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Decentralized model predictive based load frequency control in an interconnected power system

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ABSTRACT

This paper presents a new load frequency control (LFC) design using the model predictive control (MPC) technique in a multi-area power system. The MPC technique has been designed such that the effect of the uncertainty due to governor and turbine parameters variation and load disturbance is reduced. Each local area controller is designed independently such that stability of the overall closed-loop system is guaranteed. A frequency response model of multi-area power system is introduced, and physical constraints of the governors and turbines are considered. The model was employed in the MPC structures. Digital simulations for both two and three-area power systems are provided to validate the effectiveness of the proposed scheme. The results show that, with the proposed MPC technique, the overall closed-loop system performance demonstrated robustness in the face of uncertainties due to governors and turbines parameters variation and loads disturbances. A performance comparison between the proposed controller and a classical integral control scheme is carried out confirming the superiority of the proposed MPC technique.

1. Introduction

In LFC problem, area load change and abnormal conditions lead to mismatches in frequency and scheduled power interchanges between areas. These mismatches have to be corrected by the LFC system. LFC objectives, i.e. frequency regulation and tracking the load demands, maintaining the tie-line power interchanges to specified values in the presence of modeling uncertainties, system nonlinearities and area load disturbances, determine the LFC synthesis as a multi-objective optimization problem [1,2].

The fixed parameters controller, like an integral controller or a PI controller, is widely employed in the LFC application. Fixed parameters controllers are designed at nominal operating points and may no longer be suitable in all operating conditions. For this reason, adaptive gain scheduling approaches have been proposed for LFC synthesis [3,4].

This method could to overcome the disadvantages of the conventional PID controller like. The need of adaptation of controller parameters, but actually, it faces some difficulties, like the instability of transient response as a result of abruptness in the system parameters, in additionally, Impossibility of obtaining accurate linear time invariant models at variable operating points [3].

Recently, the model predictive control (MPC) appears to be an efficient strategy to control many applications in industry; it has many advantages such as very fast response, robustness against load disturbance and parameters uncertainty. Its straightforward design procedure is considered as a major advantage of the MPC. Given a model of the system, only an objective function incorporating the control objectives needs to be set up. Additional physical constraints can be easily dealt with by adding them as inequality constraints, whereas soft constraints can be accounted for in the objective function using large penalties. Moreover, MPC adapts well to different physical setups and allows for a unified approach [5,6].

Recently, some papers have reported the application of MPC technique on the load frequency control issue [7–9]. In [7], 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 [8] the usage of MPC in multi-area power system is discussed, but, only by economic viewpoint, it presented a new model predictive load frequency control including economy logic for LFC cost reduction. In [9], Feasible Cooperation-Based MPC (FC-MPC) method is used in distributed LFC instead of Centralized MPC which is impractical for control of large-scale, geographically expansive systems, such as power systems, In spit of the good effort done in [9], the paper did not

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deal with the problem of system's parameters mismatch, it only discussed the effect of load change, in addition, the range of load change used in the cases of study is very large and inappropriate in load frequency control issue.

This paper sheds the light on the impacts of parametric uncertainties beside the load change effect in an interconnected power system with decentralized model predictive based load frequency control. In this paper, each local area controller can be designed independently. The MPC technique law produces its optimal output derived from a quadratic cost function minimization based on the dynamic model of the specified area. The technique calculates the optimal control signal while respecting the given constraints over the output frequency deviation and the load change. The effects of the physical constraints such as generation rate constraint (GRC) and speed governor dead band [1] are considered. The power system with the proposed MPC technique has been tested through the effect of uncertainties due to governors and turbines parameters variation and load disturbances using computer simulation. A comparison has been made between the MPC and the traditional integral controller, which is widely used in practical industries, confirming the superiority of the proposed MPC technique. The simulation results proved that the proposed controller guarantees the robust performance in the presence of uncertainties due to governors and turbines parameters variation and loads disturbances.

The rest of the paper is organized as follows: the description of the dynamics of the interconnected power system is given in Section 2. A general consideration about MPC and its cost function are presented in Section 3. The proposed methodology is applied to two and three-area power system as a cases study, in Section 4. Finally, the paper is concluded in Section 5.

2. System dynamics

A multi-area power system comprises areas that are interconnected by tie-lines. The trend of frequency measured in each control area is an indicator of the trend of the mismatch power in the interconnection and not in the control area alone. The LFC system in each control area of an interconnected (multi-area) 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 N-control areas [1].

In this section, a frequency response model for any area-i of N power system control areas with an aggregated generator unit in each area is described [1].

