On Design of a Robust Load Frequency Controller for Interconnected Power Systems

Lili Dong, Member, IEEE, Yao Zhang

Abstract — A novel design of a robust decentralized load frequency controller (LFC) is proposed for an inter-connected three-area power system, for the purpose of regulating area control error (ACE) in the presence of uncertainties in system dynamics and external disturbances. The design is based on the concept of active disturbance rejection control (ADRC). Estimating and mitigating the total effect of various uncertainties in real time, ADRC is particularly effective against a wide range of parameter variations, model uncertainties, and large disturbances. Furthermore, with only two tuning parameters, the controller provides a simple, easy-to-use solution to complex engineering problems in practice. Here, an ADRC-based LFC solution is developed for the power systems with turbines of various types, such as non-reheat, reheat, and hydraulic. The simulation results verified the effectiveness of the ADRC.

Index Terms — LFC, ADRC, ACE, inter-connected power system, stability, robustness.

I. INTRODUCTION

A large-scale power system is composed of multiple control areas that are connected with each other through tie lines [1]. As active power load changes, the frequencies of the areas and tie-line power exchange will deviate from their scheduled values accordingly. As a result, the performance of the power system could be greatly degraded [2]. The local governor of the power system can adjust generator output to partially compensate power load change. However, with this type of governor, when the system load increases, the system frequency decreases and vice versa [3]. Therefore a supplementary controller is essential for the power system to maintain the system frequency at 60 Hz (a scheduled frequency in North America) no matter what the load is. This type of supplementary controller is called automatic generation control (AGC), or more specifically, load frequency control (LFC). For stable operation of power systems, both constant frequency and constant tie-line power exchange should be provided [4]. Therefore an area control error (ACE), which is defined as a linear combination of power net-interchange and frequency deviations [1], is generally taken as the controlled output of LFC. As the ACE is driven to zero by the LFC, both frequency and tie-line power errors will be forced to zeros [1].

In the past six decades, there has been a significant amount of research progress made on LFCs. During the early stage of research, the LFC was based on centralized control strategy [5, 6], which is mainly for “the need to exchange information from control areas spread over distantly connected geographical territories along with their increased computational and storage complexities” [3]. In order to overcome the limitation, decentralized LFC has recently been developed, by which each area executes its control based on locally available state variables [7]. Among various types of decentralized LFCs, the most widely employed in power industry is PID control [8-12]. The PI controller tuned through genetic algorithm linear matrix inequalities (GALMI) [11] becomes increasingly popular in recent years. PID controller is simple to implement but usually gives long settling time (about 10 to 20 seconds) and produces large frequency deviation [13]. With recent progress in control technologies, advanced controllers have come into adoption for load frequency controls. With the change of power flow conditions, parameters in a power system model fluctuate almost every minute [14]. To solve this problem, both $H_{\infty}$ [15, 16] and adaptive controllers [17, 18] are applied to the power system. The controllers not only identify parameter uncertainties but also regulate the ACE. In addition, a μ-synthesis control technique was introduced in [19] to compensate modeling uncertainties. Fuzzy logic based LFC is presented in [20, 21]. Such a controller is often combined with PI or PID controllers to optimally adjust PID gains. Most of the existing LFCs apply to the control areas comprising of thermal turbines, only a few of them [15] treat both thermal and hydraulic turbines.

This paper presents a novel solution in the form of a decentralized robust LFC for a three-area interconnected power system. Its performance is evaluated in the presence of parameter uncertainties and large power load changes. The power system studied here contains reheat, non-reheat, and hydraulic turbine units, which are distributed in the three areas respectively. This solution is based on active disturbance rejection control (ADRC), an emerging control technology that estimate and mitigate uncertainties, internal and external, in real time, resulting in a controller that does not require accurate model information and is inherently robust against structural uncertainties commonly seen in power systems. Particularly, compared to other complex advanced controllers [15-21], the ADRC only has two tuning parameters, making it simple to implement in practice. So far the ADRC has been successfully employed in MEMS, power converter, and web tension [22-26]. Here in the paper, it is the first time that the ADRC is
II. DYNAMIC MODEL

