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Distributed Model Predictive Control for Two-area Interconnected Power System

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Abstract. For the problem of uncertain external disturbances which are always present in modern power systems, this study proposes a distributed model predictive control (DMPC) scheme for the load frequency control (LFC) problem of the multi-area interconnected power system. In this paper, the dynamic model of multi-area interconnected power system is introduced, and the DMPC is proposed to replace the traditional PI control. For the constraint of generator power rate of change, the control system uses the dynamic equation of state of the interconnected power system as the DMPC prediction model. The disturbance is the change of the load and the input change of the governor. The predicted output is the area control error (ACE). The power system consists of subsystems that contain their own controllers, and the controllers in each region integrate the information of the other controllers into the control targets to facilitate coordination. The DMPC algorithm proposed in this paper ensures the applicability and stability of the DMPC algorithm in the LFC system and reduces the communication requirements at the same time. Simulation results show that closed loop performance and robustness are greatly improved compared with the traditional methods.

1. Introduction

The interconnection of power systems, composed of interconnected subsystems, is achieved through tie lines. In a power system, a generator set is allocated in each area and is responsible for the load in its own area while exchanging power with the surrounding area. Due to different power generation capacity and power system load, the system frequency deviates from its nominal value, and the active power flow between the areas deviates from its shrinkage value. After disturbances in the power system (such as changes in system load), we need to adjust the load reference set point so that the regional frequency deviation is zero. In fact, we can think of it as a problem of interference attenuation. This problem is about extensive power systems with input limitations [1].

A research of dissimilar control options for LFCs can be discovered in [2,3]. Targeting for better dynamic performance, many controllers for power system LFC problems have been proposed. The most widely used controllers are fixed gain types such as PI or PID controllers. Literature [4] proposed a new regulation method to design the PID load frequency controller of power system. Whether the LFCs can be successfully implemented or not, the parameter information of the control areas is very important, but they often change according to the inexact model's defense. To defeat this technical difficulty, we used intelligent control technology. In recent twenty years, more and more attention has been paid to the application of intelligent technologies such as fuzzy system, artificial neural network...
and genetic algorithm in many aspects of power system [5]. In [6], the adaptive fuzzy output of generator is proposed to control the excitation in power system. In [7], a method of load frequency control applied to two-zone power system is proposed, which uses a fuzzy gain scheduling proportional-integral controller. Literature [8] proposed a control scheme based on artificial neural fuzzy inference system (ANFIS) to optimize and update the control gain of AGC based on load variation.

Papers on the use of MPC technology for LFC have been reported recently (e.g. [9–16] and the reference there in). In [9], the MPC controller is used to obtain fast response and robustness to parameter uncertainties and load changes, but only for single-zone load frequency control applications. The use of MPC in multi-area power systems is discussed in [10], but only from an economic point of view. It presents a new model to predict the economic logic of LFC including LFC cost reduction. In [11], a prediction scheme is proposed for LFC, which is about state constraints, in the interconnected power system of two regions. In [12], the performance of MPC-based LFC systems has been studied under an extensive scope of operating prerequisite. However, MPC controllers in [11, 12] all have centralized controllers that do not adequately regulate extensive-scope power systems. So, there are lots of decentralized or distributed architectures proposed (e.g. [12-14]). But, the controller of each subsystem does not consider the interconnected area and has been independently designed. In this case, the range of load changes will be very large, which is not suitable for LFC [14].

In this paper, we propose to use distributed model predictive control strategy to control LFC in multi-area interconnected power system. The controllers in each subsystem will have information exchange. The whole big system is composed of many subsystems, so each Subsystems have their own MPC controllers, which exchange measured and predicted amounts. At the same time, we also consider the generator power constraint and compare with the traditional PI control strategy. The simulation results show that the distributed model predictive control strategy has better performance.

2. Multi-area power system

LFC system in the extensive-scope power system interconnection control area, it is necessary to exchange information with other areas for local frequency control. Therefore, the tie line power signal is indispensable for the dynamic LFC system model. In Figure 1, there are M regional power systems. As LFC can only operate a little smaller system interference, simple linear models are commonly used for LFC designs. Table 1 provides some basic power system terminology. The symbol Δ is used to indicate an error from the steady state.

