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Robust Control of Multi-Machine Power Systems Caused by Perturbation of Mechanical Input Power and Variable Unknown Communication Time-Delay[1]

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Abstract: The paper describes the problem of control of multi-machine power systems under parametric uncertainties, perturbed mechanical input power and unknown variable communication time-delay. The algorithm is proposed for the case when only relative speeds of each electrical generator are measured. The algorithm synchronizes the multi-machine power system with the required accuracy in the normal mode and under symmetrical 3-phase short circuit faults which occur on transmission lines. Efficiency of the scheme is illustrated by modeling of the three machine power systems.

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1. INTRODUCTION

Currently there is a growing interest in control of multi-machine power systems especially in the context of Smart Grid (Butler, 2009, Farhangi, 2010). The most components of generating electricity in power systems are electric generators. Therefore, a necessary condition for quality control of power systems is design of a simple and reliable controller for generators.

There exist a lot of methods for control of multi-machine power systems. In (Qu et al., 1992) decentralized robust control algorithm for power systems is considered. Transient control of the sustained oscillations that can occur after a major disturbance to a power system is investigated. The proposed control strategies are linear and require only local relative angle and velocity measurements for the model case, plus the measurement of mechanical power if turbine dynamics are included. The overall power system is shown to be exponentially stable in the large. The results are obtained without any linearization of the power system model.

In (Guo at al., 2000) the problem of robust control is designed for a multi-machine power system presented by a model of differential-algebraic equations of the third order obtained in (Anderson and Fouad, 1977). It is assumed that parameters of power system are partially known and angle, relative speed, active electrical power and mechanical input power of each generator are available for measurement. The authors solve the problem in two steps. At the first step the authors use direct feedback linearization while at the second step they apply robust algorithm for control of linear model. Since, control system (Guo at al., 2000) becomes unstable when faults (a symmetrical 3-phase short circuit fault which occurs on one of the transmission lines) are occurred. The faults should be removed by opening the breakers of the fault lines.

The work (Ortega et al., 2005) is devoted to control of multi-machine power systems where generator models are presented by the third order differential-algebraic equations and the models of the load, the transmission lines and the infinite buses are described by algebraic equations. The authors use the interconnection and damping assignment passivity-based control for synchronization of power system. Synthesized control algorithm requires measurements of the angles, relative speeds and transition EMF (electromotive force) directed along the transverse axis and parameters of the power system.

The paper (Mahmud et al., 2012) describes the nonlinear observer-based excitation controller for multi-machine power systems. It is assumed that only angle of each generator is available for measurement and parameters of power system are known. Exact feedback linearization is used to design the observer. The observed states of power system are directly used as the input to the controller where the control law does not need to be expressed in terms of all measured variables.

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Implementation of algorithms (Qu et al., 1992, Guo at al., 2000, Ortega et al., 2005, Mahmud et al., 2012) requires measurement of the state vector for each generator, knowledge of the power system parameters. Besides the mechanical input power should be constant and known and models of multi-machine power systems do not take into account the possible presence of a communication time delay. Consider each problem in more detail.

Algorithms (Qu et al., 1992, Guo at al., 2000, Ortega et al., 2005, Mahmud et al., 2012) require the measurement of the state vector of each generator such as angles and relative speed of the rotor generators, electrical power, transient EMF etc. However, the angle and the active electric power cannot be measured accurately at faults and, sometimes, in normal mode (Guo at al., 2000).

In (Qu et al., 1992, Ortega et al., 2005, Mahmud et al., 2012) all the algorithms require knowledge of the power system parameters. For example, if the faults (symmetrical 3-phase short circuit faults) occur on transmission lines then algorithms of (Qu et al., 1992, Ortega et al., 2005, Mahmud et al., 2012) do not ensure the synchronization in the multi-machine power system.

Control systems (Qu et al., 1992, Guo at al., 2000, Ortega et al., 2005, Mahmud et al., 2012) are designed under assumption of a constant mechanical input power. However, the synchronization loss may occur if mechanical input power is perturbed. Perturbed mechanical input power is a consequence of the mechanical torque ripple or regular oscillations of network loads. This situation usually occurs if the generators are driven by the piston engine (Wenhua et al., 1993). Moreover, we can observe low frequency low-damped processes due to coincidence with the so-called reverse frequency of diesel and natural vibration frequency of the generator rotor.

Communication time-delay is occurred in large geographic multi-machine power systems. Also, communication time-delay is occurred in information transmission channels, processing, measuring and controlling devices. There are cases this time delay is unknown and variable.