In this section, the dynamic model of a three-area interconnected power system will be developed. As shown in Fig.1, each area of the power system consists of one generator, one governor, and one turbine unit. It includes three inputs, which are the controller input $U(s)$ (also denoted as $u$), load disturbance $\Delta P_L(s)$, and tie-line power error $\Delta P_{tie}(s)$, one ACE output $Y(s)$, and one generator output $\Delta f$. In Fig.1, $\Delta P_v$ is denoted as valve position change, $\Delta P_e$ electrical power, and $\Delta P_m$ mechanical power. The ACE alone is a measurable output. For each area, it is defined by (1), where $B$ is area frequency response characteristic [1].

$$ACE = \Delta P_m + BAf$$

We use transfer function (TF) to model the one-area generator unit. Let the transfer function from $\Delta P_e(s)$ to $\Delta P_m(s)$ be $G_E(s) = \text{Num}_E(s) / \text{Den}_E(s)$, where $\text{Num}_E(s)$ and $\text{Den}_E(s)$ are the numerator and denominator of the $G_E(s)$. The representations of $\text{Num}_E(s)$ and $\text{Den}_E(s)$ vary from different generating units. For the non-reheat turbine unit, $G_E(s)$ is given by

$$G_E(s) = \frac{\text{Num}_E(s)}{\text{Den}_E(s)} = \frac{1}{(T_1 s + 1)(T_2 s + 1)} \quad (2)$$

For reheat turbine unit, we have

$$G_E(s) = \frac{\text{Num}_E(s)}{\text{Den}_E(s)} = \frac{F_0 T_1 s + 1}{(T_1 s + 1)(T_2 s + 1)(T_3 s + 1)} \quad (3)$$

modified and applied to the power system with three different turbine units. Some preliminary results of the research were published in [27], where the performance of the ADRC was compared with a LMI tuned PID controller [12] for the power system with only non-reheat turbine units.

This paper is organized as follows. The dynamic modeling of the power system is given in Section II. The ADRC design is introduced in Section III. Simulation results are shown in Section IV. The concluding remarks are made in Section V.
For hydraulic turbine unit, we have
\[ G_{ET}(s) = \frac{\text{Num}_{ET}(s)}{\text{Den}_{ET}(s)} = \frac{(T_s+1)(-T_s+1)}{(T_s+1)[T_s(R_s/R)+s+1](T_s/2)+1} \]
(4)

Define the transfer function of the generator as
\[ G_{gen}(s) = \frac{1}{\text{Den}_{gen}(s)} - \frac{1}{Ms + D} \]
(5)

The parameters in (2)-(5) are defined in Table III of Appendix.

From Fig.1, the output \( Y(s) \) for each area can be represented by
\[ Y(s) = G_{f}(s)U(s) + G_{i}(s)\Delta P_{f}(s) + G_{ia}(s)\Delta P_{ia}(s) \]
where \( G_{f}(s) \), \( G_{i}(s) \), and \( G_{ia}(s) \) are the TFs between the three inputs and ACE output respectively, and they are expressed as
\[ G_{fr}(s) = \frac{\text{Num}_{fr}(s)}{\text{Den}_{fr}(s) + \text{Den}_{ia}(s)} \]
\[ G_{ir}(s) = \frac{-\text{Num}_{ir}(s)}{\text{Den}_{ir}(s) + \text{Den}_{ia}(s)} \]
\[ G_{ia}(s) = \frac{\text{Num}_{ia}(s) - \text{Den}_{ia}(s)}{\text{Den}_{ia}(s) + \text{Den}_{ia}(s)} \]
(6)

The ADRC controlled interconnected power system is shown in Fig.2. Under a decentralized control strategy, the ADRC controller is placed in each area acting as local LFC. Three decentralized areas are connected to each other through tie lines. Non-reheat, reheat and hydraulic turbine units are distributed in the three areas orderly. The parameter values of the system are obtained from [1, 14] and are listed in Table IV of Appendix. Substituting the parameter values into the \( G_{f}(s) \) between the controller input and ACE output, we will have
\[ G_{fr}(s) = \frac{1.05}{0.015s^2 + 0.2015s^2 + 0.52s + 1.05} \]
\[ G_{ir}(s) = \frac{2.205s + 1.05}{0.21s^2 + 1.801s + 3.928s^2 + 9.275s + 1.05} \]
\[ G_{ia}(s) = \frac{-5.25s^2 + 4.2s + 1.05}{1.14s^2 + 8.2s^2 + 7.945s^2 + 6.235s + 1.05} \]
(10)
(11)
(12)

where \( G_{fr}(s) \) denotes the TF for area 1, \( G_{ir}(s) \) the TF for area 2, and \( G_{ia}(s) \) the TF for area 3. From (12), we can see that the transfer function of hydraulic unit has a positive zero, which can bring instability to the system. This problem can be solved by fine tuning the controller parameters. The system with hydraulic turbine unit will be stabilized by the controller too. The controller design and parameter tuning are introduced in the following section.