Currently, the choice of frequency control is due to overheating or overheating. Figure 2 shows the detailed structure of the thermal plant. Table 1 shows the variables and parameters of the model. The thermal power plant includes speed governing subsystem (SG), reheat time delay subsystem (RTD),
steam turbine unit (STU) and power system (PS). The state space model can be inferred directly from the block diagram:

**STU:**
\[
\Delta \dot{P}_{g_i} = -\frac{1}{T_{pi}} \Delta P_{g_i} + \frac{1}{T_{pi}} \Delta P_{ri}
\]

**SG:**
\[
\Delta \dot{X}_{gi} = -\frac{1}{T_{gi} R_i} \Delta \omega_i - \frac{1}{T_{gi}} \Delta X_{gi}
\]

**RTD:**
\[
\Delta \dot{P}_{ri} = -\frac{K_{r_i}}{T_{Gi} R_i} \Delta \omega_i + \left( \frac{1}{T_{ri}} - \frac{K_{r_i}}{T_{Gi}} \right) \Delta X_{gi} - \frac{1}{T_{ri}} \Delta P_{ri}
\]

The frequency deviation \( \Delta \omega_i \) for each area \( i \) (\( i = 1, 2 \)) can be expressed as
\[
\Delta \omega_i = -\frac{1}{T_{pi}} \Delta \omega_i - \frac{K_{pi}}{T_{pi}} \Delta P_{tie12} + \frac{K_{pi}}{T_{pi}} \Delta P_{gi} - \frac{K_{pi}}{T_{pi}} \Delta P_{L_i} + \frac{1}{T_{Gi}} \Delta P_{ci}
\]

The tie-line power flow between areas \( i \) and \( j \) can be described as
\[
\Delta P_{tie}^j = T_{12} (\Delta \omega_i - \Delta \omega_j)
\]
\[
\Delta P_{tie} = -\Delta P_{tie}^j
\]

Figure 2. Block diagram of two-area thermal power plant.

| Parameter | Value | Parameter |
|-----------|-------|-----------|
| \( \Delta \omega_i \) | Frequency deviation | HZ |
| \( \Delta P_{g_i} \) | Generator output power deviation | P.u.MW |
| \( \Delta X_{gi} \) | Governor valve position deviation | p.u |
| \( \Delta P_{L_i} \) | Load disturbance | P.u.MW |
| \( K_{pi} \) | Power system gain | HZ/P.u.MW |
| \( K_{r_i} \) | Reheat turbine gain | HZ/P.u.MW |
| \( T_{pi} \) | Power system time constant | s |
| \( T_{r_i} \) | Reheat turbine time constant | s |
| \( T_{Gi} \) | Thermal governor time constant | s |
| \( T_{ri} \) | Turbine time constant | s |
| \( T_{ij} \) | Tie-line (between areas \( i \) and \( j \)) stiffness coefficient | P.u.MW |
| \( P_{tie}^j \) | Tie-line power flow between areas \( i \) and \( j \) | P.u.MW |
| \( P_{tie,i} \) | Total tie-line power flow between areas-\( i \) and others | P.u.MW |
In a large electrical system, Area Control Error (ACE) indicates an electrical mismatch between the area load and the power. The \( \text{ACE}_i \) of the control area can be expressed as the sum of the frequency deviation \( \Delta \omega \) times the \( K_{bi} \) bias factor and tie-line power change \( \Delta P_{\text{tie},i} \),

\[
\text{ACE}_i = K_{bi} \Delta \omega + \Delta P_{\text{tie},i}
\]  

(6)