The overall generator-load dynamic relationship between the incremental mismatch power $(\Delta P_{mi} - \Delta P_{Li})$ and the frequency deviation (Δf_i) can be express

$$\Delta \dot{f}_i = \left(\frac{1}{2H_i}\right)\cdot \Delta P_{mi} - \left(\frac{1}{2H_i}\right)\cdot \Delta P_{Li} - \left(\frac{D_i}{2H_i}\right)\cdot \Delta f_i - \left(\frac{1}{2H_i}\right)\cdot \Delta P_{tie,i} \tag{1}$$

the dynamic of the governor can be expressed as:

$$\Delta \dot{P}_{mi} = \left(\frac{1}{T_{ti}}\right)\Delta P_{gi} - \left(\frac{1}{T_{ti}}\right)\Delta P_{mi} \tag{2}$$

the dynamic of the turbine can be expressed as:

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

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

$$\Delta \dot{P}_{tie,i} = 2\pi \cdot \left[\sum_{\substack{j=1\\ j\neq i}}^{N} T_{ij}\Delta f_i - \sum_{\substack{j=1\\ j\neq i}}^{N} T_{ij}\Delta f_j\right] \tag{4}$$

In a multi-area power system, in addition to regulating area frequency, the supplementary control should maintain the net interchange power with neighbouring areas at scheduled values. This is generally accomplished by adding a tie-line flow deviation to the frequency deviation in the supplementary feedback loop. A suitable linear combination of frequency and tie-line power changes for area i, is known as the area control error (ACE),

$$ACE_i = \Delta P_{tie,i} + B_i \Delta f_i \tag{5}$$

Eqs. (1) to (4) represent the frequency response model for N power system control areas with one generator unit in each area and can be combined in the following state space model:

$$\left\{\begin{array}{l}
\begin{bmatrix}\Delta \dot{P}_{gi}\\ \Delta \dot{P}_{mi}\\ \Delta \dot{f}_i\\ \Delta \dot{P}_{tie,i}\end{bmatrix} = \begin{bmatrix} -\frac{1}{T_{gi}} & 0 & -\frac{1}{R_i T_{gi}} & 0\\ \frac{1}{T_{ti}} & -\frac{1}{T_{ti}} & 0 & 0\\ 0 & \frac{1}{2H_i} & -\frac{D_i}{2H_i} & -\frac{1}{2H_i}\\ 0 & 0 & 2\pi\cdot\sum\limits_{\substack{j=1\\ j\neq i}}^{N} T_{ij}\Delta f & 0 \end{bmatrix}\begin{bmatrix}\Delta P_{gi}\\ \Delta P_{mi}\\ \Delta f_i\\ \Delta P_{tie,i}\end{bmatrix}\\
+\begin{bmatrix}0 & 0\\ 0 & 0\\ -\frac{1}{2H_i} & 0\\ 0 & -2\pi\end{bmatrix}\begin{bmatrix}\Delta P_{Li}\\ \Delta v_i\end{bmatrix} + \begin{bmatrix}\frac{1}{T_{gi}}\\ 0\\ 0\end{bmatrix}\Delta P_{ci}\\
y = ACE_i = \begin{bmatrix}0 & 0 & B_i & 1\end{bmatrix}\begin{bmatrix}\Delta P_{gi}\\ \Delta P_{mi}\\ \Delta f_i\\ \Delta P_{tie,i}\end{bmatrix}
\end{array}\right. \tag{6}$$

where ΔP_{gi} is the governor output change of area i; ΔP_{mi} the mechanical power change of area i; Δf_i the frequency deviation of area i; ΔP_{Li} the load change of area i; ΔP_{ci} the supplementary control action of area i; y_i the system output of area i; H_i the equivalent inertia constant of area i; D_i the equivalent damping coefficient of area i; R_i the speed droop characteristic of area i; T_{gi}, T_{ti} the governor and turbine time constants of area i; ACE_i the control error of area i; B_i the frequency bias factor of area i; T_{ij} the tie-line synchronizing coefficient with area j; $\Delta P_{tie,i}$ the total tie-line power change between area i and the other areas; and ΔV_i is the control area interface, $\Delta V_i = \sum_{\substack{j=1\\ j\neq i}}^{N} T_{ij}\Delta f_j$.

