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Supervisory predictive control of power system load frequency control

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ABSTRACT

Objective: The objective of this paper is to develop a hierarchical two-level power system load frequency control.

Design: At the button level, standard PI controllers are utilized to control area's frequency and tie-line power interchanges. At the higher layer, model predictive control (MPC) is employed as a supervisory controller to determine the optimal set-point for the PI controllers in the lower layer. The proposed supervisory predictive controller computes the optimal set-points such that to coordinate decentralized local controllers. Blocking and coincidence point technology is employed to alleviate the computational effort of the MPC. In order to achieve the best closed loop performance, the MPC controller is designed to take generation rate constraint and non-minimum phase of thermal and hydro units into account.

Main outcome measure: The effectiveness of the proposed scheme is verified through time-based simulations on a four-area power system and the responses are then compared with the PI controller and the centralized MPC.

Conclusion(s): The results reveal that the proposed control scheme offers reliable and satisfactory control performance compared to the PI controller and centralized MPC.

Introduction

In multi-area power systems, imbalance between the total generated power and electrical load demand leads to undesired frequency and scheduled tie-line power variations. Load frequency control (LFC) is the mechanism by which a balance between power generation and demand is satisfied. The main goals of the power system LFC is to keep the system frequency and the inter-area tie power as close as possible to the scheduled values during normal operation, and when the system is subjected to disturbances or sudden changes in load demands [1].

Real power systems are often frequently large-scale systems which are composed of many interacting subsystems. Therefore, it is difficult to control such systems with centralized control structures due to the required inherent computational complexities, reliability problems and communication bandwidth limitations. Furthermore, there are several kinds of physical limitations such as generation rate constraints which have significant effects on the dynamic of power system LFCs [2].

Many researchers in the area of power system LFC have been employed PI type controllers [3–6]. Two-degree-of-freedom Internal Model Control (IMC) method has been used in [3] for PID tuning of the LFC system. Design of load frequency controller using sequential quadratic programming has been performed in [4]. Application of Bacteria Foraging (BF) and craziness particle swarm optimizations (CPSOs) to find PI gain controller have been proposed in [5,6], respectively. The PI type controllers have simplicity in design and implementation and provide high reliability in their operation. However, the PI controller has limited ability to deal with system generation rate constraint. Moreover, it is a decentralized control philosophy which provides poor system performance if the subsystems interact significantly.

To overcome the disadvantages of the PI controllers, a number of efforts have been made to employ centralized model predictive control [7–10]. The model predictive control is a modern control theory which is known as a practical high performance technology. The main advantages of the MPC are constraint handling ability, straightforward multivariable formulation and full compensation of delayed system [11]. Design of decentralized and distributed MPC have been proposed in [7–9]. However, decentralized MPC provides uncoordinated control actions and distributed MPC increases the complexity of implementation. In order to provide coordinated control actions with low real-time computation, a centralized functional MPC has been presented in [10]. However, the reported scheme presents reliability problem and provides system

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Nomenclature

Symbols	
ACE_i	area control error
i	area number
R_i	droop characteristic
D_i	area load frequency characteristic
β_i	frequency bias
T_{ij}	synchronizing coefficient between area i and j
$T_{g,i}$	governor time constant
$T_{t,i}$	turbine time constant (thermal unit)
T_1	turbine time constant (hydro unit)
T_2	turbine time constant (hydro unit)
T_W	turbine time constant (hydro unit)
w_1	lead compensator parameter
w_2	lead compensator parameter
$M_i(2H_i)$	area equivalent inertia
Δf_i	change in area frequency (Hz)
$\Delta P_{c,i}$	change in governor load set ponit
$\Delta P_{g,i}$	change in governor valve position
$\Delta P_{t,i}$	change in turbine power
$\Delta P_{tie,i}$	tie-line power deviation
$\Delta P_{L,i}$	power demand deviation
Abbreviations	
GRC	generation rate constraint
LFC	load frequency control
MIMO	multi-input multi-output
MPC	model predictive control
PI	proportional integral
PMU	phasor measurement unit
WAMS	wide area measurement system

instability when the MPC or communication links start to fail. In addition, application of the Laguerre based functional MPC for a real power system can be so complicated.

