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Abstract: *This paper presents a decentralized model predictive based load frequency control for multi-area power systems. An MPC controller is designed for each area to decrease the effect of load disturbances and parameter uncertainties owing to variations in power system's parameters. Also to estimate load changes, Fast Output Sampling (FOS) method is used. The estimated signal is defined as a measured disturbance for MPC controller. The MPC method uses feed-forward control strategy for rejecting load disturbance effect in each power system area. A three-area power system has been considered as a test case to evaluate the proposed control scheme's performance. The results have been compared with a recent proposed robust LMI based PI control strategy. This comparison confirms that the proposed method has better performance than the LMI based PI control design in the presence of disturbances and uncertainities so that the frequency deviation and power flow changes between areas are effectively damped to zero with small oscillations in a short time.*

Keywords: Load frequency control, Model predictive control, Fast output sampling method, Load disturbance, Parameter uncertainty.

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].

Usually, the load frequency controllers used in the industry are proportional-integral (PI) type. This is because of their simple structure and possibility of their online tuning based on trial-and-error approaches. However, recently some robust control methods have been proposed to design more effective PI controllers to solve the LFC problem [2,3].

In the past two decades, many control strategies using various decentralized robust and optimal control methods have been proposed for the LFC design of power systems by several researchers [4-9]. Recently, Model predictive control (MPC) has been also introduced as a new method for load frequency control design.

Model Predictive Control (MPC) has developed considerably in the last decades both in industry and in academia. It is a model based control strategy where an optimization procedure is performed in every sampling interval over a prediction horizon, yielding an optimal control action. The optimization criterion, or objective function, is chosen in such a way as to satisfy the controlled system dynamics and constraints, penalize system output deviation from the desired trajectory, and minimize control effort. It has many advantages such as very fast response, robustness and stability against nonlinearities, constraints and parameters uncertainties [10]. Regarding desirable properties of MPC, these controllers are applied in a wide range of different industries, particularly in the process industries [11]. Furthermore, a possibility to incorporate economic objectives into the optimization criterion makes the MPC a good candidate for power system control.

A few applications of model predictive controllers on LFC are available in the literatures [12-16]. In [12], a decentralized MPC base on the wedge control philosophy is proposed to load frequency control which is compatible with control performance standards CPS1 and CPS2 set by NERC. The usage of MPC in multi-area power system is discussed, only by economic viewpoint in [13]. It presented a new model predictive load frequency control including economy logic for LFC cost reduction. In [14], a new state contractive constraint-based predictive control (SCC-MPC) is proposed for LFC synthesis of a two area power system. In [15], feasible cooperationbased MPC (FC-MPC) method is used in distributed LFC instead of centralized MPC and it has been applied to a four control area as a large scale power system. This paper only has investigated the effect of very large load changes on the frequency and power flow between areas. A decentralized MPC is proposed recently for load frequency control problem in [16], where the performance of the controller against parameter uncertainties and load changes on two and three control area power system is evaluated. In this paper, the variation of governor and turbine parameters are considered as uncertainties while in practice these parameters may not change for a long time. Actually the main source of uncertainty is related to variations of power system parameters rather than generating unit parameters. Also, the range of load change that used in [16] is not very large; nevertheless, the results do not show better behavior in transient response in comparison with conventional PI.

The present paper addresses a decentralized model predictive scheme to LFC synthesis of multi area power systems considering large load changes and parameter uncertainties of power system. In the proposed controller, load changes and interconnection between control areas are defined as measured and unmeasured disturbances, respectively. Since, the load change is not measurable in a power system practically, Fast Output Sampling (FOS) method has been used to estimate load disturbance as an input to MPC controller. Furthermore, feed-forward controller is used by the MPC to reject the effect of load disturbance. To evaluate the effectiveness of the proposed controller, a three area interconnected power system is considered as a test case. Validation of the MPC controller has been done also by its comparison with the addressed robust PI control design in [3]. The simulation results show that the proposed controllers guarantee the robust performance in the presence of uncertainties due to power system parameters variation and loads disturbances.