The above frequency response model (1)–(6) for area-\( i \) of two power system control areas can be combined in the following state space model:

\[
\begin{bmatrix}
\Delta \dot{\omega}_i \\
\Delta \dot{P}_{\text{tie},i} \\
\Delta \dot{P}_{p,i} \\
\Delta \dot{X}_{g,i}
\end{bmatrix} = \begin{bmatrix}
-\frac{1}{T_{pi}} & \frac{K_{pi}}{T_{pi}} & \frac{K_{pi}}{T_{pi}} & 0 \\
0 & 0 & -\frac{1}{T_{pi}} & \frac{1}{T_{pi}} \\
-\frac{1}{T_{gi} R_i} & 0 & 0 & -\frac{1}{T_{gi}} \\
K_{ci} & 0 & \frac{1}{T_{ci}} & -\frac{1}{T_{ci}}
\end{bmatrix} \begin{bmatrix}
\Delta \omega_i \\
\Delta P_{\text{tie},i} \\
\Delta P_{p,i} \\
\Delta X_{g,i}
\end{bmatrix} + \begin{bmatrix}
0 \\
0 \\
-\frac{K_{ci}}{T_{ci}} \\
\frac{1}{T_{ci}}
\end{bmatrix} \Delta \omega_i + \begin{bmatrix}
0 \\
0 \\
\Delta P_{p,i} \\
0
\end{bmatrix} + \begin{bmatrix}
-\frac{1}{T_{ci}} \\
0 \\
0 \\
0
\end{bmatrix} \Delta X_{g,i}
\]  

\[
\begin{bmatrix}
\Delta \omega_i \\
\Delta P_{\text{tie},i} \\
\Delta P_{p,i} \\
\Delta X_{g,i}
\end{bmatrix} = \begin{bmatrix}
K_{bi} & 1 & 0 & 0 \\
0 & \frac{1}{T_{ci}} & 0 & \frac{1}{T_{ci}}
\end{bmatrix} \begin{bmatrix}
\Delta \omega_i \\
\Delta P_{\text{tie},i} \\
\Delta P_{p,i} \\
\Delta X_{g,i}
\end{bmatrix}
\]  

(7a)

(7b)

In power systems, the change in generation can not exceed the maximum rate specified. The power generation rate constraint is typically \( 10\%/\min \) (\( \cong 0.0017 \) p.u.MW/s) [16]. Considering the constraint of generation rate, the limit of output power deviation rate of generator is [16]

\[
\left| \Delta \dot{P}_{g,i} \right| \leq 0.0017 \text{ p.u.MW/s}
\]  

(8)

which can be considered as state constraints. In addition, the load reference set point is constrained as [16]

\[
\left| \Delta P_{s,i} \right| \leq 0.3
\]  

(9)

This is a control entry restriction. Both (8) and (9) time zones are hard obstacles. In all control zones, changes in local power consumption (load) change the rated operating frequency. The controller \( i \) in every control zone manipulates the set point \( P_{s,i} \) to drive the frequency deviation \( \Delta \omega_i \) and the tide deviation for the binding line tends to be zero.

In general, formulate the LFC problem as follows: For each zone, a local distributed controller has been designed that coordinates the controller when frequency translation errors, frequency mismatches, and current maneuver information arrive generation rate constraints and Load reference set point constraints.

3. Controller design and implementation
In this section, we first design a distributed model predictive controller for a two-area interconnected power system with state and input constraints. Then, for comparison, PI controllers of two-area interconnected power system are respectively designed. Figure 3 shows the DMPC block diagram of District L power system. \( \Delta P_{\text{tie}} \) is very important for LFC problems with frequency, generator output,
governor valve position, tie line active power, load disturbance. The state variable (10) selected in the equation can be measured directly by the local controller. DMPC in all regions exchanges control information via network communication which is a reliable network technology that provides high speed communication of power grid application [15].

![Block diagram of DMPC for L-area interconnected power system.](image)

With a set of state variables $x_i = [\Delta \phi_i \Delta P_{ie,i} \Delta P_{ij} \Delta Y_{ij} \Delta P_{ij}]^T$, control input $u_i = \Delta P_{ij}$, disturbance input $\alpha_i = \Delta P_{Li}$ and output $y_i = ACE_i$, the partitioned model for subsystem $i$ of the three-area power system can be described as the state-space model:

$$\dot{x}_i(t) = A_{ii}x_i(t) + B_{ii}u_i(t) + E_{ii}(\alpha_i(t) + \sum_{j \neq i} (A_{ij}x_j(t) + B_{ij}u_j(t)))$$  \hspace{1cm} (10a)

$$y_i = C_{ii}x_i(t)$$  \hspace{1cm} (10b)

