Model Predictive Load Frequency Control of two-area Interconnected Time Delay Power System with TCSC

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Abstract. In order to reduce the influence of non-linear constraint and time delay on load frequency control of interconnected power system, this paper, based on Model Predictive Control (MPC), designed a load frequency control scheme for two-area interconnected power system with TCSC device. First, considering the Generation Rate Constraint (GRC) and time delay, this paper builds the dynamics model of two-area interconnected power system with Thyristor Controlled Series Compensation device (TCSC). Then the whole system is decomposed into two subsystems. And each subsystem has its own local area MPC controller. Second, collaborative control is implemented by integrating the control information (measurement value, predictive value, etc.) of subsystems’ MPC controllers into the local control goal. In the end, under consideration of physical constraints, the Matlab simulation is conducted. The calculation results showed that the MPC strategy has better dynamic performance and robustness compared to the traditional PI control.

1. Introduction
Load frequency control (LFC) is one of the most important measures to ensure the power quality and maintain the system frequency stability of power system. Modern power grid now has evolved into multiple-control-area interconnected power system. With the increasing information exchange among control areas, open network communication will certainly replace the traditional private cable communication. The adjustment of communication method will amplify the effect of communication delay on the power system control. Data communication would degrade the control performance of LFC, and even may lead to system instability [1]. Hence, the controller design considering the influence of time delay is a crucial problem in power system control.

One obvious advantage of the classical PI controller is its simple structure, but it uses continuous experimental method to adjust the parameters. And with the scale expansion of power system, the influence of nonlinear conditions (time delay, GRC, dead band, et al.) on the PI control will be magnified. So it is difficult for PI control to achieve satisfactory control performance in such circumstance[2]. [3] used discrete-time sliding mode control theory to design load frequency controller considering time delay. But this controller requires specified system model and it is not appropriate to promote in large power grids. In [4], when system parameters changed, it used variable structure controller to ensure the system’s dynamic characteristics nearly unaffected. But, when considering the generation rate constraint and dead band, this method often can’t make the system converge. [5] used an adaptive fuzzy control strategy to optimize PI control. Despite it achieved satisfactory performance,
the algorithm is too complex and requires online system model identification. Those drawbacks mentioned above make it hard to implement in actual system.

Model predictive control is a system-model-based control algorithm, which will execute optimization process during every single sampling interval and calculate the optimal control action [6]. MPC has following significant features: 1. It uses model prediction, hence the MPC can adopt a variety of prediction models, which makes the MPC has strong adaptability for various control objects; 2. Rolling optimization will be carried out during MPC sampling process, and this rolling optimization, which is built on the basis of actual feedback information, is repeated on-line. Rolling optimization could make MPC effectively handle the uncertainties caused by time delay, parameter deviation, et al. Compared to traditional PI control, which only relies on first-order model to optimize, the MPC has better robustness; 3. MPC can directly reflect and deal with the performance indexes and hard constraints (such as GRC and governor dead band), which makes the MPC controller more suitable to control requirements of actual power system.

Considering the time delay and physical hard constraint, this paper proposed a two-area MPC cooperative control scheme to improve the control performance of two-area interconnected power system. TCSC device was also added in the tie-line to reduce the low frequency oscillation during the system’s dynamic process. The Matlab simulation results confirmed that in comparison to traditional PI control the proposed MPC strategy has faster response time and better robustness.

2. Dynamic model of interconnected power system considering time delay

Based on the classical two-area interconnected power system Automatic Generation Control (AGC) model [2], this paper designed a two-area interconnected power system AGC model containing TCSC and fixed communication delay. The model was showed in Figure 1. Fixed communication delay was added both in the MPC controllers’ upstream and downstream channel, time delay coefficient was set to 0.391. Time delay MPC controllers of different areas were designed based on this AGC model.

As can be seen from Figure 1, supposing any control area \( i \in \Pi_M \), interconnected with another control area \( j (i \neq j) \) through tie-line. A simplified model for any area \( i \) has integrated an aggregated generator unit [6]. The overall generator-load dynamic relationship between incremental generator power \( \Delta P_{\text{mech},i} \), load increment \( \Delta P_{L_i} \) and system frequency deviation \( \Delta f_i \) can be expressed as [7]:

\[
\Delta f_i = \frac{1}{2\pi} \left( \frac{1}{M_{i}^{a}} \Delta P_{\text{mech},i} - \frac{1}{M_{i}^{a}} \Delta P_{L_i} - \frac{1}{M_{i}^{a}} D_i \Delta \omega_i - \frac{1}{M_{i}^{a}} \Delta P_{\text{th},i} \right) \tag{1a}
\]

\[
\Delta \omega_i = 2\pi \Delta f_i, M_{i}^{a} = \frac{T_{pi}}{2\pi} \tag{1b}
\]

In the equations, above, \( D_i \) represents load frequency adjustment coefficient of area \( i \); \( T_{pi} \) represents generator unit time constant of area \( i \).

