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Robust control of multi-machine power systems with compensation of disturbances

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ABSTRACT

The paper is devoted to the robust control with compensation of disturbances for power systems under parametric uncertainties. It is shown that problem can be solved when only relative speed of each generator is available for measurement. The proposed control algorithm synchronizes the 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 proposed scheme is illustrated by modeling of a power systems consisting of three and fifty generators.

Introduction

Currently there is a growing interest in control of power systems especially in the context of Smart Grid [1–3]. There exist many methods and approaches for control of power systems. In [4] decentralized robust stabilization algorithm for power systems is proposed. 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 classical model case, plus the measurement of mechanical power if turbine dynamics are included. In [4] the authors show that the proposed algorithm ensures the exponential stability of the closed-loop system. The results are obtained without any linearization of the power system model.

In [5,6] the problem of robust decentralized control is solved for a power system described by a model of differential–algebraic equations of the third order obtained in [7,8]. 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 they use direct feedback linearization while at the second step they apply robust algorithm for control of linear model. Note that the control system [5,6] may become unstable when faults (a symmetrical 3-phase short circuit fault which occurs on one of the transmission lines) occur. The faults should be removed by opening the breakers of the fault lines.

In [9] adaptive synchronization algorithm is proposed for power systems which models are represented by the network of second order differential equations. A control law design is based on passivity and speed gradient methods.

The work [10] is devoted to control of power systems where generator models are described by the third order differential–algebraic equations [7,8] 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 electromotive force (EMF) directed along the transverse axis. It also requires knowledge of the power system parameters.

The paper [11] deals with the full-order nonlinear observer-based excitation controller for 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 nonlinear observer. The observed states of power system are directly used as the input to the

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controller, while the control law does not need to be expressed in terms of all measured variables.

In [12] the nonlinear observer-based control for stabilization of power systems by using the excitation of synchronous generators is proposed. The strategy goal is to attain maximum damping injection and to increase the transient stability, while voltage regulation performance should be maintained. Implementation of the control needs sensing currents and rotor speed and knowledge of system parameters.

In [13] the feedback linearization approach and high order sliding mode control are combined to stabilize and decentralize nonlinear multi-machine power systems. Each machine is modeled as an independent uncertain dynamic subsystem where the uncertainty is a disturbance that represents the effects of the rest of the system on that particular machine. A local high order sliding mode stabilizer is designed to regulate the rotor angle of each generating unit under high level external disturbances.

The paper [14] deals with the decentralized coordinated control for enhancing transient stability of large power systems. A modified equal area criterion is proposed as the transient stability judgment criterion. A hierarchical decentralized coordinated excitation control is designed which consists of both upper level coordinating control and lower level decentralized control. The controller is designed by using H_1 robust control method so as to deal with the uncertainties of the system.

In [15] the decentralized nonlinear excitation controller based on a nonlinear optimal predictive control theory for multi-machine power systems is presented. It does not require online optimization of the proposed excitation controller and huge computation burden is avoided. There are prediction horizon and control order needed to be determined at the design stage. The proposed controller requires local and direct measurements used as input signals.

In [16] the stability of the power system is ensured by limiting the amount of transmitted power between the system areas. The controllability brought by the high voltage direct current (HVDC) links is a possible access to increase the stability and thereby the power transfer. A coordinated control strategy is used for multiple HVDC links to improve both transient and small signal stability. The input–output exact feedback linearization is used to map the nonlinear system model to a linear model seen from the input to the output. Linear quadratic regulator design is used. An extension of the internal node representation by including the dynamics of the HVDC links in the nonlinear differential swing equations is developed.

Note that the implementation of most existing algorithms requires knowledge of the system parameters. Many papers require the measurement of the state vector of each generator. However, the angle and the active electric power cannot be measured accurately at faults and, sometimes, in normal mode [5,6].

This paper is aimed at the design of excitation controllers to enhance transient stability. These controllers are proposed to replace the traditional automatic frequency regulator plus power system stabilizer control structure [17]. Such controllers can be successfully implemented by modern devices such as FACTs controllers [18]. The speed of the generator rotor can be measured, for example, with the help a wide-area phasor measurement units [18]. They provide a variable structure control system where all controllers are tuned on-line. The proposed controllers can be connected with the power system, where some energy sources are controllable grid-connected small-scale windmill, like in [19,20].

The paper deals with the system models with unknown parameters and partially measured state vector of each generator. We use the so called method of auxiliary loop for compensation of unknown disturbances in power system. This method was first proposed for compensation of parametric uncertainties and external bounded disturbances in [21]. 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 [21] is applied to control of electrical generator in [22,23]. In [24] the method of auxiliary loop is generalized for control of dynamical systems.

In addition we study the control problem for power systems with compensation of disturbances. It is assumed that the system parameters are unknown and relative speed of each generator is available for measurement. The proposed algorithm provides synchronization of power systems with the required accuracy in the normal mode and under symmetrical 3-phase short circuit faults which occur on transmission lines.

The paper is organized as follows. The problem statement is presented in Section 'Problem statement'. In Section 'Synthesis of control system' the application of the auxiliary loop method for control of power systems is considered. The new algorithm for robust control of multi-machine power systems with compensation of disturbances and main result are proposed in Section 'Control system and main result'. In Section 'Examples' the efficient of proposed scheme is illustrated by modeling of a power systems consisting of three generators and fifty generators. Concluding remarks are given in Section 'Conclusion'. Appendix gives the proof of the auxiliary loop algorithm for control of power systems.

Problem statement

Consider the power systems where ith subsystem is described by the following differential–algebraic equations:

– Mechanical dynamics:

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

– Electrical dynamics:

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

– Electrical equations:

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

Here $\delta_i(t)$ is an angle of the ith 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), $\Delta P_{ei}(t) = P_{ei}(t) - P_{mi}$ (p.u.), $P_{ei}(t)$ is an electrical power (p.u.), P_{mi} is a mechanical input power (p.u.), 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