This paper presents a new scheme for power system LFC to maintain the performance of the centralized MPC while keeping the reliability of the local PI controller. In this paper, a hierarchical two-level optimal control strategy for the load frequency control of the multi-area power systems is presented. The lower control layer consists of the decentralized PI controllers which are independent of one another. The higher control layer consists of supervisory predictive controller which determines set-points for the lower control layer in order to obtain system coordination. Blocking and coincidence method, which is simple in design and application, is employed to alleviate computational burden of the MPC. In addition, the MPC based supervisory controller is designed to consider the GRC and non-minimum phase characteristic of the thermal and hydro units. Moreover, unlike to the centralized MPC which provides reliability problems, the proposed control strategy remains in operation even if any failure happens in the higher control layer.

To verify the effectiveness of the proposed approach, time-based simulations are carried out on the four-area of hydrothermal power system. The system performance is investigated in the normal and failure conditions, and the results are compared with the PI and centralized MPC controllers.

The proceeding sections of this paper are organized as follows. In Section 'Power system lfc dynamic and problem statement', a brief description of the LFC dynamic with problem statement is presented. Section 'Model predictive control for power system LFC' provides the technical background of the model predictive control. In Section 'Controller design and implementation', the design procedure of the proposed controller is described. Section 'Simulation results and discussion' provides time-based simulations with detailed discussions and finally, the conclusion is presented in Section 6.

Power system LFC dynamic and problem statement

Generations in the large interconnected power system comprises of thermal, hydro, nuclear and gas power generation. However, due to technical and economical considerations, the common choices for the LFC commitment are the thermal or hydro units [12]. For the purposes of LFC, power systems are decomposed into several control areas with tie-lines providing interconnections among them. Each area typically consists of numerous generators and loads. Due to coherency, it is common to lump all the generators in an area as a single equivalent generator, and likewise for the loads [9]. The block diagram representations of a control area with the thermal and hydro units are illustrated in Fig. 1. The system parameters are given in the list of symbols.

As shown in Fig. 1(a) and (b), thermal and hydro units for power system consist of three parts: governor dynamic, turbine dynamic and generator dynamic. The LFC model further contains generation rate constraint, droop characteristic and the dynamic of tie-lines interchange. The generator and turbine dynamic for thermal and hydro units can be expressed as [3]:

For thermal unit:

$$\frac{d}{dt}\Delta P_{ti} = \frac{1}{T_{ti}}\Delta P_{gi} - \frac{1}{T_{ti}}\Delta P_{ti} \tag{1}$$

$$\frac{d}{dt}\Delta f_i = \frac{1}{2H_i}\Delta P_{mi} - \frac{1}{2H_i}\Delta P_{Li} - \frac{D_i}{2H_i}\Delta f_i - \frac{1}{2H_i}\Delta P_{tie,i}$$

For hydro unit:

$$\frac{d}{dt}\Delta P_{ri} = \frac{1}{T_2}\left(1 - \frac{T_1}{T_2}\right)\Delta P_{gi} - \frac{1}{T_2}\Delta P_{ri} \tag{2}$$

$$\frac{d}{dt}\Delta P_{ti} = \frac{6T_1}{T_w T_2}\Delta P_{gi} + \frac{6}{T_w}\Delta P_{ri} - \frac{2}{T_w}\Delta P_{ti}$$

$$\frac{d}{dt}\Delta f_i = \left(\frac{1}{2H_i}\right)\Delta P_{ti} - \frac{T_1}{T_2 H_i}\Delta P_{gi} - \frac{1}{H_i}\Delta P_{ri} - \frac{1}{2H_i}\Delta P_{Li} - \left(\frac{D_i}{2H_i}\right)\Delta f_i - \left(\frac{1}{2H_i}\right)\Delta P_{tie,i}$$

the dynamic of governor can be formulated as:

$$\frac{d}{dt}\Delta P_{gi} = \left(\frac{1}{T_{gi}}\right)\Delta P_{ci} - \frac{1}{R_i T_{gi}}\Delta f_i - \frac{1}{T_{gi}}\Delta P_{gi} \tag{3}$$

the total tie-line power change between area-i and other areas can be expressed as:

$$\frac{d}{dt}\Delta P_{tie,i} = 2\pi\left(\sum_{j=1,j\neq i}^{N} T_{ij}\Delta f_i - \sum_{j=1,j\neq i}^{N} T_{ij}\Delta f_j\right) \tag{4}$$

From the control point of view, in comparison with thermal units, the main features of hydro units are their non-minimum phase characteristic, poorly damped poles and higher permissible rate of generation [12].

An important constraint in the power system LFC is a limitation on the variation rate of mechanical movement which is known as generation rate constraint. The GRC has significant impact on the dynamic response of the power system and the effective inclusion