

Decentralized Model Predictive Load-Frequency Control for deregulated power systems in a tough situation

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Abstract-- In this paper a decentralized Model Predictive Controller (MPC) is proposed to load-frequency control in deregulated power systems under harsh conditions such as loss of power generation or loss of controllers in some control areas. To nullify these effects on frequency deviations, the MPC controller uses feed-forward control strategy in each area. The performance of the proposed controller is validated in different scenarios on a multi-area power system. Comparing simulation results with recent proposed robust LMI based PI control strategy, it can be seen that the decentralized MPC scheme effectively regulates frequency without using any emergency control strategy even in severe conditions.

Keywords- *feed-forward control, load frequency control, model predictive control, multi area power system*

I. INTRODUCTION

Frequency deviation problem has been one of the major subjects in power system which is a direct result of imbalance between the electrical power demand and the power generation as well as the tie line power flow changes between two different areas in the deregulated power network. Load Frequency Control (LFC) is to keep the system frequency at the nominal value, maintain the net inter-area tie-line power flows at their pre-specified values considering load changes, modeling uncertainties and system nonlinearities [1, 2].

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. [3] applied a decentralized H_∞ optimal control combined with an observer for LFC problem. This controller shows a better behavior for damping load disturbances over the conventional optimal control strategies. The effectiveness of the proposed method was validated on three-area and six-area networks involving both thermal and hydraulic power plants in the presence of load disturbances. Later, in [4], a systematic method for robust sequential decentralized load frequency controllers using μ -synthesis in a multi-area power system was proposed. At each design step, the information about the controllers design in the previous step is taken into account in the synthesis procedure. Also in [5], two robust decentralized

control design methodologies for the LFC are proposed. The first one is based on control design using the linear matrix inequalities (LMI) technique and the second one is tuned by a robust control design algorithm. Moreover, in [6], a decentralized LFC synthesis is formulated as an H_∞ -control problem and is solved using an iterative LMI algorithm that gains lower order proportional-integral (PI) controller than [5]. Both controllers are tested on a three-control area power system with three scenarios of load disturbances to demonstrate their robust performances.

Although the above research works have considered control of load frequency under normal load fluctuations, none of them investigated the performance of the proposed controllers under sever conditions like power generation or controller breakdown.

These conditions might be so tough that despite of load frequency control as secondary control loop on system, leads a power system's frequency to drop quickly if the remaining generation no longer matches the load demand. Resulted large frequency deviations can degrade load performance, overload transmission lines and even lead to system collapse. In these situations, the emergency control and protection schemes such as under-frequency load shedding is mostly used to restore the system frequency [1].

However some works have investigated these tough conditions only by considering the secondary control loop, LFC controller. [7] Has introduced an Active Disturbance Rejection Controller (ADRC) to regulate the frequency error for a three-area interconnected power system when it has been faced to power generation loss and controller breakdown in some areas. Although the ADRC controller stabilizes frequency deviations, it could not set it to desired nominal frequency.

For this reason a decentralized model predictive controller is proposed which is capable of frequency regulation in its nominal quantity under severe conditions. The impact of other areas and load changes are defined as unmeasured and measured disturbance respectively for MPC controller in each area. The MPC controller then uses feed-forward control strategy to cancel the effect of measured disturbance on the system. The comparison of the proposed controller with previous works shows that it could regulate frequency in its nominal quantity, while other controllers degraded under emergency conditions.

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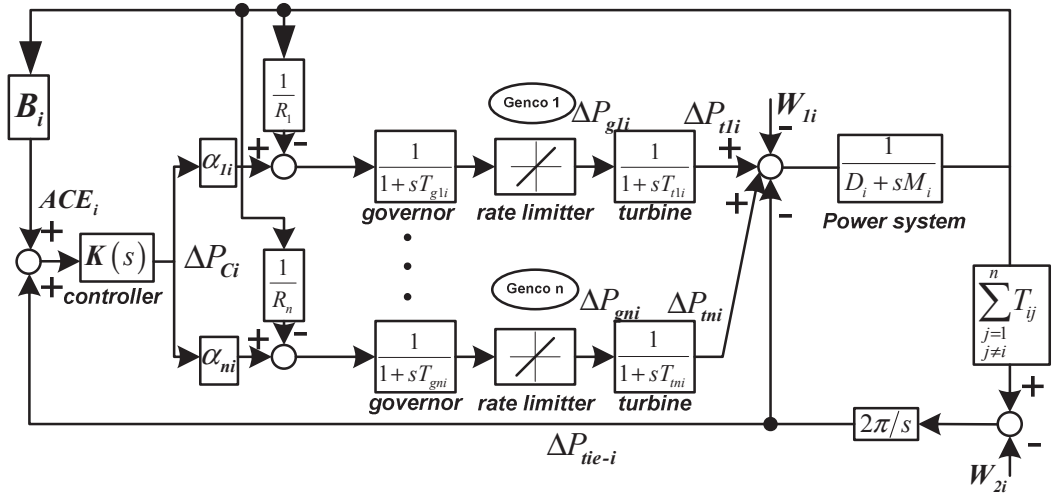