3. Model predictive control

The MPC has proved to efficiently control a wide range of applications in industry such as chemical process, petrol industry, electromechanical systems and many other applications. The MPC scheme is based on an explicit use of a prediction model of the system response to obtain the control actions by minimizing an objective function. Optimization objectives include minimization of the difference between the predicted and reference response, and the control effort subjected to prescribed constraints. The effectiveness of the MPC is demonstrated to be equivalent to the optimal control. It displays its main strength in its computational expediency, real-time applications, intrinsic compensation for time delays, treatment of constraints, and potential for future extensions of the methodology. At each control interval, the first input in the optimal sequence is sent into the plant, and the entire calculation is repeated at subsequent control intervals. The purpose of taking new measurements at each time step is to compensate for unmeasured disturbances and model inaccuracy, both of which cause the

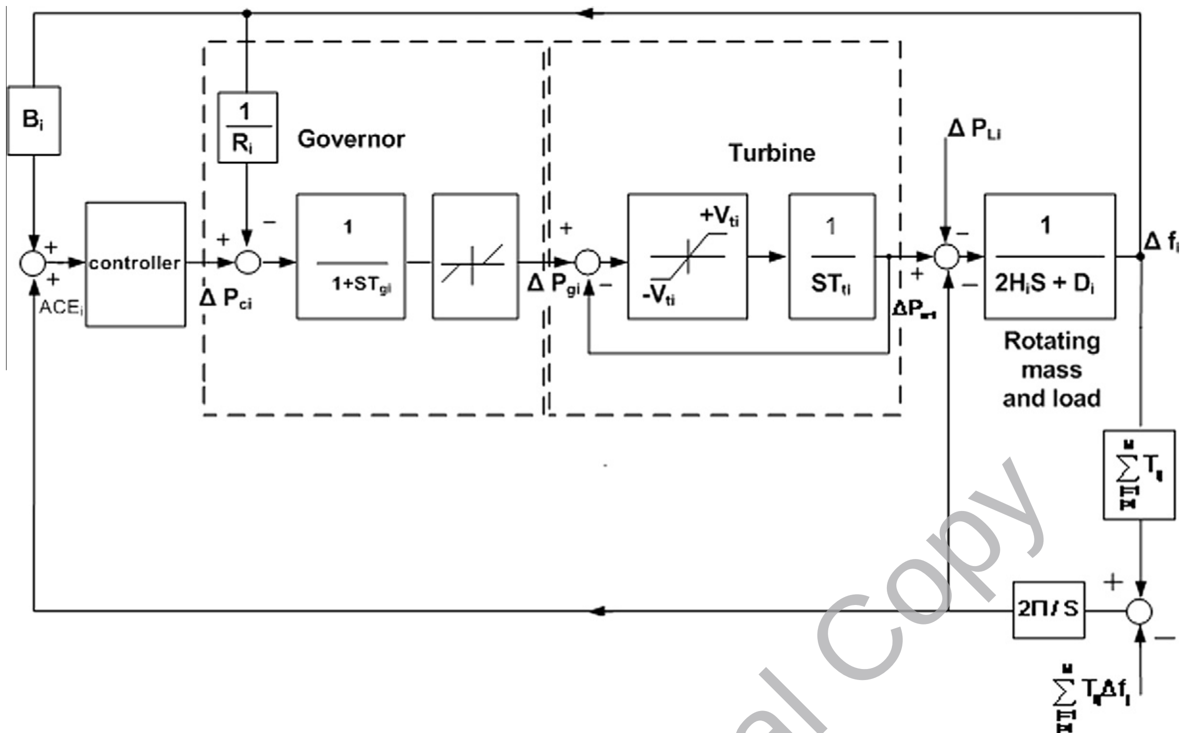

Fig. 1. Dynamic model of a control area in an interconnected environment.

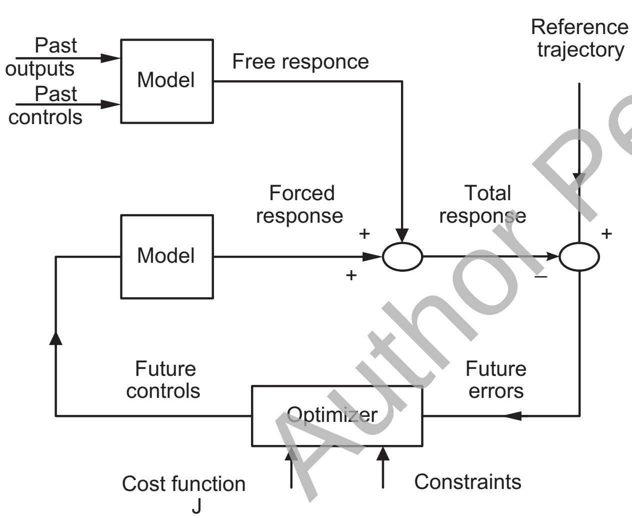

Fig. 2. A simple structure of the MPC controller.

system output to be different from the one predicted by the model [5,6].