$A_{ii} = \begin{bmatrix} \frac{1}{T_{Pi}} & \frac{-K_{Pi}}{T_{Pi}} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \sum_j K_{Sij} & 0 & 0 & 0 \\ 0 & 0 & -1 & \frac{1}{T_{Ti}} \\ -1 & 0 & 0 & \frac{1}{T_{Gi}} \end{bmatrix}$, $B_{ii} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$, $E_{ii} = \begin{bmatrix} K_{Pi} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$, \hspace{1cm} (11a)

$A_{ij} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -T_{ij} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$, $B_{ij} = 0$, $C_{ii} = [K_{Bi} \ 1 \ 0 \ 0 \ 0]$. \hspace{1cm} (11b)

The system model is used to predict future changes in the controller and to evolve within a certain virtual time. To clearly distinguish the actual system from the system model, we use a bar ($\bar{x}, \bar{u}$) to
represent the variables inside the controller, indicating that the predicted value is not needed and will not be the same as the actual value.

The $\tilde{x}_i(t; x_i(t), t)$ is a predictor of the subsystem, starting with the actual state of the $x_i(t)$ at time $t$ and controlled by the open-loop input function $\overline{u}_i(t)$. We assume that the state variables $x_i$ and the disturbance $\omega_i$ can be measured or evaluated directly by the controller $i$.

For each subsystem $i = 1; 2$, the problem of optimal control of the open context in time $t$ is as follows:

$$\min_{\overline{u}_i(t)} J_i(x_i(t), \overline{u}_i(t))$$

(12)

With

$$J_i(x_i(t), \overline{u}_i(t)) = \int_0^\tau \left( \sum_{j=1}^n (A_{ij}x_j(t) + B_{ij}\overline{u}_j(t))^2 + R_i \right) d\tau$$

(13)

Subject to

$$\dot{x}_i(t; x_i(t), t) = x_i(t)$$

(14a)

$$\frac{\overline{x}_i(t) - \overline{x}_i(t)}{T_{Ch_{ij}}} \leq 0.0017, \forall \tau \in [t, t + T_p]$$

(14b)

$$\overline{u}_i(t) \leq 0.3, \forall \tau \in [t, t + T_p]$$

(14c)

In the above problem, the $T_p$ is a limited range of predictions, and the control and prediction ranges are chosen to be the same value for ease of explanation. $Q_i \in R^{n \times n}$ and $R_i \in R^{n \times n}$ denote positive definite and symmetric weighting matrices. The weighting matrices $Q_i$ and $R_i$ in the objective function (13) are chosen as $Q_i = Q = \text{diag}(1000, 0, 0, 1000)$ and $R_i = R_i = 1$. Pay attention to the initial condition of (14b). The system model is used to predict the future of the controller that is initialized by the real measuring system state. In this equation, assume that the range of predictive control and the range of predicted states are the same. Assume that the $x_i$ state variables and $\omega_i$ disturbances can be measured or estimated directly by the controller $i$. Distribution model for two-point power system The prediction controller can be designed by the following algorithm.

For the $i$-th controller, the DMPC algorithm is described as follows:

Step1 Communication: Send out its previous predictions $\overline{x}_i(t; x_i(t), t)$, $\tau \in [t, t + T_p]$ to other controllers and also receive information $\overline{x}_j(t; x_j(t), t)$, $\tau \in [t, t + T_p]$ from other controllers;

Step2 Initialization: At sampling time $t_i$, given measured $x_i(t_i)$ and $\omega_i(t_i)$, set $\overline{x}_i(t_i) = x_i(t_i)$ and $\overline{u}_i(t_i) = \omega_i(t_i)$;

Step3 Optimization: Solve the optimal control problem (14);

Step4 Assignment: If the optimal control problem (14) is feasible, $u_i(t_k) = \overline{u}_i(t_k)$, otherwise, $u_i(t_k) = \overline{u}_i(t_{k-1});$

Step5 Prediction: Predict the future states $\overline{x}_i(t; x_i(t_k), t_k), \tau \in [t_{k+1}, t_k + T_p]$;

Step6 Implementation: Application control $u_i(t_k)$, set $k = k + 1$ and return Step1 at the next sample time;
4. Simulation results
In this section, we study the system's response to changes in step load. The simulation of DMPC is performed at a sampling time of $T = 2 \text{ s}$ and a prediction range of $T_p = 15 \text{ s}$.