2. Dynamic Model

In practice, a large-scale power system consists of a number of interconnected control areas with some generation companies (GenCos), each of which is composed of three major parts: governor, turbine and generator. The governor corrects load errors by changing output position valve (PV). Physical constraints on PVs limit their position's rate of change and prevent them from rapid variations. Also, turbine turns natural power into mechanical torque, which drives the generator to generate electric power. Tie-line power deviation is proportional to the integral of the frequency difference between the two areas connected with the tie-line. These deviations from scheduled values are defined as Area Control Error (ACE). The ACE for each control area can be expressed as a summation of tie-line power change (ΔP_{tie}) and frequency deviation (Δf) multiplied by a bias factor *B*.

$$ACE = B\Delta f + \Delta P_{tie} \quad (1)$$

In the steady state, the generation should be matched with the load, driving the tie-line power and frequency deviations to zero. The frequency control provided by the load's and governor's natural sensitivity to the frequency change is called the primary frequency control loop. However, the primary control loop rarely restores the balance between generation and demand in a small bound around the nominal frequency, therefore a supplemental or secondary control unit is needed.

Usually a large scale power system has many control areas with several Gencos putting together. Fig. 1 shows the block diagram of control area-i, which includes *n* Gencos, from an N-control area power system.

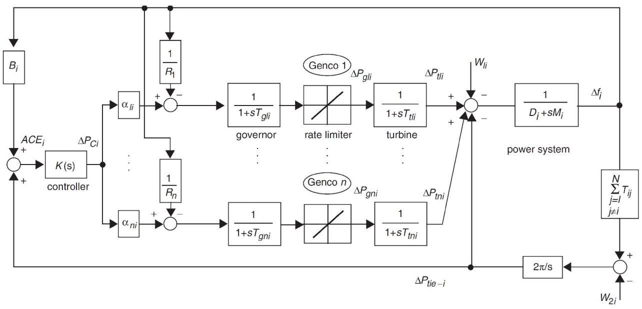

Fig. 1 :General control area of a power system including *n* Gencos [1]

Generally, Power systems have a highly non-linear and time-varying nature. However, for the purpose of frequency control synthesis and analysis in the presence of load disturbances, a simple low-order linearized model is used. By ignoring the nonlinearities in the model, a linearized mathematical model of area *i* with n generating units can be written [1,17]:

$$\Delta\dot{P}_{gki} = -\frac{1}{T_{gki}}\Delta P_{gki} + \frac{1}{T_{gki}}\left(\frac{1}{R_k}\Delta f_i + \alpha_{ki}\Delta P_{ci}\right)$$

$$\Delta\dot{P}_{tki} = -\frac{1}{T_{tki}}\Delta P_{tki} + \frac{1}{T_{tki}}\Delta P_{gki} \qquad ;\ k = 1, \dots, n \quad (2)$$

$$\Delta\dot{f}_i = -\frac{D_i}{M_i}\Delta f_i + \frac{1}{M_i}\left(\sum_{l=1}^{n}\Delta P_{tli} - \Delta P_{tie_i} - w_{1i}\right)$$

The tie-line power deviation between area *i* and area *j* is defined as:

$$\Delta P_{ij} = T_{ij}\left(\Delta\delta_i - \Delta\delta_j\right) \quad (3)$$

Where $\Delta\delta_i$ and $\Delta\delta_j$ are the phase angle deviations in areas *i* and *j*. With $\Delta\dot{\delta}_i = 2\pi\Delta f_i$, a state equation for ΔP_{tie_i} for area *i* can be written:

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

Dynamic model of the system as described with equations (2) and (4) in a state space form is given with:

$$\begin{aligned} \dot{x}_i &= A_i x_i + B_{ui} u_i + B_{Wi} W_i \\ y_i &= C_i x_i \end{aligned} \tag{5}$$

