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The role of coupling-frequency weighting exponent on synchronization of a power network

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HIGHLIGHTS

- A new power network model with coupling-frequency weighting exponent is proposed.
- The influence of weighting exponent on synchronizability of power network is studied.
- The synchronization cost caused by phase differences of power plants is proposed and studied

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ABSTRACT

Second-order Kuramoto-like oscillators with dissimilar natural frequencies are used as a coarse-scale model for an electrical power network that contains generators and consumers. This paper proposes a new power network model with coupling-frequency weighting exponent. Furthermore, the influence of the weighting exponent on synchronization of a power network is investigated through numerical simulations. It is observed that the synchronizability is significantly influenced by the coupling-frequency weighting coefficient with different magnitude categories. Furthermore, the synchronization cost caused by phase differences of power plants on the synchronization of the proposed power network model is studied. Numerical simulation shows that the synchronization cost will get larger with the coupling-frequency weighting exponent increasing further.

1. Introduction

The synchronization process of large populations of weakly coupled oscillators is a fascinating topic in various scientific disciplines such as physics, biology, and sociology [1–4]. It was well known that Kuramoto model and its variations provide the simplest setting to study the collective behavior, where all the oscillators in a large-scale network are locked to a common frequency, although their native frequencies are different and rather distributed [5,4,6]. As we know, the power network is closely related to the interacted Kuramoto oscillators, in particular, the second-order Kuramoto-like model [7–9]. Power network is generally formed by a large number of oscillators with the purpose to deliver electricity from the generating units (power plants) to the end users (houses, industries etc.) A node in power network is defined to be a point at which power is injected by a generator or extracted by consumers, or to other points. A link is then defined as a connection between any pair of such nodes. As a complex and large-scale system, the power network has rich nonlinear dynamics, and its synchronization and transient stability are very important issues [10–14]. In power grids, power plants must keep a proper synchronization to avoid energy supply disturbances and blackouts [15]. The existence of a status of synchronization is dependent on

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competition between the phase differences and the natural frequencies of oscillators. Moreover, it is commonly agreed that the coupling schemes of a network with oscillator nodes usually are impacted by the native frequencies of the oscillators' own. For power networks near the center of the frequency distribution, only small coupling strength is needed to make them lock together; whereas for those near both ends of the frequency distribution, large coupling strength is required to realize synchronization [16,17]. This implies that the coupling strength plays an important role on achieving the synchronization of all the oscillators in power networks. So far, many previous works mainly considered the influence of the topology structure, instead of the oscillator itself, on the synchronization of a power network. Very recently, Zhu studied the effects of coupling-frequency correlations on synchronization in complete graphs, where the weighted coupling exponent plays an important role [18]. Motivated by their works, we discuss the synchronization problem of a power network model with coupling-frequency weighting exponent by adjusting the coupling strength. Here, we focus on the relationship between the synchronizability of the power network and the weighting exponent.

As known, in power grids, the phases of the voltages of generators and consumers are required to be synchronized around a certain specific frequency. It is well known that power networks consisting of phase oscillators rely on not only frequency synchronization, but also phase synchronization. Generally, frequency synchronization is easily achievable than phase synchronization because the phase difference among the frequency-synchronized oscillators often keeps a non-zero constant. Due to the phase difference in the voltage among generators and consumers, power loss that is consumed as heat in power lines is inevitable. From above point of view, it is reasonable to regard the phase difference in power networks as synchronization cost. Considering political and economic conditions, it is necessary to reduce the synchronization loss among the plants due to the phase difference in the frequency-synchronized power plants. Therefore, it is interesting to know if the frequency synchronization of a power network with coupling-frequency weighting exponent can be ensured by adjusting weighting exponent, and even more in which magnitude categories of the weighting exponent the synchronization cost is lower.

Motivated by the above discussion, it will be investigated in which magnitude categories of the weighting exponent in a power network will influence on its synchronization, and how large the synchronization cost caused by phase differences of power plants during the synchronization of the power network is. This paper is organized as follows. A new power network model with coupling-frequency weighting exponent is presented in Section 2. The synchronization manifold is introduced in Section 3. In Section 4, the influence of the coupling-frequency weighting exponent on synchronizability of the power network is studied in detail. Section 5 devoted to study the synchronization cost of the proposed model with different weighting exponents. The conclusions of this work are drawn in Section 6.

2. The coupling-frequency weighting power network model

In order to understand the oscillatory dynamics of a power network and the collective phenomena emerging through their nonlinear dynamics, coarse-scale models of the power network is considered [19]. We consider an oscillator model where each element is one of two types of elements, generator or consumer. Suppose a power network consisting of N rotating machines. Each machine is characterized by the same type equation of motion with the electric power P_j, where it generates power (when $P_j > 0$) or consumes power (when $P_j < 0$). Furthermore, the state of each machine is determined by its mechanical phase angle $\theta_j(t)$ and phase velocity $\dot{\theta}_j(t)$.

During the regular operation, generators and consumers within the network run with the same frequency $\Omega = 2\pi \times 50$ Hz. The phase of each element is then described as

$$\theta_j(t) = \Omega t + \phi_j(t), \tag{1}$$

where $\phi_j(t)$ stands for the phase difference to the reference phase Ωt.

The equation of motion for the phase deviation $\phi_j(t)$ is obtained via the principle of energy conservation at each element and can be described by

$$P_{source,j} = P_{diss,j} + P_{acc,j} + P_{trans,j}. \tag{2}$$

The dissipated energy, which is caused by the rotation of the mechanical rotor is described as follows:

$$P_{diss,j} = \kappa(\dot{\theta}_j)^2, \tag{3}$$

where κ is a damping coefficient.

The kinetic energy accumulated is given by

$$P_{acc,j} = \frac{1}{2} I \frac{\mathrm{d}}{\mathrm{d}t} (\dot{\theta}_j)^2, \tag{4}$$

where I is the moment of inertia.

The power transmitted between two elements i and j is proportional to the sinus of the phase difference and the capacity of transmission line. Here, we assume that the voltage angles and the rotor angles are the same and the maximum capacity of the transmission line is $P_{\max,i,j}$. So the transmitted power follows

$$P_{trans,ij} = P_{\max,ij} \sin(\theta_i - \theta_j). \tag{5}$$