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.

Keywords: Load frequency control, Supervisory control, Model predictive control, Generation rate constraint

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...
Nomenclature

Symbols

\(ACE_i\)  
area control error

\(i\)  
area number

\(R_i\)  
droop characteristic

\(D_i\)  
area load frequency characteristic

\(f_i\)  
frequency bias

\(T_{gi}\)  
synchronizing coefficient between area \(i\) and \(j\)

\(T_{gi,i}\)  
governor time constant

\(T_{ti}\)  
turbine time constant (thermal unit)

\(T_{ti,j}\)  
turbine time constant (hydro 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

\(\Delta f_i\)  
change in area frequency (Hz)

\(\Delta P_{ei}\)  
change in governor load set point

\(\Delta P_{gi}\)  
change in governor valve position

\(\Delta P_{t_i}\)  
change in turbine power

\(\Delta P_{tie,i}\)  
tie-line power deviation

\(\Delta P_{Li}\)  
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

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:

\[
\frac{d}{dt} \Delta P_{gi} = \frac{1}{T_{gi}} \Delta P_{gi} - \frac{1}{T_{wi}} \Delta P_{ni} + \frac{D_{gi}}{T_{gi}} \Delta f_i \tag{1}
\]

For hydro unit:

\[
\frac{d}{dt} \Delta P_{ni} = \frac{1}{T_{ni}} \left( 1 - \frac{T_1}{T_2} \right) \Delta P_{gi} - \frac{1}{T_2} \Delta P_{ni} \tag{2}
\]

\[
\frac{d}{dt} \Delta P_{ni} = \frac{6T_1}{T_{ni}T_2} \Delta P_{gi} + \frac{6}{T_w} \Delta P_{ni} - \frac{2}{T_w} \Delta P_{ni} \tag{3}
\]

\[
\frac{d}{dt} \Delta P_{t_i} = \left( \frac{1}{2H_i} \right) \Delta P_{t_i} - \frac{T_1}{2H_i} \Delta P_{g_i} - \frac{1}{H_t} \Delta P_{ni} - \frac{D_{t_i}}{2H_i} \Delta f_i - \left( \frac{1}{2H_i} \right) \Delta P_{tie,i} \tag{4}
\]

The dynamic of generator can be formulated as:

\[
\frac{d}{dt} \Delta P_{g_i} = \left( \frac{1}{g_i} \right) \Delta P_{a_i} - \frac{1}{g_i} \Delta P_{g_i} \tag{5}
\]

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

\[
\frac{d}{dt} \Delta P_{tie,i} = 2\pi \left( \sum_{j=1, j\neq i}^{N} T_{ji} \Delta f_j - \sum_{j=1, j\neq i}^{N} T_{ij} \Delta f_i \right) \tag{6}
\]

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
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