The dynamic of the turbine can be expressed as
\[ \Delta P_{\text{mech},i} = \frac{1}{T_u} \Delta P_{\text{mech},i} - \frac{1}{T_u} \Delta P_{\text{mech},i} \]  
(2)

\( \Delta P_{ri} \) represents steam valve position deviation of area \( i \); \( T_u \) represents turbine time constant of area \( i \).

The dynamic of the governor can be expressed as
\[ \Delta \dot{P}_{vi} = \frac{1}{T_{Gi,ref}} \Delta P_{\text{ref},i} - \frac{T_u}{R^2 T_{Gi,ref}} \Delta \omega_i - \frac{1}{T_{Gi,ref}} \Delta P_{ri} \]  
(3)

\( T_{Gi,ref} \) represents governor time constant of area \( i \); \( \Delta P_{\text{ref},i} \) represents deviation of load reference set point of area \( i \); \( R^2 \) represents load damping coefficient of area \( i \).

The tie-line power flow between area \( i \) and \( j \) can be described as
\[ \Delta P_{tie,ij} = \Delta P_{tie,ij} + \Delta P_{tie,j} \]  
(4a)

\[ \Delta P_{tie,ij} = \Delta P_{tie,ij} \]  
(4b)

\( T_{tie,ij} \) represents the tie-line stiffness coefficient.

The total tie-line power flow between area \( i \) and other areas could be represented as \( \Delta P_{tie,i} \) :
\[ \Delta P_{tie,i} = \sum_{j=1}^{M} \Delta P_{tie,ij} = \sum_{j=1}^{M} \Delta T_{ij} \Delta \omega_j - \sum_{j=1}^{M} \Delta T_{ij} \Delta \omega_j \]  
(5)

This paper used Tie-line Bias Control (TBC) to control Area Control Error (ACE). The area control error \( ACE_i \) for area \( i \) can be expressed as the aggregation of angular velocity deviation \( \Delta \omega_i \) multiplied by a bias factor \( \beta_i \) and add a tie-line power exchange \( \Delta P_{tie,i} \) :
\[ ACE_i = \beta_i \Delta \omega_i + \Delta P_{tie,i} \]  
(6)

The state space model of control area \( i \) of multi-area interconnected time delay power system can be expressed as follow:
\[
\begin{bmatrix}
\dot{x}_i(t) = Ax_i(t) + Bu_i(t - \tau_i) + Dv_i(t) \\
y_i(t) = Cx_i(t)
\end{bmatrix}
\]  
(7)

\[ \begin{bmatrix}
\Delta f_i \\
\Delta \omega_i \\
\Delta P_{tie,i}
\end{bmatrix}^T = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]  

\[ \begin{bmatrix}
\frac{D}{T_p} & \frac{1}{T_p} & \frac{-1}{T_p} \\
0 & \frac{1}{T_u} & \frac{1}{T_u} \\
\frac{1}{R^2 T_{Gi,ref}} & \frac{-1}{T_{Gi,ref}} & 0 \\
\frac{2\pi}{T_j} \sum_{j=1}^{M} T_j & 0 & 0
\end{bmatrix}
\]

\[ A = \begin{bmatrix}
\frac{D}{T_p} & \frac{1}{T_p} & \frac{-1}{T_p} \\
0 & \frac{1}{T_u} & \frac{1}{T_u} \\
\frac{1}{R^2 T_{Gi,ref}} & \frac{-1}{T_{Gi,ref}} & 0 \\
\frac{2\pi}{T_j} \sum_{j=1}^{M} T_j & 0 & 0
\end{bmatrix}
\]

\[ B = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

\[ C = \begin{bmatrix}
0 & 0 & 1
\end{bmatrix}
\]  

\[ D = \begin{bmatrix}
0 & 0 & 0
\end{bmatrix}
\]
\[ ACE_i = \beta \Delta \omega_i + \Delta P_{me,i} \]

In the above equations: \( \Delta f \) represents frequency deviation; \( T_{pi} \) represents the time constant of generator unit; \( D_i \) represents load frequency adjustment coefficient; \( T_n \) represents damping; \( T_{Gi} \) represents governor time constant; \( R_i' \) represents load damping coefficient; \( B_i \) represents the frequency deviation coefficient; \( T_{ij} \) represents tie-line stiffness coefficient; \( \Delta P_{mech} \) represents mechanical power deviation; \( \Delta P \) represents the deviation of load reference set point; \( \Delta P_{mc,i} \) represents the tie-line power flow deviation; \( ACE_i \) is the area control error signal of area \( i \).