Fig. 1. Dynamic model of one area in a multi-area power system

II. DYNAMIC MODEL

In practice, a large scale power system has many control areas, with several Generation Companies (Gencos) putting together. Fig.1 shows a typical LFC block diagram of control area- i , which includes n -Gencos, from a multi-area power system.

As can be seen in Fig.1, each area includes some Gencos, each of which composed of three major parts: governor, turbine and generator. 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. A common non-reheat turbine unit is employed in the paper. Moreover tie-line power deviation (ΔP_{tie-i}) is proportional to the integral of the frequency difference between two areas connected with the tie-line. The Area Control Error (ACE) defined as tie-line deviations from scheduled values is equal to $B\Delta f + \Delta P_{tie-i}$ as shown in the figure. The controller's objective is to drive frequency deviations and overall tie-line power flow between areas to zero in the presence of disturbances and parameter variations.

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, 8]:

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

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

$$\Delta \dot{f}_i = -\frac{D_i}{M_i} \Delta f_i + \frac{1}{M_i} \left(\sum_{l=1}^n \Delta P_{tli} - \Delta P_{tie_i} - w_{1i} \right) \quad (3)$$

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

$$\Delta P_{ij} = T_{ij} (\Delta \delta_i - \Delta \delta_j) \quad (4)$$

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

$$\Delta \dot{P}_{tie_i} = \sum_{j=1}^N \Delta \dot{P}_{ij} = 2\pi \sum_{j=1}^N T_{ij} (\Delta f_i - \Delta f_j) \quad (5)$$

Dynamic model of the system as described with equations (1-3) and (5) in a state space form is given with:

$$\begin{aligned} \dot{x}_i &= A_i x_i + B_{ui} u_i + B_{Wi} W_i \\ y_i &= C_i x_i \end{aligned} \quad (6)$$

Where:

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

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

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

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

$$A_{11} = \begin{bmatrix} -\frac{D_i}{M_i} & -\frac{1}{M_i} \\ 2\pi \sum_{j=1, j \neq i}^N T_{ij} & 0 \end{bmatrix}; A_{12} = \begin{bmatrix} \frac{1}{M_1} & 0 \\ 0 & 0 \end{bmatrix} \dots \begin{bmatrix} \frac{1}{M_n} & 0 \\ 0 & 0 \end{bmatrix}$$

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

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

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

In the state-space model representation (6), 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

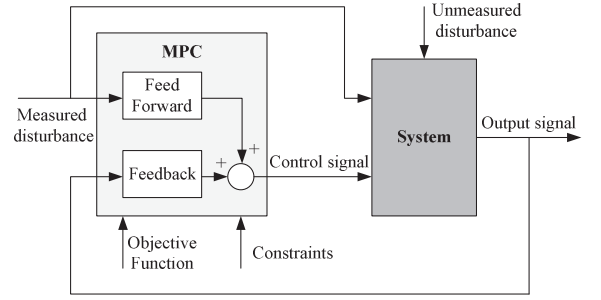


Fig. 2. General MPC scheme with feed-forward controller

III. CONTROLLER STRUCTURE

Model Predictive Control is a method in which the control input is obtained by online solving of a constrained optimal control problem in each time step, over a finite prediction horizon. The constraints are likely to be on inputs, outputs or state variables of the system which are very common in practical processes. The objective function is chosen so that it penalizes system output deviation from the desired trajectory, and minimizes control effort. Solving optimization problem leads to an array of optimal control inputs which the first element is applied as the current control action on the system. This strategy is repeated again in next time steps until desired control specifications have been satisfied.

When the effect of some disturbances is measurable 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 [9]. 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.

An MPC control scheme which has considered both feedback and feed-forward control signals has been illustrated in Fig. 2. Since there is always differences between estimated and real quantity of disturbance signals, feedback and feed-forward actions are combined together so that the feed-forward control removes most of the effect of the measured disturbance, and the feedback control removes the rest - as well as dealing with unmeasured disturbances.