Fig. 2 shows a simple structure of the MPC controller. An internal model is used to predict the future plant outputs based on the past and current values of the inputs and outputs and on the proposed optimal future control actions. the prediction has two main components: the free response which being expected behavior of the output assuming zero future control actions, and the forced response which being the additional component of the output response due to the candidate set of future controls. For a linear system, the total prediction can be calculated by summing both of free and forced responses; reference trajectory signal is the target values the output should attain. The optimizer is used to calculate the best set of future control action by minimizing a cost function (J), the optimization is subject to constraints on both manipulated and controlled variables [10].

The general object is to tighten the future output error to zero, with minimum input effort. The cost function to be minimized is generally a weighted sum of square predicted errors and square future control values, e.g. in the Generalized Predictive Control (GPC):

$$J(N_1, N_2, N_u) = \sum_{j=N_1}^{N_2} \beta(j)[\hat{y}(k+j|k) - w(k+j)]^2 + \sum_{j=1}^{N_u} \lambda(j)[u(k+j-1)]^2 \tag{7}$$

where N_1, N_2 are the lower and upper prediction horizons over the output, N_u is the control horizon, $\beta(j)$, $\alpha(j)$ are weighting factors. The control horizon permits to decrease the number of calculated future control according to the relation: $\Delta u(k+j) = 0$ for $j \geqslant N_u$.

The $w(k+j)$ represents the reference trajectory over the future horizon N.

Constraints over the control signal, the outputs and the control signal changing can be added to the cost function as follows:

$$\begin{aligned} u_{\min} &= u(k) \leq u_{\max} \\ u_{\min} &\leq \Delta u(k) \leq \Delta u_{\max} \\ y_{\min} &\leq y(k) \leq y_{\max} \end{aligned} \tag{8}$$

Solution of Eq. (7) gives the optimal sequence of control signal over the horizon N while respecting the given constraints of Eq. (8).

The MPC technique has many advantages, in particularly it can pilot a big variety of process, being simple to apply in the case of multivariable system, can compensate the effect of pure delay by the prediction, inducing the anticipate effect in closed loop, being a simple technique of control to be applied and also offer optimal solution while respecting the given constraints. On the other hand, this type of restructure required the knowledge of model for the system, and in the present of constraints it becomes a relatively more complex regulator than a simple conventional controller