Where:

$$x_i = [\Delta f_i \quad \Delta P_{tie_i} \quad \Delta P_{g1i} \quad \Delta P_{t1i} \quad \cdots \quad \Delta P_{gni} \quad \Delta P_{tni}]$$

$$u_i = \Delta P_{ci} \;\; ; \;\; W_i = [w_{2i} \quad w_{1i}]^T \;\; ; \; w_{2i} = 2\pi \sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij}\Delta f_j$$

$$w_{1i} = \Delta P_{di} \quad ; \quad w_{2i} = 2\pi \textstyle\sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij}\Delta f_j$$

$$A_i = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \;\; ; \;\; B_{ui} = \begin{bmatrix} 0_{2\times 1} \\ B_{u2} \end{bmatrix} \;\; ; \;\; B_{Wi} = \begin{bmatrix} B_{W1} \\ 0_{2n\times 2} \end{bmatrix}$$

$$A_{11} = \begin{bmatrix} -\frac{D_i}{M_i} & -\frac{1}{M_i} \\ 2\pi \sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij} & 0 \end{bmatrix} ; \; A_{12} = \begin{bmatrix} \begin{bmatrix} \frac{1}{M_i} & 0 \\ 0 & 0 \end{bmatrix} & \cdots & \begin{bmatrix} \frac{1}{M_i} & 0 \\ 0 & 0 \end{bmatrix} \end{bmatrix}$$

$$A_{21} = \begin{bmatrix} \begin{bmatrix} -\frac{1}{T_{g1i}R_1} & 0 \\ 0 & 0 \end{bmatrix} \\ \vdots \\ \begin{bmatrix} -\frac{1}{T_{gni}R_n} & 0 \\ 0 & 0 \end{bmatrix} \end{bmatrix} \;\; ;$$

$$A_{22} = \begin{bmatrix} \begin{bmatrix} -\frac{1}{T_{g1i}} & 0 \\ \frac{1}{T_{t1i}} & -\frac{1}{T_{t1i}} \end{bmatrix} & \cdots & 0_{2n-2\times 2n-2} \\ \vdots & \ddots & \vdots \\ 0_{2n-2\times 2n-2} & \cdots & \begin{bmatrix} -\frac{1}{T_{gni}} & 0 \\ \frac{1}{T_{tni}} & -\frac{1}{T_{tni}} \end{bmatrix} \end{bmatrix}$$

$$A_{u2} = \begin{bmatrix} \begin{bmatrix} \frac{\alpha_1}{T_{g1i}} \\ 0 \end{bmatrix} \\ \vdots \\ \begin{bmatrix} \frac{\alpha_n}{T_{gni}} \\ 0 \end{bmatrix} \end{bmatrix} \; ; \; B_{W_{1i}} = \begin{bmatrix} 0 & -\frac{1}{M_i} \\ -1 & 0 \end{bmatrix} \; ; \; C = [\beta_i \quad 1 \quad 0_{1\times 2n}]$$

In the state-space model representation (5), x_i is the area state vector, y_i is the area output vector, u_i is the area input (ΔP_{ci}), and W_i is the area disturbance that includes changes in local load w_{1i} , as well as the area interface w_{2i}. The other parameters are described as follows.

f	area frequency
ACE	area control error
P_g	governor valve position
P_c	governor load set point
P_t	turbine power
P_{tie}	net tie-line power flow
P_d	power demand (area load disturbance)
M	equivalent inertia constant
D	area load damping coefficient
T_g	governor time constant
T_t	turbine time constant
T_{ij}	tie-line synchronizing between areas *i* and *j*
B	frequency bias
α	Participation factor
R	drooping characteristic
Δ	deviation from nominal values
N	number of control areas

3. Model Predictive Control with feed-forward controller

Model Predictive Control (MPC) has been proved as an effective and accepted control strategy to stabilize dynamical systems in the presence of nonlinearities, uncertainties, constraints and delays, especially in process industries. A general MPC scheme is shown in Fig. 2. As could be seen, the MPC controller consists of prediction and controller unit .The prediction unit includes system and disturbance model which forecast future behavior of system based on its current output, measured disturbance, unmeasured disturbance and control signal over a finite prediction horizon. The predicted output is exploited by control unit as known parameters in an optimization problem which minimizes an objective function in presence of system constraints. Solving of this problem leads to an optimal control sequence over a control horizon. The first element of this sequence is injected into the plant and the whole procedure is repeated in the next sampling interval with the prediction horizon moved one sampling interval forward.

There are a number of formulations of the MPC strategy that are different either in a way the system model is obtained or in a formulation of the objective function. However, they all usually consist of same steps which are completely illustrated in [10,18].

