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Distributed model predictive load frequency control of multi-area interconnected power system

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ABSTRACT

This paper presents a load frequency control (LFC) design using the distributed model predictive control (DMPC) technique for the multi-area interconnected power system. The dynamics model of multi-area interconnected power system is introduced, and Generation Rate Constraint (GRC) and load reference setpoint constraint are considered. The overall system is decomposed into several subsystems and each has its own local area MPC controller. These subsystem-based MPCs exchange their measurements and predictions by communication and incorporate the information from other controllers into their local control objective so as to coordinate with each other. Analysis and simulation results for a three-area interconnected power system show possible improvements on closed-loop performance, computational burden and robustness, while respecting physical hard constraints.

Introduction

Power systems are composed of several interconnected subsystems or control areas, and one area is connected to another by the tie-lines. Each area has its own generator or group of generators, and it is responsible for its own load and scheduled power interchanges with neighboring areas. Because of the differences in generation and load in a power system, systems frequency deviates from its nominal value and active power flow interchanges between areas deviate from their contracted values. Load frequency control (LFC) is an important control problem in the dynamical operation of interconnected power systems. The purpose of the LFC is to drive the frequency deviation and the inter-area power flow through tie-lines to zero by manipulating the load reference setpoint following a disturbance (e.g. a step-change in the system load). Actually, considering the Generation Rate Constraint and the load reference setpoint limitation, this task can be theoretically described as a disturbances attenuation problem of large-scale systems with state and input constraints.

Recently, there is a growing interest in the LFC problem of power systems and many different control methods have been suggested in order to achieve better control performance, based on various control techniques such as proportional–integral–derivative (PID) control (e.g. [1–5]), robust control (e.g. [6–12]), fuzzy control (e.g. [13–17]) and sliding-mode control (e.g. [18–20]). However, most control methods are implemented in a centralized manner (e.g. [6,13,15,18] and the reference therein). The controller has the full knowledge about the overall system and computes all the control inputs for the system. For any system, centralized controller can achieve better performance because the effect of interconnections among subsystems are taken into account exactly. Furthermore, any conflicts among controller objectives are resolved optimally. But centralized control is not well suited for control of large-scale, geographically expansive power systems, due to the required inherent computational complexity, stability and robustness, and communication bandwidth limitations [21]. On the other hand, some control methods mentioned above are based on the decentralized control framework (e.g. [4,22,10] and the reference therein). The effects of the interconnected subsystems are assumed to be negligible and are ignored in the decentralized control framework. In many situations, however, the previous assumption is not valid and leads to reduced control performance. To achieve better closed-loop control performance, some level of communication may be established between the different controllers, which leads to the distributed control of interconnected power system. In addition, some classical control (e.g. [1–4]) methods mentioned above could yield unsatisfactory performance since the effects of nonlinearities such as Generation Rate Constraint and

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load reference setpoint constraint were not considered. In order to deal with these issues, advanced distributed control strategies have to be investigated and implemented.

With the on-line solution of the optimization problem, MPC presents a possibility of managing on-line the tradeoff between disturbance attenuation and control (and/or state) constraints, which appears to be an efficient strategy to control many applications in industry. Recently, some papers have reported the application of MPC technique on the LFC issue (e.g. [23–31] and the reference therein). In [23], fast response and robustness against parameter uncertainties and load changes can be obtained using MPC controller, but, only for single area load frequency control application. In [24] the usage of MPC in multi-area power system is discussed, but, only by economic viewpoint. It presented a new model predictive LFC including economy logic for LFC cost reduction. In [25], a new state contractive constraint-based predictive control scheme was proposed for LFC of two-area interconnected power system. This model predictive control algorithm consists of a basic finite horizon MPC technique and an additional state contractive constraint. The crucial function of the additional state contractive constraint is to guarantee the stability of the control scheme. In [26], the design of LFC system based on MPC is investigated for improving power system dynamic performance over a wide range of operating conditions. However, the MPC controllers of [25,26] are both implemented in centralized fashions (cent-MPC), which is impractical for control of large-scale power systems. For this reason, many decentralized or distributed MPC structures have been developed and applied recently (e.g. [28–30]). A decentralized model predictive control (decent-MPC) scheme for the LFC of multi-area interconnected power system is presented in [28]. However, each local area controller is designed independently and does not consider the Generation Rate Constraint that is only imposed on the turbine in the simulation. This solution may result in poor systemwide control performance of power system with significantly interacting subsystem. In [30], Feasible Cooperation-Based MPC method is used in distributed LFC instead of centralized MPC. In spite of the good effort done in [30], the paper did not deal with the problem of system's parameters mismatch and Generation Rate Constraint. In addition, the range of load change used in the cases is very large and inappropriate for the LFC issue [30].

In this paper, we propose the LFC method by using DMPC for the multi-area interconnected power system, in which the controllers coordinate with each other by exchanging their information. In our scheme, the overall system is decomposed into several subsystems, each of which is dealt with by a local MPC controller. The subsystem-based MPCs exchange their measurements and predictions by incorporating this information in their local control objectives. Moreover, Generation Rate Constraint and load reference setpoint limitation are considered. Comparisons of response to step load change, computational burden and robustness have been made between DMPC, cent-MPC and decent-MPC. The results confirm the superiority of the proposed DMPC technique.