In a multi-area power system, the power generation change could not exceed the scheduled maximum rate. For thermal power generator units, the generation rate constraint should be considered as 10%/min (\( \cong 0.0017 \) p.u./s) [8]. In order to meet the generation rate constraints, the generator output power deviation rate should be restricted as [9]:

\[ |\Delta P_{mech}| = \left| \frac{\Delta P_{1c} - \Delta P_{mech}}{T_{CHi}} \right| \leq 0.0017 \text{ p.u.} / \text{s} \]  

The above equation can be used as state constraints. In addition, the load reference setpoint should be constrained as [6]:

\[ |\Delta P_{ref}| \leq 0.3 \]  

Equation (9) could be considered as control input constraints. Both (9) and (10) are time-domain hard constraints.

3. Control model of TCSC

In this paper TCSC device was installed on the tie-line between these two control areas to manipulate the effective impedance and control the power flow. The two-area interconnected power system parameters can be expressed as follow:

\[ \Delta \dot{\delta}_{12} = (\Delta \omega_1 - \Delta \omega_2) \]  

\[ \Delta \delta_1 = \frac{1}{M_1} \Delta P_{mech} - \frac{1}{M_1} \Delta P_{1} - \frac{1}{M_1} D_1 \Delta \omega_1 - \frac{1}{M_1} T_{12} \Delta \delta_{12} + \frac{1}{M_1} K_{12} \Delta X_{12} \]  

\[ \Delta \delta_2 = \frac{1}{M_2} \Delta P_{mech} - \frac{1}{M_2} \Delta P_{2} - \frac{1}{M_2} D_2 \Delta \omega_2 + \frac{1}{M_2} T_{12} \Delta \delta_{12} - \frac{1}{M_2} K_{12} \Delta X_{12} \]  

\[ \Delta X_{12} = -\Delta P_{me,12} = T_{12} \Delta \delta_{12} - K_{12} \Delta X_{12} \]  

\( \Delta X_{12} \) is the effective impedance deviation, which can be controlled by the TCSC device installed on the tie-line. It is noteworthy that the equations (9)~(10) are equal to system model represented by equations (1)~(5) when the value of \( \Delta X_{12} \) is zero. We could control the local MPC controllers from area 1 and area 2 respectively to manipulate the \( \Delta P_{ref} \) and \( \Delta P_{mech} \) to force \( \Delta \omega_1 \) and \( \Delta \omega_2 \) close to zero.

At the same time, using the TCSC device to control \( \Delta X_{12} \) and make the phase angle difference \( \Delta \delta_{12} = \Delta \delta_1 - \Delta \delta_2 \) become zero.

The principle of choosing TCSC to control the \( \Delta X_{12} \) is using thyristor to control the capacitors which are series in the tie-line. It could regulate the impedance of tie-line in a wide range, conduct continuous smooth adjustment rapidly, improve cable transmission capacity and reduce the area oscillation.

Figure 2 demonstrated the model of TCSC controller. The model is mainly composed by the host controller and additional control. The host controller is generally expressed as first-order inertial unit, and its first-order dynamic model is as follow:
\[
T_{\text{TCSC}} = \frac{1}{T}(-X_{\text{TCSC}} + -X_{\text{TCSCO}} + \Delta X_c)
\]

\(X_{\text{TCSC}}\) is the equivalent output reactance of TCSC, \(X_{\text{TCSCO}}\) is reference impedance, \(\Delta X_c\) is deviation signal, \(T\) is the time constant of dynamic unit. While these parameters are fixed, which depend on the physical structure of TCSC. Output signal \(\Delta X_c\) is deviation signal, which is composed by \(X_{\text{TCSCO}}\) and \(\Delta X_c\). \(\frac{K_c}{1+T_c s}\) is the response delay, \(K_c\) is the first-order inertial gain, \(T_c\) is time constant.

Additional control is used to accomplish specific control requirements, which is the key to the TCSC. The purpose of installing TCSC device is to suppress the system oscillation. For this reason, choosing the damping control as the additional control unit is the best option.

Figure 2. TCSC controller model

Figure 3. Damping control unit for system stable

From equation (11) we can know that the purpose of installing TCSC device in the AGC system is to reduce \(\Delta X_{12}\) thus reducing the tie-line exchange power \(\Delta P_{12}\) to decrease system oscillation. Damping control unit was chosen in this paper as shown in Figure 3.

\(\frac{K_p s}{1 + s T_w}\) is the DC blocking unit; \(T_w\) is filter time constant, which is usually between 10–20 seconds; \((1 + s T_2)^{1/3} / (1 + s T_1)^{1/3}\) is the lead-lag compensation unit of damping controller. In this transfer function, only magnificent factor \(K_p\), advanced network parameter \(T_2\) and lag network parameter \(T_1\) required designing.