Response to step load change: in this case, the proposed performance of DMPC with respect to the step load disturbance is studied. To simulate system disturbances, Zone 1 load increased 20% and Zone 2 load increased 15%. Evaluate the load disturbance rejection performance of DMPC formulations and compare them with PI performance.

| Parameter          | Description                             | Value  |
|--------------------|-----------------------------------------|--------|
| $K_{P_1}$          | Power system gain                       | 120HZ/P.u.MW |
| $T_{P_1}$          | Power system time constant              | 20s    |
| $T_{ri}$           | Reheat turbine time constant            | 10s    |
| $T_{Gi}$           | Thermal governor time constant          | 0.1s   |
| $T_{Ti}$           | Turbine time constant                   | 0.3s   |
| $K_{Bi}$           | Frequency bias factor                   | 0.425P.u.MW/HZ |
| $R_i$              | Speed drop due to governor action       | 2.5HZ/P.u.MW |
| $T_{12}$           | Interconnection gain between control areas | 0.545P.u.MW |

The frequency deviation response curve of the first and second control areas are shown in Fig.4. As shown in these figures, the PI controller provides zero-frequency deviation. In addition, it provides Area 1 and Area 2 with 32 seconds and 35 seconds of settling time. The results show that the MPC controller is higher than the PI controller. DMPC provides satisfactory performance, respectively, 22 seconds and 26 seconds of the corresponding resolution time. Compared with the traditional PI controller, the establishment time and efficiency of the closed-loop system are obviously improved.
The area control error response curve of the first and second control areas are illustrated in Fig.5. As shown in these figures, the PI controller zeroes the ACE deviation. In addition, for area-1, the ACE stabilization time is 34 s. And for area-2, the ACE stabilization time is not completely stabilized at 35 s. The results show that the MPC controller is better than the PI controller. DMPC performance is satisfactory, the ACE stability times are 25 s and 27 s. Compared with the traditional PI controller, the setup time is shortened, and the closed-loop system performance is greatly improved.

The tie-line switching power deviation response curve of the first and second control areas are illustrated in Fig.6. As demonstrated in this figure, the PI controller brings frequency deviations to zero. Moreover, it offers tie-line switching power deviation settling time of 35 s. The DMPC offers satisfactory performance and provide frequency settling time of 20 s, respectively.

As shown in the results, all controllers change the generated power to match the load fluctuations. However, DMPC operates more efficiently than PI controller. These figures show that MPC based controllers are faster than PI controllers and rapidly lower ACE and frequency oscillations. Since DMPC considers parameter uncertainty, it gives satisfactory results than PI.

5. Conclusion
In this paper, a new control construct based on DMPC is proposed for AGC interconnected power system. For large systems with state and input constraints, we establish the LFC problem of multi-domain power systems as a noise cancellation problem, representing the need for transmitter and generator speed. Enter the controller. The DMPC algorithm is proposed for this control, where connected electrical systems are divided into subsystems, every system of that is an independent MPC
controller. The MPC of this subsystem exchanges measurements and coordinates. Based on the two connected electrical systems, the controller design predicts the diffusion model to be discussed. Results confirm the benefits of designing a DMPC controller that achieves comparable performance to PI while maintaining generator speed and load reference set point within limits. Moreover, the AGC system under the new controller can significantly reduce the overshoot of the grid frequency offset, ACE and tie line switching power variation, significantly shorten the regulation time and adjustment of the response speed. And overshoot characteristics have also been significantly improved. The AGC system with DMPC control has better dynamic response than the traditional AGC system with PI control.

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