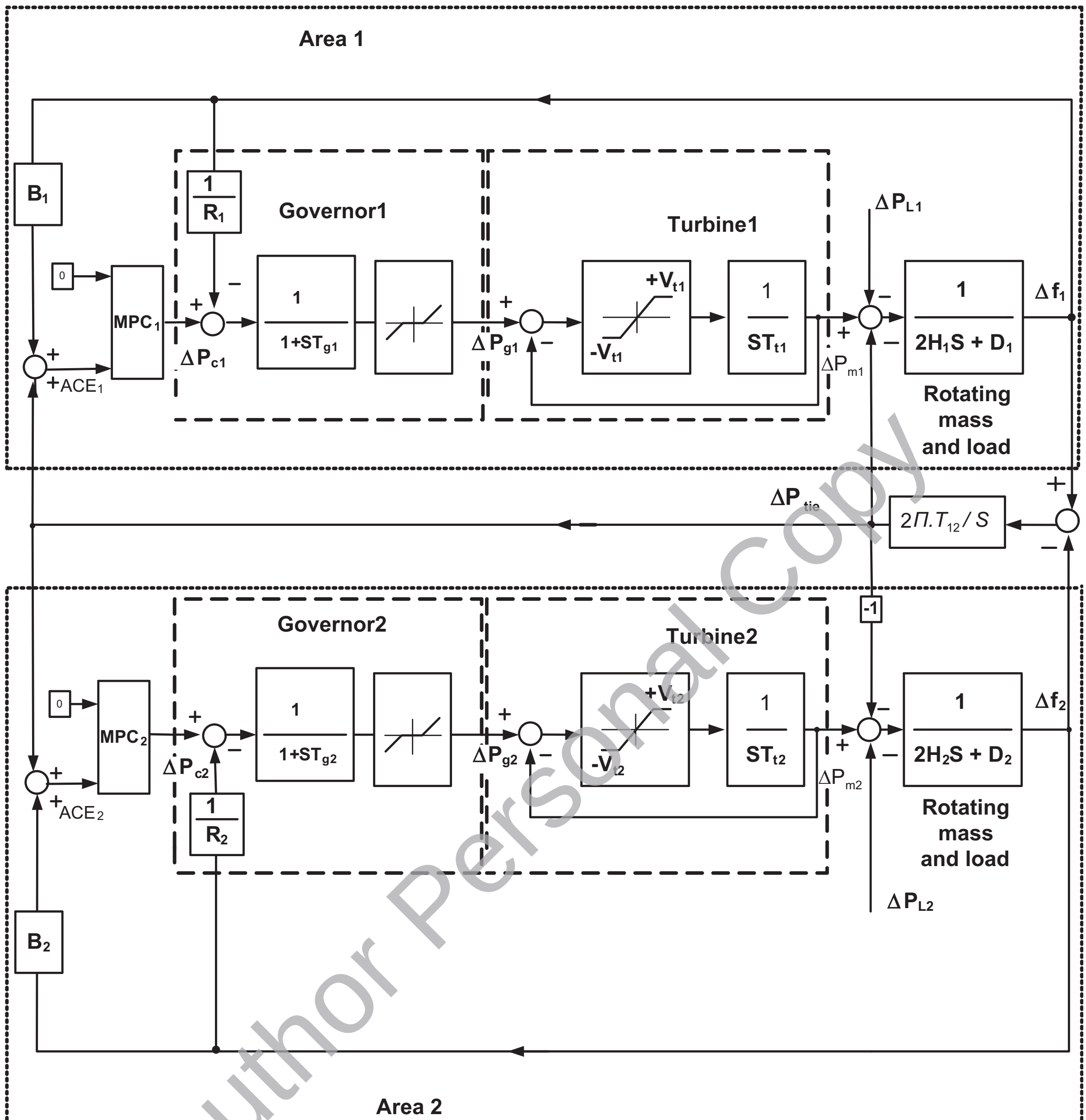

Fig. 3. The block diagram of two area power system including the proposed MPC controllers.

such as a PID for example, and it takes more time for on-line calculations.

4. Results and discussions

Computer simulations have been carried out in order to validate the effectiveness of the proposed scheme. The Matlab/Simulink software package has been used for this purpose.

The parameters of the decentralized MPC controllers are set as follows:

prediction horizon = 13,

control horizon = 2,
weights on manipulated variables = 0,
weights on manipulated variable rates = 0.1,
weights on the output signals = 1,
sampling interval = 0.0002 s.

Constraints are imposed over the control action, and frequency deviation are considered as follows:

max control action = 0.25 pu,
min control action = −0.25 pu,
max frequency deviation = 1 pu,
min frequency deviation = −1 pu.

For all studied areas in this paper, the simulation studies are carried out for the proposed controllers with generation rate con-

Table 1
Parameters and data of a practical two area power system.

Area	K (s)	D (pu/HZ)	$2H$ (pu s)	R (Hz/pu)	T_g (s)	T_t (s)	T_{12}
Area-1	−0.3/s	0.015	0.1667	3.00	0.08	0.40	0.20
Area-2	−0.2/s	0.016	0.2017	2.73	0.06	0.44	

straint (GRC) of 10% per minute and the maximum value of dead band for governor is specified as 0.05 pu for each area [1].

4.1. Scenario A

In this scenario, two-control area power system, shown in Fig. 3 is considered as a test system to illustrate effectiveness of the proposed control strategy. Each area consists of the overall rotating mass and load and an aggregated generator unit including one nonlinear turbine with GRC, and one governor with dead-band constraint [1], as each local area controller can be designed independently. On the other hand, the frequency deviation is used as a feedback for the closed loop control system. The measured and reference area control error ACE_i, ACE_{ref} = 0 Hz are fed to the model