IV. SIMULATION RESULTS

To illustrate the effectiveness of proposed control strategy, a three-area power system, with three GenCos in each area is considered as a test case which has been shown in Fig.3. The proposed MPC controller is applied to each area considering load changes as measured disturbance. Also the effect of other areas is defined as unmeasured disturbance.

To design 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.

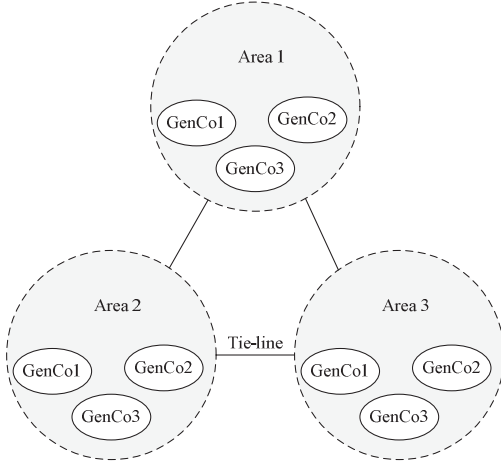


Fig. 3. Three control area power system

Performance of the MPC controller has been validated through two different simulation scenarios and comparing its result with robust PI controller [6]. In the first case generation unit breakdown is considered while the second case describes the effects of controller breakdown.

Scenario 1: In order to simulate the extreme condition, the three-area model is modified so that one generating unit is cut off from the whole system at a specific time. In this case, load changes which considered for each area is: $\Delta P_{d1} = 100 MW$, $\Delta P_{d2} = 80 MW$ and $\Delta P_{d3} = 50 MW$ and added to the three areas at $t = 2$ seconds. Generating company 3 (Genco3) in Area 1 is tripped at the 20th second.

The responses of three areas are shown in Fig. 4. From the simulation result, we can see that after outage of generating company 3 (Genco3) from Area 1, the Δf of three areas and ACE of Area 2 and Area 3 still converges to zero despite the model changes but ACE 1 has some steady state errors.

Except ACE 1, MPC is still able to effectively control the system output to track the reference with little overshoot and negligible oscillation while the robust PI controller drives the ACE to zero with an obvious oscillation since the system model has changed significantly. However, we should also notice that the control effort ΔP_c of the robust PI controller is much smoother than the MPC.

Scenario 2: two large, step-input load changes are added to areas 2 and 3 with the magnitudes of $\Delta P_{d2} = 100 MW$ and $\Delta P_{d3} = 80 MW$ while the controllers of areas 2 and 3 are assumed to be out of services. This case is to test the reliability of the controlled system in tough situation.

