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Robust multivariable predictive based load frequency control considering generation rate constraint

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ABSTRACT

In this paper, a robust multivariable Model based Predictive Control (MPC) is proposed for the solution of load frequency control (LFC) in a multi-area power system. The proposed control scheme is designed to consider multivariable nature of LFC, system uncertainty and generation rate constraint, simultaneously. A constrained MPC is employed to calculate optimal control input including generation rate constraints. Economic allocation of generation is further ensured by modification of the predictive control objective function. To achieve robustness against system uncertainty and variation of parameters, a linear matrix inequality (LMI) based approach is employed. To validate the effectiveness of the proposed controller, time-based simulations on a three-area power system are performed and the results are then compared with PI controller. The results evaluation reveals that the proposed control strategy offers satisfactory performance in the presence of system constraint and provides robust performance for an extensive range of system uncertainty.

1. Introduction

In multi-area power systems, imbalance between total generated power and electrical load demand leads to undesired frequency and scheduled tie-line power variations [1]. The main objectives of load frequency control (LFC) in an interconnected multi-area power system are minimizing frequency and tie-line scheduled power deviations, ensuring zero steady state error and reducing overshoot and settling time [2].

Since several generation units may participate in an LFC task, power system LFC is a multivariable control problem. In addition, different kinds of physical limitations such as parameters uncertainty and generation rate constraints (GRCs) have major effects on the dynamic of power system LFC [3]. These features make load frequency control a robust, constrained and multivariable control problem.

Among the many efforts undertaken to design the LFC controller, always several features of the LFC system have been neglected. Application of bacteria foraging and craziness particle swarm optimizations to find PI gain controller has been proposed in [4,5], respectively. However, these approaches are optimal and can provide some shortcomings in the presence of system uncertainty. A robust LFC design using characteristic matrix eigenvalue has been reported in [6]. Two-degree-of-freedom Internal Model Control (IMC) method has been used in [7] for PID tuning of LFC system. In [8], design of load frequency controller using sequential quadratic programming has been performed. Despite the promising results achieved by robust controller, however, these approaches cannot take the GRC into account.

To take the effect of system constraints into account, an application of model predictive control for power system LFC has been considered in a number of papers. MPC is a modern, high performance and yet practical control approach which is recognized as an effective tool to deal with constrained control problem [9]. The MPC allows operation as close as possible to system constraints, which frequently leads to more profitable operation [10]. The other attribute of MPC is its simple and straightforward formulation for multivariable system. An economy oriented LFC using MPC has been peoposed in [11]. In [12], a generation rate constrained MPC has been proposed for the power system LFC. The authors imposed GRC on the governor set-point signal instead of the governor valve position. This is a simplifying assumption which significantly reduces the control performance. Applications of decentralized MPC have been presented in [13,14]. However, the GRC was imposed on the governor set-point signal. Design and application of distributed MPC for the power system LFC has been accomplished in [15]. However, the GRC was not included in the LFC task. In [16], a centralized functional MPC is employed to optimize MPC for power system LFC. The proposed approach, however, is only an optimal approach and is designed for control areas containing single unit i.e. it cannot incorporate economic

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allocation of generation power. In spite of many efforts which have been devoted for the application of MPC for the LFC system, all of them have neglected the effect of system uncertainty and further have several shortcomings in taking the GRC into account. Furthermore, all the aforementioned robust PI and MPC controllers did not consider the multivariable nature of power system LFC, and instead, a simple single input single output (SISO) controller is designed. Since SISO design is convenient, it is clearly a compromise and it is preferable to address the LFC system by multivariable methods.

This paper presents a new control design which simultaneously considers the multivariable nature of LFC, GRC and robustness against system uncertainty. To achieve these goals, a two step design is performed. First, an optimal multivariable MPC (OMMPC) design considering the GRC is performed. The multivariable design, however, cannot provide economic allocation of the generated power. To eliminate this shortcoming, an extra term is added in the control cost function. The proposed MPC technique derives its output based on the minimization of the multi-objective quadratic cost function subjected to the GRC. Next, to upgrade OMMPC and to design a robust multivariable MPC (RMMPC), the plant model uncertainty is described by a multi-plant model. The problem is then converted to a worst-case optimization which is reduced to a convex minimization involving linear matrix inequality (LMI) [9]. The RMMPC provides its output by solving this LMI problem. To validate the effectiveness of the proposed scheme, time-based simulations at different situations are carried out on the three-area power system and the results of RMMPC, OMMPC and PI controller are then compared with one another.

The proceeding sections of this paper are organized as follows. In Section 2, a brief description of the LFC dynamic with problem statement is presented. Multivariable formulation and economic allocation of generation is presented in Section 3. In Section 4, the design of robust LMI based MPC is described. Section 5 provides time-based simulations with detailed discussions and finally, the conclusion is given in Section 6.