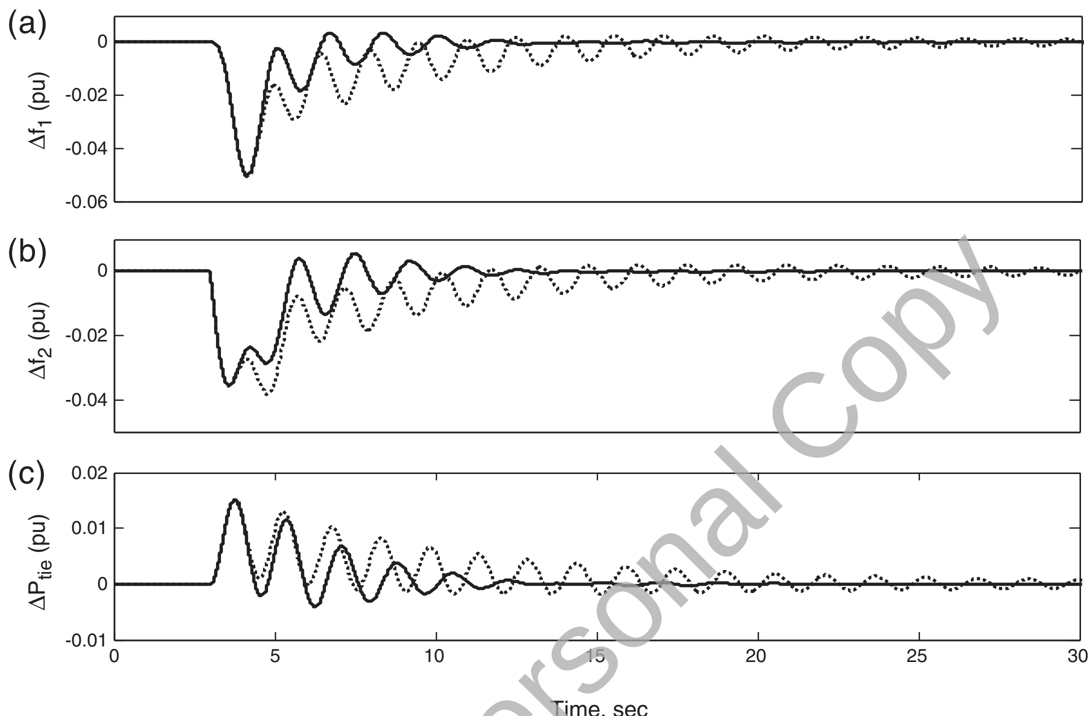

Fig. 4. Power system responses to case1 of scenario A with MPC (solid) and conventional (dotted) controller: (a) frequency deviation in area-1, (b) frequency deviation in area-2, and (c) tie-line power change.

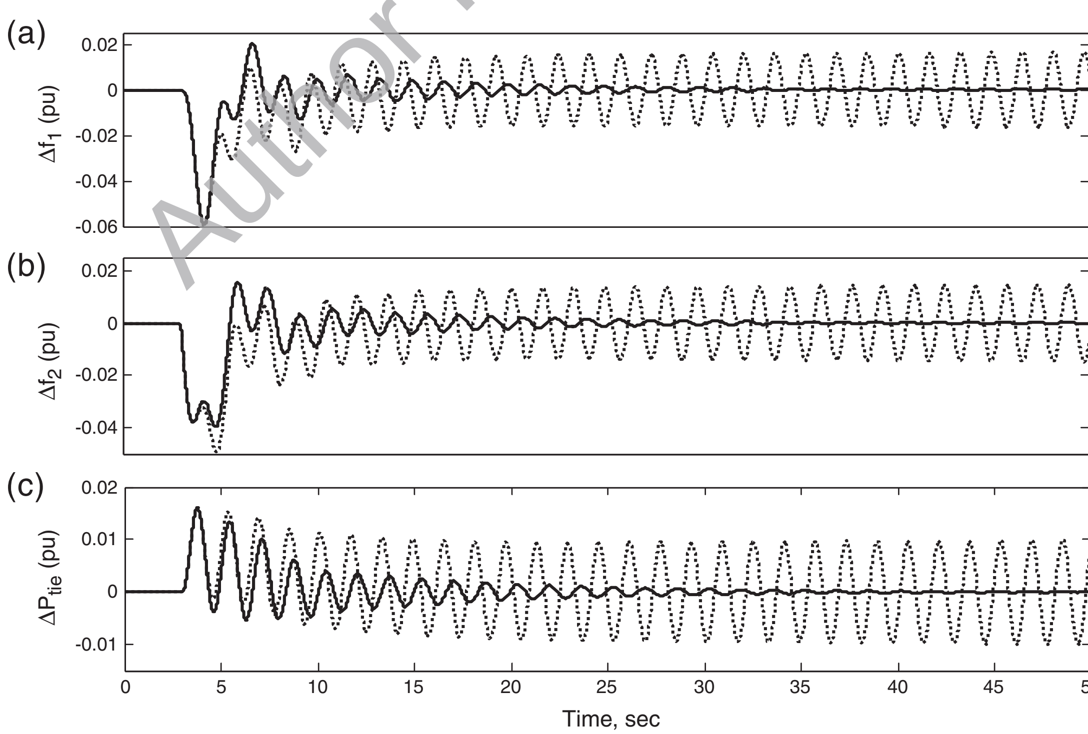

Fig. 5. Power system responses to case2 of scenario A with MPC (solid) and conventional (dotted) controller: (a) frequency deviation in area-1, (b) frequency deviation in area-2, and (c) tie-line power change.