When the effect of some disturbances is measureable or can be estimated, the MPC controller can provide feed-forward compensation for such disturbances as they occur to attenuate their impact on the output. Unlike feedback controller, feed-forward does not need to wait until the effect of disturbance become apparent before taking corrective actions. Therefore, it cancels these effects more effectively in comparison with only using feedback in MPC controller. A more precisely disturbance-output model identified, a more effectively measured disturbance would be rejected. Since there is always difference between exact and identified model, feed-forward control has to be used in combination with feedback control; the feed-forward control removes most of the measured disturbance effect, and the feedback control removes the rest as well as dealing with unmeasured disturbances. Feed-forward is easily incorporated into predictive control. All that has to be done is to include the effects of the measured disturbances in the predictions of future outputs. The optimizer will then take these into account when computing the control signal. More details of this strategy could be found in [18].

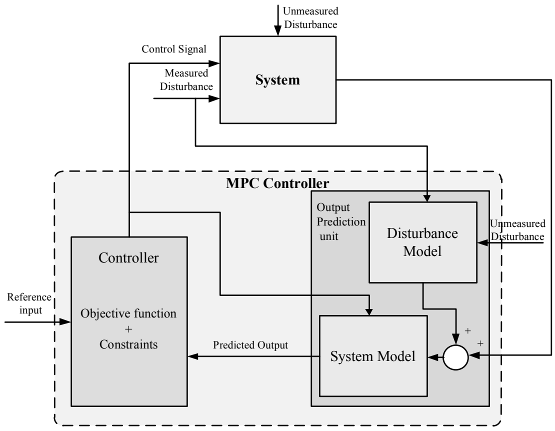

Fig. 2 :A general MPC scheme

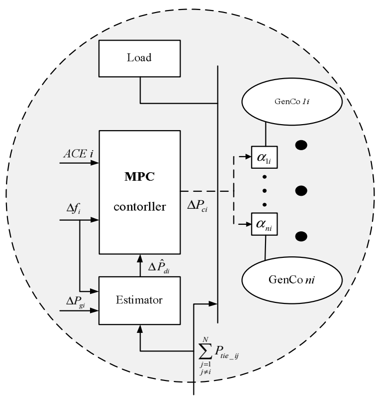

Fig. 3: Proposed control strategy for area *i*

4. Model Predictive Load Frequency Control

In this section, the decentralized model predictive control scheme is adopted on the LFC problem in a general N-control area power system described in section 2. For this reason, an MPC controller is applied to each control area to drive the tie-line power and frequency deviations to zero in the presence of load changes and parameter uncertainties, while the interconnection between control areas is considered. The proposed MPC controller uses a feed forward control strategy to reject the effect of load disturbances. Fig. 3 illustrates the proposed strategy for area *i*. As it can be seen in this structure, an MPC controller has been used to generate the control signal based on ACE_i , Δf_i and $\Delta \hat{P}d_i$ as its inputs. Since, load changes in power systems are not measurable practically, an estimator unit is used to obtain $\Delta \hat{P}d_i$. In this case, a disturbance estimation method based on fast output sampling (FOS) [20] is proposed, which is suitable due to availability of multiple measurements of output signals in each sampling period of the MPC controller.

4.1 FOS method based disturbance estimation

Fast output sampling (FOS) is an estimation technique appropriate for continuous time system controlled with discrete-time control signal, where the output signal can be sampled several times during a period of the control signal. FOS shows better performance than standard estimation techniques, because it reduces the estimation error to zero after just one sampling period [19,20].

The principle of using FOS estimation technique in system control is shown in Fig. 4. Firstly, the last N subsamples of the output signal y(t), measured in the most recent sampling period τ, are used to estimate the disturbance, where the subsamples' period is *T*. The estimated disturbance is then used as controller input to compute the control signal for the next sampling period [20].

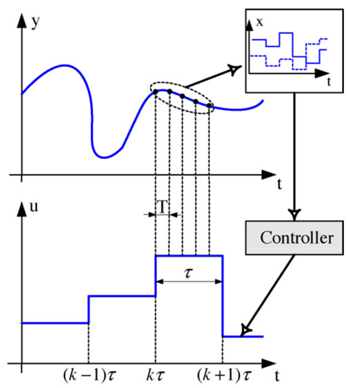

Fig. 4: The usage of the FOS estimation method in system control [29]

To demonstrate the effectiveness of the proposed control design, some simulations were carried out. In these simulations, the proposed controllers were applied to the three-control area power system shown in Fig. 5. - The test system consists of three control areas interconnected through high voltage tie-lines, with three GenCos within each area. These areas are modeled as presented in section2, and their parameters are given in [3,4].