4. Simulation and analysis

According to the LFC dynamic model of time delay AGC system mentioned in the chapter 2, the Matlab/Simulink simulation software was used to build the model of two-area time delay power system with TCSC. In this simulation, choosing the local balance criterion of fluctuating power in TBC control model as the control target. The sampling period is 0.1s, prediction horizon is 13s, the control domain is 2s and the delay constant of fixed communication delay is 0.391. This chapter would compare the MPC strategy and classical PI control strategy to verify the superiority of the proposed MPC strategy.
A practical two-area power system has the following nominal parameters listed in table 1 [10], units in this table are per-unit value. The GRC for both two areas must be taken into consideration by adding limiters to the turbines. Each control area has its own load frequency MPC controller.

| Table 1. Parameters of two-area interconnected power system model. |
|---------------------------------------------------------------|
| **Area 1** | **Area 2** |
| \(a_1 = 0.39\) | \(a_2 = 0.4\) |
| \(K_{i1} = -0.2805\) | \(K_{i2} = -0.3358\) |
| \(T_{g1} = 10\) | \(T_{g2} = 10\) |
| \(T_{CH1} = 50\) | \(T_{CH2} = 10\) |
| \(B_1 = 0.347\) | \(B_2 = 0.3214\) |
| \(M_{1}'' = 3.5\) | \(M_{2}'' = 4.0\) |
| \(T_{p1} = 0.1667\) | \(T_{p2} = 0.2017\) |
| \(T_{i1} = 1\) | \(T_{i2} = 0.4\) |
| \(D_1 = 0.015\) | \(D_2 = 0.016\) |
| \(R_1 = 3\) | \(R_2 = 2.73\) |
| \(T_{e1} = 0.1\) | \(T_{e2} = 0.4\) |
| \(T_{g1} = 10\) | \(T_{g2} = 0.5042\) |
| \(K_{i1} = 0.03\) | \(K_{i2} = 10\) |
| \(T_{p} = 10\) | \(T_{u} = 10\) |

4.1. Simulation of load disturbance

Using the parameters given in the Table 1, 0.01pu load disturbance was generated in Area 1 and 0.02pu load disturbance was generated in Area 2. Both load disturbances were generated at \(t = 30s\). Using PI algorithm and MPC algorithm to conduct simulation respectively to compare their control performance. The simulation results of frequency deviation and tie-line power deviation were presented in Figure 4.1~Figure 4.3.

![Figure 4.1](image1.png)  ![Figure 4.2](image2.png)  ![Figure 4.3](image3.png)

**Figure 4.1.** Response to step load disturbance in area 1: MPC (solid line), PI (dashed line)

**Figure 4.2.** Response to step load disturbance in area 2: MPC (solid line), PI (dashed line)

**Figure 4.3.** Tie-line power response to step load disturbance: MPC (solid line), PI (dashed line)

Figure 4.1~Figure 4.3 showed that when using MPC, for both areas, the dynamic response time is about 15s, maximum frequency deviation is about 0.075Hz; Taking PI control into comparison, the dynamic response time is 40s, and the maximum frequency deviation is about 0.125Hz. It can be concluded that the MPC controller this paper designed has lower oscillation, the maximum oscillation amplitude is reduced by 40%; the response time is shortened by 62%. The control performance has significant improvement after adopting the MPC strategy.

4.2. Simulation of time delay constant change
The time delay constant of those simulations carried out above is 0.391. In this section, delay constant would be set to 3 different values to test the effect of time delay on the performance of MPC strategy. The simulation in this section is based on the simulation of Section 4.1, the only difference is the value of time delay constant. Set three different time delay constants are respectively DT1=0.391, DT2=0.618 and DT3=0.724. The simulation results are presented in the Figure 5.

![Figure 5](image_url)

Figure 5. The control performance of MPC under different time delay

Figure 5 demonstrated the result that with the increase of time constant, the maximum value of frequency deviation will be increased and the dynamic response time will be increased gradually during the control process. But the control performance of this MPC strategy is still acceptable under the power system’s requirement.

5. Conclusion
This paper transformed the multi-area interconnected power system LFC problems into the anti-interference problems of large power systems with state input constraints. Considering the impact of valve position limit, GRC and time delay, two-area interconnected power system model was built. The local area MPC controller was specially designed for each area. Meanwhile, using classical PI control strategy in this model to compare the control performance of these two different control strategy. Simulation results revealed that under the consideration of non-linear constraints (GRC, communication delay, et al), both control methods can make the system response to stable status. Compared to the classical PI control strategy, the MPC strategy this paper proposed has better dynamic performance and anti-interference. The dynamic response speed of MPC is 40% faster than PI. When comes to the system parameters shift, the MPC strategy still can guarantee an acceptable control performance, which proved that the proposed strategy has better robustness and adaptability.

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