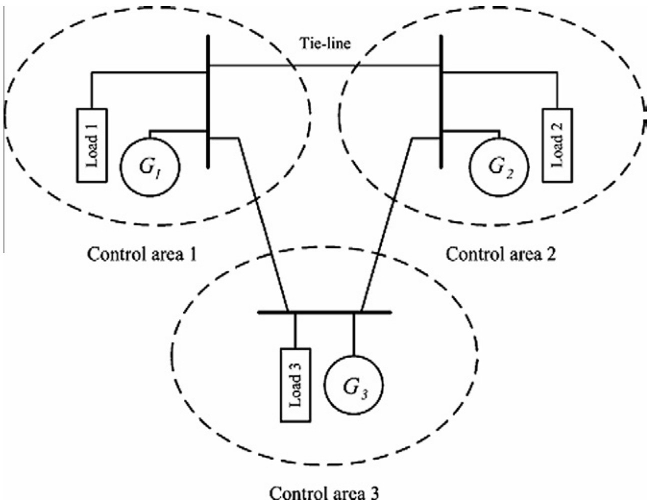

Fig. 6. Three-control area power system.

predictive controller in order to obtain the supplementary control action ΔP_{ci} which add to the negative frequency feedback signal.

The resulting signal is fed the governor giving the governor valve position which supplies the turbine to give the mechanical power change ΔP_{mi} which is affected by the load change ΔP_{Li} and the tie-line power change $\Delta P_{tie,i}$ giving the input of the rotating mass and load block to provide the actual frequency deviation Δf. In addition, the tie-line flow deviation is added to the frequency deviation in the supplementary feedback loop to give the area control error ACE_i.

A practical two areas power system having the following nominal parameters [1] listed in Table 1.

The simulation studies are carried out for the proposed controllers with generation rate constraint (GRC) of 10% per minute and the maximum value of dead band for governor is specified as 0.05 pu for each area [1].

4.1.1. A-1 Case 1

The system performance with the proposed MPC controllers at nominal parameters is tested and compared with the system per-

Table 2
Parameters and data of a practical three-control area power system.

Area	K (s)	D (pu/HZ)	$2H$ (pu s)	R (Hz/pu)	T_g (s)	T_t (s)	T_{ij}
Area-1	−0.3/s	0.015	0.1667	3.00	0.08	0.40	T_{12} = 0.20 T_{13} = 0.25
Area-2	−0.2/s	0.016	0.2017	2.73	0.06	0.44	T_{21} = 0.20 T_{23} = 0.15
Area-3	−0.4/s	0.015	0.1247	2.82	0.07	0.3	T_{31} = 0.25 T_{32} = 0.12

