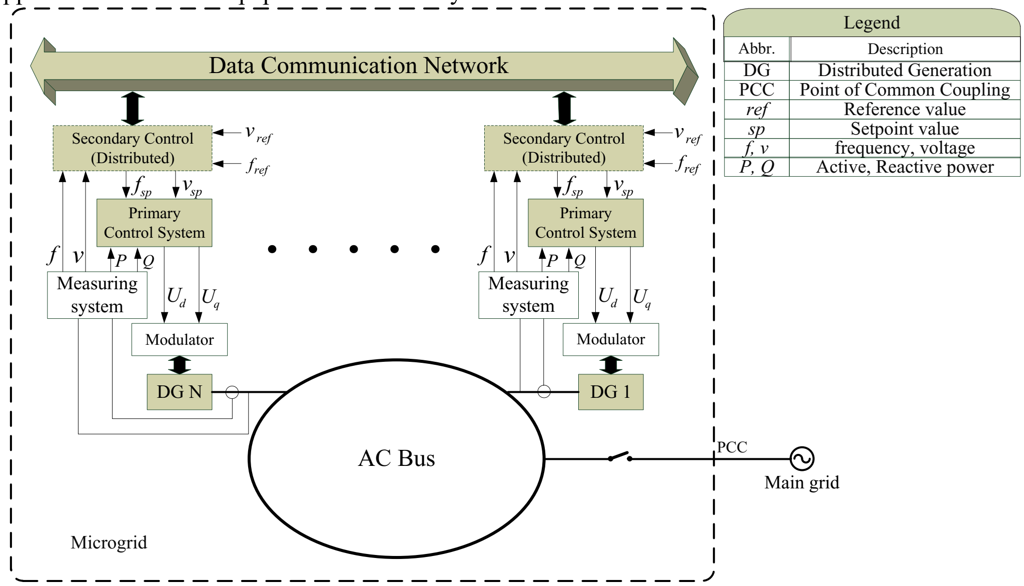

Fig. 1. Typical microgrid control system.

3. Pinning control of complex networks

Let us consider a network (V, E) with N nodes denoted by the set V and the set of edges as E. Each node is generally assumed to be a dynamical system with the following dynamical equation:

$$\frac{dx_i}{dt} = F(x_i) - \sigma \sum_{j=1}^{N} l_{ij} H x_j \tag{4}$$

where $x_i \in R^N$ is the state vector, $F{:}R^N \to R^N$ defines the individual systems' dynamical equation which is considered identical for all nodes, and σ represents unified coupling strength. l_{ij} is the $(i,j)^{th}$ element of the Laplacian matrix of the network $L = D - A$, where D is a diagonal matrix whose non-zero elements are degrees of nodes in the network graph and A is the adjacency matrix. Non-zero elements of H determine the coupled states of nodes in the network. The goal is to pin (i.e. synchronize) all nodes to the following desired state (i.e. $x_1(t) = x_2(t) = \ldots = x_N(t) = s(t)$):

$$\frac{d(s(t))}{dt} = F(s(t)) \tag{5}$$

In order to pin the dynamical network to this reference, one should design a suitable control signal u_i for the following dynamical nodes:

$$\frac{dx_i}{dt} = F(x_i) - \sigma \sum_{j=1}^{N} l_{ij} H x_j + \sigma b_{ii} u_i, \quad i = 1,2,\ldots,N \tag{6}$$

where $b_{ii} = 1$ for driver nodes, otherwise $b_{ii} = 0$. It means that to control the whole network, it is enough to control a subset of nodes (not all of them). As a result, the objective of pinning control is to design control signal(s) for driver node(s) in such a way that $\|x_i(t) - s(t)\| \to 0$, $i = 1, 2, \ldots, N$ in a finite time [21, 22].

4. Voltage control of DGS as a pinning control problem

A network of N generation units ($i = 1,2,\ldots,N$) each of them with the voltage v_{oi} at the terminal is considered. These generation units are connected through a power network with admittance matrix $Y = [Y_{ij}]$ where Y_{ij} represents the admittance of the power line between generators i and j. $Y_{ij} = 0$ if there is no direct link between generators i and j and Y_{ii} is the whole admittance connected to node i. From the graph theory, the Kirchhoff current law for a network with N voltage sources ($i = 1, .., N$) can be presented in the following matrix form:

$$\underbrace{\begin{bmatrix} Y_{11} & -Y_{12} & \cdots & -Y_{1N} \\ -Y_{21} & Y_{22} & \cdots & -Y_{2N} \\ \vdots & \vdots & \vdots & \vdots \\ -Y_{N1} & -Y_{N2} & \cdots & Y_{NN} \end{bmatrix}}_{Y} . \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix} = 0 \xrightarrow{e_i = y_i - y_{ref}} Y . \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_N \end{bmatrix} = 0 \tag{7}$$

in which, y_i is defined in (2) and $Y_{ii}=\sum_j Y_{ij}$. It means that the disturbance in the voltage error at the terminal of the i^{th} DG caused by other generation units is:

$$d_i = Y_{ii}^{-1} \sum_{\substack{j=1 \\ j \neq i}}^{N} Y_{ij} e_j \tag{8}$$

Substituting (8) in (3), the dynamical equation of the voltage error in i^{th} DG of the microgrid can be written as:

$$\dot{e}_i = \mathbf{A} e_i + \mathbf{B} u_i + Y_{ii}^{-1} \sum_{\substack{j=1 \\ j \neq i}}^{N} Y_{ij} e_j = \underbrace{(\mathbf{A} - I)}_{\mathbf{A'}} e_i + Y_{ii}^{-1} \sum_{j=1}^{N} Y_{ij} e_j + \mathbf{B} u_i \tag{9}$$