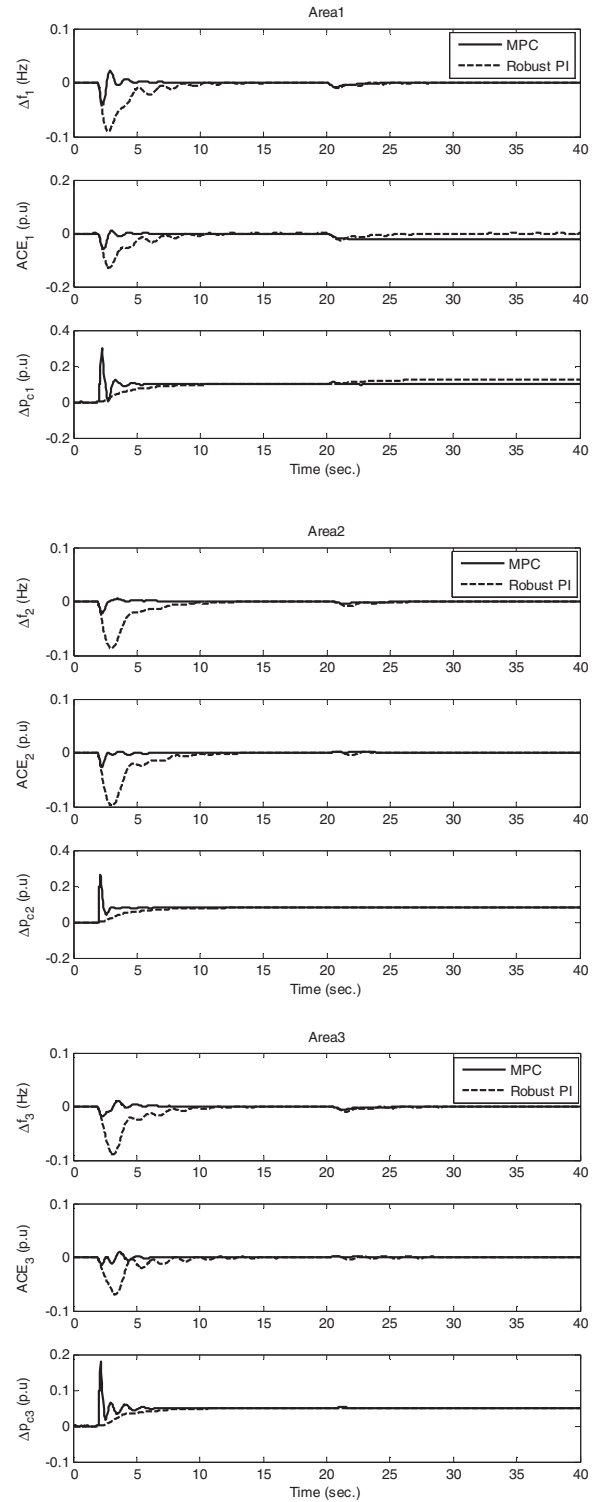


Fig. 4. System response and control signal for three areas for scenario 1; MPC (solid), Robust PI (dashed)

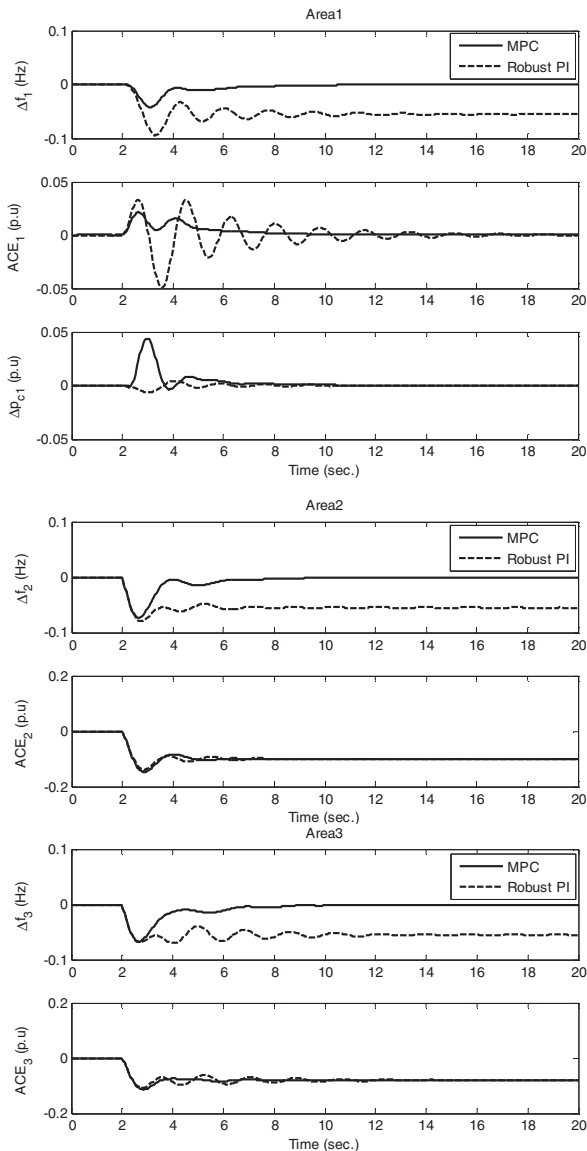


Fig. 5. System response and control signal for scenario 2; MPC (solid), Robust PI (dashed)

From the results shown in Fig. 5 we can see that the Area1's MPC controller could regulate Δf of all three areas while robust PI could only control frequency in Area 1. The ACE in areas 2 and 3 can not converge to zeroes but only be bounded under this situation. Though the ACE and Δf are still driven to zeroes in Area 1 under both MPC and robust PI controllers. Similarly, MPC produces smaller oscillations and faster response in the results of the ACE and Δf than PI controller. However, the control effort of the MPC is a little bit bigger than the Robust PI controller.

V. CONCLUSION

A decentralized model predictive control strategy which uses a combination of feedback and feed-forward actions was presented in this paper for load frequency control problem in a multi area power system. The proposed controller was applied

to a three control area power system considering two tough conditions, generator outage and controller cut-off, which may occur in deregulated power systems. Simulations show that the proposed method has better results in comparison with robust PI controller in these situations.

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VII. BIOGRAPHIES



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