In the present paper we consider the control system design for multi-machine power systems under parametric uncertainties, partially measured state vector of each generator, perturbed mechanical input power and unknown variable communication time-delay.

For synthesis of the control system we use the so called method of auxiliary loop. This method was first proposed for compensation of parametric uncertainties and external bounded disturbances in (Tsykunov, 2007). The idea of this method is in the introduction of an auxiliary loop with desired parameters parallel to the plant. The difference between the output of the plant and the output of the auxiliary loop gives a function which depends on parametric and external disturbances. Then, this function is used for implementation of control law. Method (Tsykunov, 2007) is applied to control of electrical generator with a perturbed mechanical input power in (Belyaev et al., 2013).

In addition we study the control problem for power systems with compensation of disturbances depending on unknown system parameters, perturbed mechanical input powers and unknown variable communication time-delay. It is assumed that the relative speeds of each generator are available for measurement. The proposed algorithm provides synchronization of multi-machine power systems with the required accuracy in the normal mode and under symmetrical 3-phase short circuit faults which occur on transmission lines.

2. PROBLEM STATEMENT

Consider the multi-machine power systems where i-th subsystem is described by the following differential-algebraic equations:

Mechanical Dynamics:

$$\dot{\delta}_i(t) = \omega_i(t),$$
$$\dot{\omega}_i(t) = -\frac{D_i}{2H_i}\omega_i(t) - \frac{\omega_0}{2H_i}\Delta P_{ei}(t), \quad i = 1, ..., k; \tag{1}$$

Electrical Dynamics:

$$\dot{E}'_{qi}(t) = \frac{1}{T'_{d0i}}\left(E_{fi}(t) - E_{qi}(t)\right), \quad i = 1, ..., k; \tag{2}$$

Electrical Equations:

$$E_{qi}(t) = x_{adi}I_{fi}(t) = E'_{qi}(t) - \left(x_{di} - x'_{di}\right)I_{di}(t),$$
$$E_{fi}(t) = k_{ci}u_{fi}(t),$$
$$P_{ei}(t) = \sum_{j\in N_i} E'_{qi}(t)E'_{qj}(t)M_{ij}\sin\left(\delta_i(t) - \delta_j(t)\right),$$
$$Q_{ei}(t) = -\sum_{j\in N_i} E'_{qi}(t)E'_{qj}(t)M_{ij}\cos\left(\delta_i(t) - \delta_j(t)\right), \tag{3}$$
$$I_{di}(t) = -\sum_{j\in N_i} E'_{qj}(t)M_{ij}\cos\left(\delta_i(t) - \delta_j(t)\right),$$
$$I_{qi}(t) = \sum_{j\in N_i} E'_{qj}(t)M_{ij}\sin\left(\delta_i(t) - \delta_j(t)\right),$$
$$V_{ti}(t) = \frac{1}{x_{dsi}}\sqrt{\left(E'_{qi}(t) - x'_{di}I_{di}(t)\right)^2 + \left(x'_{di}I_{qi}(t)\right)^2},$$
$$i = 1, ..., k.$$

Here $\delta_i(t)$ is an angle of the i-th generator with initial value $\delta_i(0)$ (rad), $\omega_i(t)$ is a relative speed (rad/s), ω_0 is a synchronous machine speed (rad/s), $\Delta P_{ei}(t) = P_{ei}(t) - P_{mi}(t)$ (p.u.), $P_{ei}(t)$ is an electrical power (p.u.), $P_{mi}(t) = P_{mi0} + \Delta P_{mi}(t)$, P_{mi0} is a nominal mechanical input power (p.u.), $\Delta P_{mi}(t)$ is a perturbation of mechanical input power, D_i is a damping constant (p.u.), H_i is an inertia constant (s), T'_{d0i} is a direct axis transient short circuit time constant (s), x'_{di} is a direct axis transient reactance (p.u.), x_{di} is a direct axis reactance (p.u.), x_{adi} is a mutual reactance between the excitation coil and the stator (p.u.), k_{ci} is a gain of the excitation amplifier (p.u.), $u_{fi}(t)$ is an input of the SCR amplifier of the excitation loop (p.u.), $E_{qi}(t)$ is an EMF in the quadrature axis (p.u.), $E_{fi}(t)$ is an equivalent EMF in the excitation coil (p.u.), $E'_{qi}(t)$ is a transient EMF in quadratic axis (p.u.), $I_{qi}(t)$ is a quadratic axis current (p.u.), $I_{fi}(t)$ is an excitation current (p.u.), $I_{di}(t)$ is a direct axis current (p.u.),

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