5. Simulation Results

To design of MPC controller, the sampling interval of 0.1 second, the control horizon of 20 samples (m = 2) and a prediction horizon of 100 samples (p = 10) are selected as appropriate length to achieve good control performance with manageable computations in real-time. Furthermore, Weights on system's input, output and state variables are chosen at their best quantities.

To evaluate the performance of the decentralized MPC controller, it is compared to a robust LMI based PI controller [4] in two different scenarios. In the first case, the robustness of the controllers in the presence of harsh sudden load changes which might include emergency situation such as generating unit loss is evaluated. The effectiveness of MPC controller in the face of power system uncertainty due to the inertia constant (*M*) and load damping coefficient (*D*) perturbation is shown in scenario 2.

Scenario 1: for the first scenario, a large step load change in demand is added to each area at time *t=2sec* with the following quantities: $\Delta Pd1 = 100MW$, $\Delta Pd2 = 100MW$, and $\Delta Pd3 = 100MW$. The closed-loop responses of ACE and frequency deviation (Δf) of control areas 1, 2 and 3 are identified as important, and they are presented in figures 6.a, 6.b and 6.c. It can be seen that in spite of harsh conditions, the MPC controller still has better performance than LMI based PI controller so that the ACE and frequency deviation are effectively damped to zero with small oscillations in a very short time.

Scenario 2: The robustness of decentralized MPC controller in the face of wide range of parameter uncertainty is validated in this section. In LFC practice the uncertainties is associated with power system parameters practically. For this reason, parameter change of 25% increase is considered for inertia constant (*M*) and load damping coefficient (*D*) of power system in each area. Fig.7 indicates the performance of the MPC controller in the presence of these parameter uncertainties at same load changes described in scenario 1. As it can be seen even in this sever condition the MPC controller has a faster and more stable response in comparison with the robust PI controller.

The relation between FOS, MPC and LFC is described as follows. During one sampling periods (τ), several measurements of frequency deviation $\Delta f(kT)$and tie-line power deviation $\Delta P_{tie}(kT)$ signals are gathered. Besides those subsamples, which are inputs to the MPC controller, subsamples of generated power deviation $\Delta P_g(kT)$ are also gathered as inputs to the estimator. The formulation of the proposed disturbance estimation method is completely discussed in [20].

6. Conclusion

A decentralized robust LFC synthesis strategy using MPC scheme has been propoesd for multi-area power systems. The MPC controller uses a feed-forward control strategy to reject load disturbances which has been estimated using FOS method. The proposed controller was applied to a three control area power system and was compared with a robust PI controller in the presence of load disturbances and power system's parameter uncertainties through two different scenarios. Simulation results demonstrated that the MPC controller is robust against large load changes and parameter variations and also has better performance in comparison with robust LMI based PI controller.