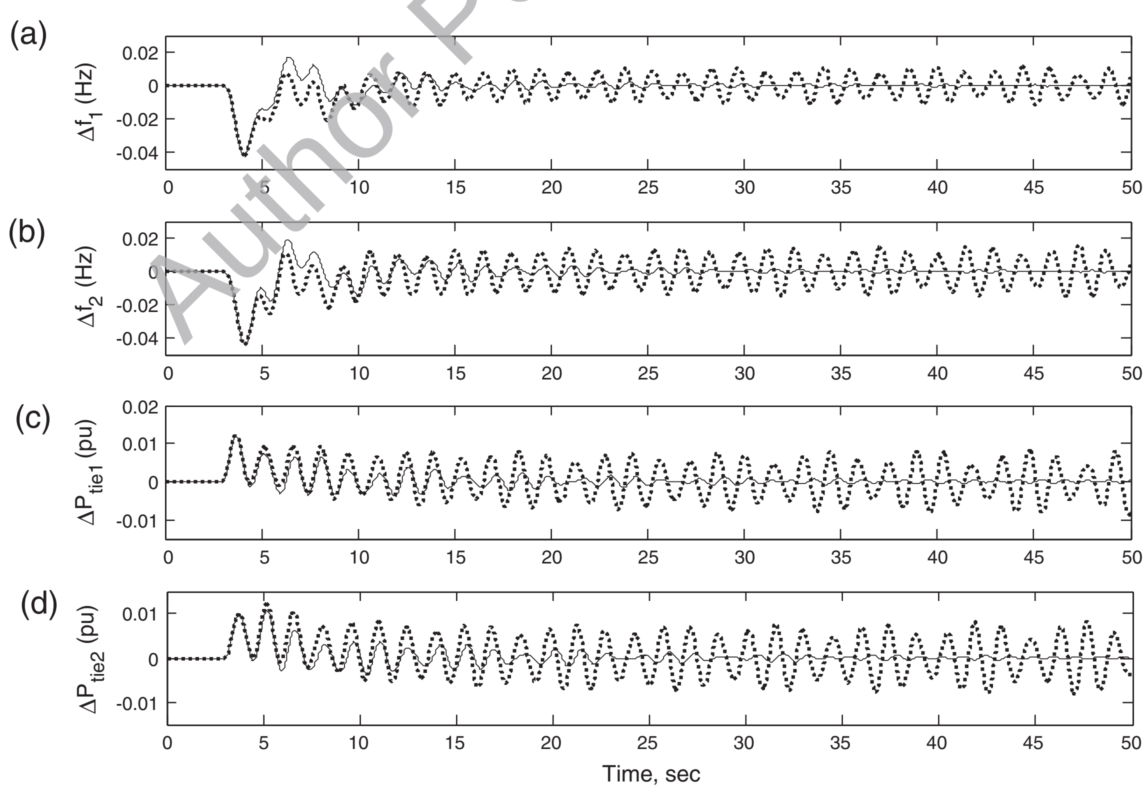

Fig. 7. Power system responses to scenario B with MPC (solid) and conventional (dotted) controller: (a) frequency deviation in area-1, (b) frequency deviation in area-3, (c) tie-line power change in area-1, and (d) tie-line power change in area-3.

formance with a conventional integrator and at only load change in area-2. Fig. 4 shows the simulation results in this case. The results from the top to the bottom are: the frequency deviations of area-1 Δf_1, the frequency deviations of area-2 Δf_2, and the tie-line power change between area-1 and area-2 $\Delta P_{tie,1}$ using both the proposed MPC and classical integrator controllers following a step load change in area-2 (ΔP_{L2} assumed to be 0.02 pu at $t = 3$ s). It is noteworthy that with the proposed MPC controller the system is more stable and fast comparing with the system with traditional integrator.

4.1.2. A-2 Case 2

The robustness of the proposed MPC controller against wide rang of parameter uncertainty is validated. In this case, the governor and turbine time constants of the two areas are increased to $T_{g1} = 0.105$ s (≅31% change), $T_{t1} = 0.785$ s (≅95% change), $T_{g2} = 0.105$ s (≅66% change) and $T_{t2} = 0.6$ s (≅38% change), respectively. Fig. 5 depicts the response of the MPC controllers in the presence of above uncertainty, at same load change described in the first case. It has been indicated that a desirable performance response has been achieved using the MPC controller while with conventional integrator, the performance and stability is seriously degraded.

4.2. B Scenario B

To illustrate the behavior of LFC system with the proposed decentralized MPC controller in a multi-area power system, consider three identical interconnected control areas as shown in Fig. 6. The simulation parameters [1] are given in Table 2. The system is tested at a simultaneous 0.02-pu load step disturbance in control area-2 and against wide rang of parameter uncertainty is validated. In this case, the governor and turbine time constants of each area is increased to $T_{g1} = 0.105$ s (≅31% change), $T_{t1} = 0.785$ s (≅95% change), $T_{g2} = 0.105$ s (≅66% change) and $T_{t2} = 0.6$ s (≅38% change), $T_{g3} = 0.15$ s (≅100% change) and $T_{t3} = 0.7$ s (≅100% change), respectively. Fig. 7 depicts the response of both the proposed MPC and classical integrator controllers in the presence of above uncertainty. This figure shows that even at this severe condition of uncertainties, system with proposed MPC controllers keeps stable, while goes to oscillation with integrator controllers.

5. Conclusion

This paper investigates robust load frequency control for interconnected power system based on the model predictive control technique. The proposed method was applied to two and three-control area power systems with parametric uncertainty and various loads conditions. Digital simulations have been carried out in order to validate the effectiveness of the proposed scheme. The proposed controller has been tested for several mismatched parameters and load disturbance.

A performance comparison between the proposed MPC and conventional integrator controllers is carried out. The simulation results demonstrate that the closed-loop system is robust against the parameter perturbation of the system and has desirable performance in comparison of classical integral control design in all of the performed test scenarios.

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