2. Power system LFC dynamic and problem statement

A large power system consists of a number of separated control areas which are connected through tie-lines. The block diagram representation of ith area with n generation units in an N-area power system is displayed in Fig. 1. Due to large scale of most power systems, the design and implementation of decentralized controllers are preferable. Therefore, as it is shown in Fig. 1, a decentralized control scheme is proposed where each control area has its own load frequency controller. The state space model of each area is given in (1).

$$\begin{aligned}\dot{x}_i &= A_{c,i}x + B_{c,i}u_i + F_{c,i}w_i \\ y_i &= C_{c,i}x_i\end{aligned} \tag{1}$$

The state space variables of (1) are as follows:

$$x_i = [\Delta f_i, \Delta P_{tie,i}, \Delta P_{g1,i}, \ldots, \Delta P_{gn,i}, \Delta P_{t1,i}, \ldots, \Delta P_{tn,i}]^T$$
$$y_i = ACE_i = C_{c,i}x_i$$
$$u_i = [u_{i1}, \ldots, u_{in}]^T = [\Delta P_{c,i1}, \ldots, \Delta P_{c,in}]^T$$
$$w_i = [\Delta P_{L,i}, w_{2i}]$$
$$A_{c,i} = \begin{pmatrix} A_{i11} & A_{i12} & A_{i13} \\ A_{i21} & A_{i22} & A_{i23} \\ A_{i31} & A_{i32} & A_{i33} \end{pmatrix}, \quad B_{c,i} = \begin{pmatrix} B_{i1} \\ B_{i2} \\ B_{i3} \end{pmatrix}, \quad F_{c,i} = \begin{pmatrix} F_{i1} \\ F_{i2} \\ F_{i3} \end{pmatrix}$$
$$A_{i11} = \begin{pmatrix} -D_i/2H_i & -1/2H_i \\ -2\pi \sum_{j=1, j\neq i}^{N} T_{ij} & 0 \end{pmatrix}, A_{i12} = \begin{pmatrix} 1/2H_i & \ldots & 1/2H_i \\ 0 & \ldots & 0 \end{pmatrix}$$
$$A_{i22} = diag[-1/T_{g1,i}, -1/T_{g2,i}, \ldots, -1/T_{gn,i}]$$
$$A_{i33} = -A_{i32} = diag[-1/T_{t1,i}, -1/T_{t2,i}, \ldots, -1/T_{tn,i}]$$
$$A_{i21} = \begin{pmatrix} -1/(T_{g1,i}R_{1i}) & 0 \\ \vdots & \vdots \\ -1/(T_{gn,i}R_{ni}) & 0 \end{pmatrix}, \quad A_{i12} = A_{i31}^T = 0_{2\times n}, A_{i23} = 0_{n\times n}$$
$$B_{i1} = 0_{2\times n}, \quad B_{i2} = diag[1/T_{g1,i}, 1/T_{g2,i}, \ldots, 1/T_{gn,i}], \quad B_{i3} = 0_{n\times n}$$
$$C_{c,i} = [\beta_i 1 0_{1\times n} 0_{1\times n}], \quad \beta_i = D_i + \frac{1}{R_i}$$
$$F_{i1} = [-1/2H_i 0], \quad F_{i2} = 0_{n\times 1}, F_{i3} = 0_{n\times 1}$$

where

Δf_i	change in area frequency (Hz)
$\Delta P_{c,i}$	change in governor load set point
$\Delta P_{g,i}$	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
ACE_i	area control error
R_i	droop characteristic
D_i	area load frequency characteristic
β_i	frequency bias
T_{ij}	synchronizing coefficient between area i & j
$T_{g,i}$	governor time constant
$T_{t,i}$	turbine time constant
$M_i(2H_i)$	area equivalent inertia
n	number of unit in each area
i	ith control area

According to Fig. 1, in each control area, the control input is obtained by ACE signal.

$$u_i = \Delta P_{ci} = f_i(ACE_i) \tag{2}$$

All the existing LFC designs for power system were based on SISO models; although simulations were usually performed on nonlinear multiple input multiple output (MIMO) models. In a SISO design, each unit input (u_{ik}) is related to the total area input ($u_{i,tot}$) via (3).

$$u_i^T = [u_{i1}, \ldots, u_{in}]^T = [\alpha_{i1}, \ldots, \alpha_{in}]^T u_{i,tot} \tag{3}$$

where α_{ik} is distribution participation factor for generating unit k in area i and $\sum_{k=1}^{n}\alpha_{ik} = 1$. Generally, the SISO controller design and implementation is straightforward; however, it is clearly a compromise for multivariable systems and it is preferable to address the LFC design directly by multivariable methods.

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 (GRC). In the block diagram of Fig. 1, the GRC is modeled on the governor valve position ΔP_g. In [12–15], the GRC is imposed on ΔP_c which is a simplifying assumption. Since the control input signal ΔP_c is different from governor valve position signal ΔP_g, assuming identity of these two signals is not valid and causes major deviation in the calculation of optimal control input. The GRC has significant impact on the dynamic response of the power system LFC and the effective inclusion of this constraint in the control scheme will greatly improve control performance.

In a real power system, each control area contains different kind of uncertainty due to changes in system parameters, error in modeling, load variation and other related factors. Consequently, an optimal LFC design based on nominal system parameter value is not suitable for the LFC problem; and therefore, it can be inadequate to provide the desired system performance. Thus, to cope with the system parameters change, the LFC controller should be designed with a robust methodology.