Comparing (9) and (6), the voltage control in a microgrid can be defined as the following pinning control problem. Assume a microgrid with N distributed generation units connected over a power network with the admittance matrix Y. The voltage control of this microgrid can be represented as a pinning control of a network with N nodes with dynamical equation:

$$\dot{e}_i = \mathbf{A'} e_i - \sum_{j=1}^{N} l_{ij} e_j + \mathbf{B} u_i \tag{10}$$

connected over a graph with adjacency matrix $A=[a_{ij}]$ which is defined as $a_{ij} = -Y_{ii}^{-1}.Y_{ij}$ if $i \neq j$, otherwise $a_{ij} = 0$.

5. Illustrative example

To illustrate the above results, we apply the proposed method to control the voltage of an IEEE 30-bus system (Fig.2(A)). Each bus of this system is represented by a node in Fig.2(B) where generation nodes are shown in dark. Internal dynamics of dark nodes are considered as (10) and the white nodes are assumed to be static. Weight of each link in Fig.2(B) is derived from the admittance matrix of the network as explained at the end of previous section.

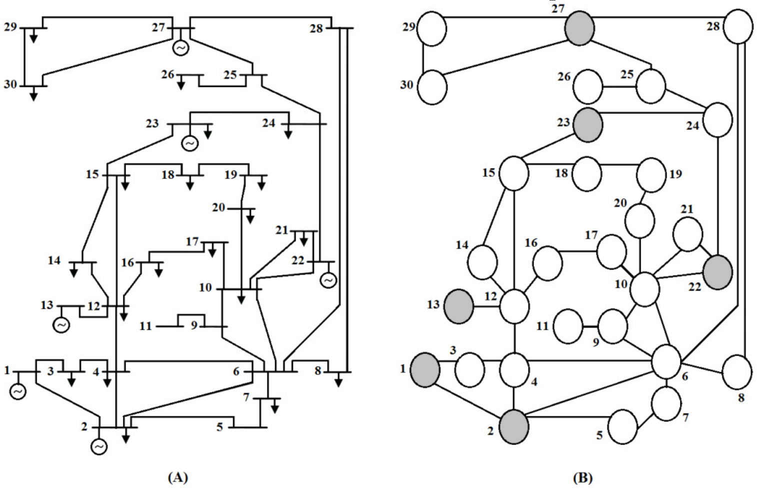

Fig. 2. IEEE 30-Bus system (A) the model [23]; (B) graph-based representation.

To analyze the stability of the controlled system, we consider the following Lyapunov functional:

$$V(t) = \frac{1}{2}\sum_{i=1}^{N} e_i(t)^T e_i(t) \tag{11}$$

Without loss of generality, we re-order the nodes such that $i = 1, 2, \ldots, l$ represent generation nodes ($l = |N_G|$ is the size of the set of generation nodes N_G). Over the trajectories of (10), derivative of (11) becomes:

$$\dot{V}(t) = \sum_{i=1}^{N} e(t)\dot{e}(t) = \sum_{i=1}^{l} e(t)\left[\mathbf{A}' e_i - Y_{ii}^{-1}\sum_{j=1}^{N} Y_{ij} e_j + \mathbf{B}u_i\right] \tag{12}$$

Let's consider a distributed secondary control scheme $u_i = \sum_{j=1}^{l} K_{ij} e_j$ in this microgrid. Using some matrix manipulation, we will have:

$$\begin{aligned}\dot{V}(t) &= \sum_{i=1}^{l} e_i(t)\mathbf{A}' e_i - \sum_{i=1}^{l} e_i(t) Y_{ii}^{-1}\sum_{j=1}^{N} Y_{ij} e_j + \sum_{i=1}^{l} e_i(t)\mathbf{B}\sum_{j=1}^{l} K_{ij} e_j \\ &= e(t)\left[\mathbf{I}_l \otimes \mathbf{A}' - \mathbf{I}_l \times \mathbf{L} + \mathbf{I}_l \times \left((\mathbf{1}_l \otimes \mathbf{B}).*\mathbf{K}\right)\right]e(t)\end{aligned} \tag{13}$$

in which $\mathbf{L}$ is a Laplacian matrix of the graph, $e(t) = [e_1(t), e_2(t), \ldots, e_N(t)]^T$, $\mathbf{K} = [K_{ij}]$. Y_G is a matrix derived from the admittance matrix Y by selecting rows related to the generation units. Symbols $\otimes$ and .* show the cross product and element-wise product of two matrices, respectively. From (13), it is clear that the voltage of the microgrid is stable if $\mathbf{I}_l \otimes \mathbf{A}' + \mathbf{I}_l \times \mathbf{L} + \mathbf{I}_l \times \left((\mathbf{1}_l \otimes \mathbf{B}) .* \mathbf{K} \right) < 0$.

6. Conclusion

In this paper, a complex network approach was proposed for modeling and performance analysis of voltage control of distributed generation systems. To model the DG, each bus is considered as a node of the graph. Nodes are connected to each other if there is a direct power like between them. The weight of each link is derived from the admittance matrix of the DG. The voltage control problem was represented as a pinning control problem of the complex network. Finally, using this method, the voltage stability condition for an IEEE 30-bus DG model was derived as a linear matrix inequality. This paper introduces a new basis for voltage stability and control of DG's.

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