The paper is organized as follows. 'Multi-area power system' describes the dynamics model of the interconnected power systems to be studied. In 'Design of distributed model predictive controller', we state briefly the DMPC algorithm and the design of DMPC controller for three-area interconnected power system. Both simulation and analysis results are given and discussed in 'Simulation and analysis'.

Multi-area power system

Modelling

A large-scale multi-area power system consists of a number of interconnected control areas which are connected by tie-lines. The trend of frequency measured in each control area is an indicator of not only the mismatch power in the interconnection and but also in the control area. The LFC system in each control area of a multi-area interconnected power system should control the interchange power with the other control areas as well as its local frequency. Therefore, the dynamic LFC system model must take into account the tie-line power signal. For this purpose, consider Fig. 1, which shows a power system with *M*-control areas [9]. Because LFC operation is limited to relatively small system disturbances, for the design of LFC, a simplified and linearized model is usually used [32]. Some basic power systems terminologies are provided in Table 1. The notation Δ is used to indicate a deviation from steady state. For example, $\Delta\omega$ represents a deviation in the angular frequency from its nominal operating value (60 Hz in the US).

Consider any control area $i \in \mathrm{II}_M$ interconnected to control area $j,\ j \neq i$ through a tie line. A simplified model for any area-*i* of *M* power system control areas with an aggregated generator unit in each area is described [9]. The overall generator-load dynamic relationship between the incremental mismatch power $(\Delta P_{\mathrm{mech}_i} - \Delta P_{Li})$ and the frequency deviation $\Delta\omega_i$ can be expressed as

$$\Delta\dot{\omega}_i = \frac{1}{M_i^a}\Delta P_{\mathrm{mech}_i} - \frac{1}{M_i^a}\Delta P_{L_i} - \frac{1}{M_i^a}D_i\Delta\omega_i - \frac{1}{M_i^a}\Delta P_{\mathrm{tie},i}. \quad (1)$$

The dynamic of the turbine can be expressed as

$$\Delta\dot{P}_{\mathrm{mech}_i} = \frac{1}{T_{\mathrm{CH}_i}}\Delta P_{v_i} - \frac{1}{T_{\mathrm{CH}_i}}\Delta P_{\mathrm{mech}_i}. \quad (2)$$

The dynamic of the governor can be expressed as

$$\Delta\dot{P}_{v_i} = \frac{1}{T_{G_i}}\Delta P_{\mathrm{ref}_i} - \frac{1}{R_i^f T_{G_i}}\Delta\omega_i - \frac{1}{T_{G_i}}\Delta P_{v_i}. \quad (3)$$

The tie-line power flow between areas *i* and *j* can be described as

$$\Delta\dot{P}_{\mathrm{tie}}^{ij} = T_{ij}\Delta\omega_i - T_{ij}\Delta\omega_j, \quad (4a)$$

$$\Delta P_{\mathrm{tie}}^{ij} = -\Delta P_{\mathrm{tie}}^{ji}. \quad (4b)$$

The total tie-line power flow between areas-*i* and the other areas can be calculated as

$$\Delta\dot{P}_{\mathrm{tie},i} = \sum_{\substack{j=1\\ j\neq i}}^{M}\Delta\dot{P}_{\mathrm{tie}}^{ij} = \sum_{\substack{j=1\\ j\neq i}}^{M}T_{ij}\Delta\omega_i - \sum_{\substack{j=1\\ j\neq i}}^{M}T_{ij}\Delta\omega_j. \quad (5)$$

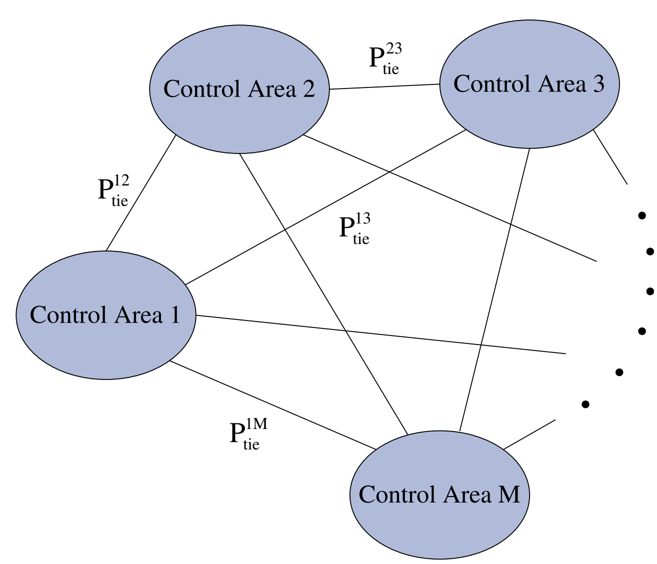

Fig. 1. Multi-area interconnected power system.