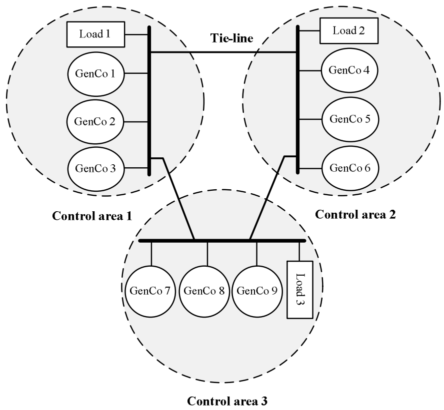

Fig. 5: Three control area power system

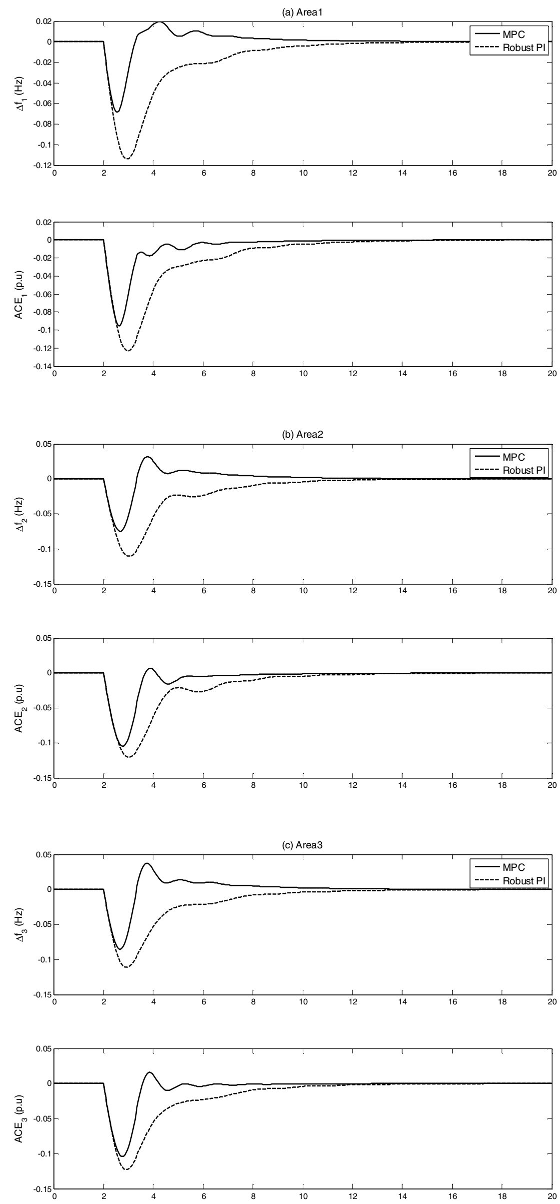

Fig. 6: System response for scenario 1; Solid (MPC), dash-dotted (Robust PI).

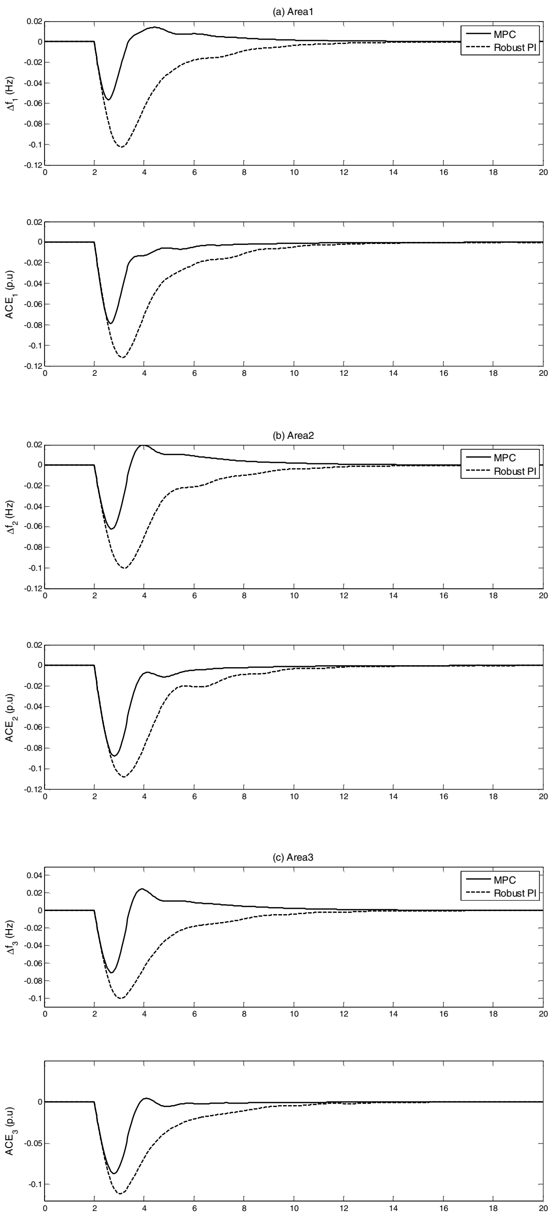

Fig. 7: System response for scenario 2; Solid (MPC), dash-dotted (Robust PI).

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