III. LFC DESIGN

We choose ADRC as a decentralized LFC for the interconnected power system. The basic idea of the time-domain ADRC is introduced in [24]. In this section, the TF expression of the ADRC will be developed for a general \( n \)-th order plant.

A. Transfer Function Derivation of \( n \)-th Order Plant

A plant with disturbance can be represented by
\[ Y(s) = G(s)U(s) + W(s) \]
(13)

where \( U(s) \) and \( Y(s) \) are the input and output respectively, \( G(s) \) is the transfer function between \( U(s) \) and \( Y(s) \), and \( W(s) \) is the generalized disturbance including unknown internal dynamics and external disturbances [24]. In (13), the TF of the general physical plant \( G(s) \) can be described as
\[ G(s) = \frac{b_n s^n + b_{n-1} s^{n-1} + \cdots + b_1 s + b_0}{a_m s^m + a_{m-1} s^{m-1} + \cdots + a_1 s + a_0} \]
(14)

where \( a_i \) and \( b_i \) \((i = 1, \ldots, n, j = 1, \ldots, m)\) are the coefficients of \( G(s) \). Making both sides of (13) divided by \( G(s) \), we will have
\[ \frac{1}{G(s)}Y(s) = U(s) + W'(s) \]
(15)

where \( W'(s) = W(s) / G(s) \). In (15), \( 1 / G(s) \) can be conducted as
\[ 1/G(s) = \frac{a_m s^m + a_{m-1} s^{m-1} + \cdots + a_1 s + a_0}{b_n s^n + b_{n-1} s^{n-1} + \cdots + b_1 s + b_0} \]
(16)

where \( c_i \) \((i = 0, \ldots, n - m)\) are coefficients of the polynomial division result, and the remainder \( G_{off}(s) \) is
\[ G_{off}(s) = \frac{d_0 s^{n-m} + d_{n-m} s^{n-m-1} + \cdots + d_1 s + d_0}{b_n s^n + b_{n-1} s^{n-1} + \cdots + b_1 s + b_0} \]
(17)

In (17), \( d_i \) \((i = 0, \ldots, m - 1)\) are coefficients of the numerator of the remainder. Substituting (16) into (15), we have
\[ \left[ c_{n-m} s^{n-m} + c_{n-m-1} s^{n-m-1} + \cdots + c_0 + G_{off}(s) \right] Y(s) = U(s) + W'(s) \]
(18)

where
\[ c_{n-m} = \frac{a_n}{b_n} \]
(19)

Equation (18) can be rewritten as
\[ c_{n-m} s^{n-m} Y(s) = U(s) - \left[ c_{n-m-1} s^{n-m-1} + \cdots + c_0 + G_{off}(s) \right] Y(s) + W'(s) \]
(20)

Making both sides of (20) divided by \( c_{n-m} \), we will have
\[ s^{n-m} Y(s) = b U(s) + D(s) \]
(21)

where \( b = 1 / c_{n-m} \), and a modified generalized disturbance is
\[ D(s) = \frac{-1}{c_{n-m}} \left[ c_{n-m-1} s^{n-m-1} + \cdots + c_0 + G_{off}(s) \right] Y(s) + \frac{1}{c_{n-m}} W'(s) \]
(22)

We will take (21) as the system model for controller design.

B. Design of Extended State Observer

From [24], the effectiveness of the ADRC is dependent on the accurate estimation of the \( D(s) \). Consequently an Extended State Observer (ESO) is developed to estimate the disturbance in real time. This can be achieved by augmenting the state variables of the system (21) to include \( D(s) \). In order to construct the ESO, the system model (21) is rewritten as
\[ sX(s) = AX(s) + BU(s) + ES(s) \]
\[ Y(s) = CX(s) \]
(23)

In (23),
\[
X(s) = \begin{bmatrix}
X_1(s) \\
X_2(s) \\
\vdots \\
X_{n-1}(s)
\end{bmatrix}
\]

\[
A = \begin{bmatrix}
0 & 1 & 0 & \cdots & 0 \\
0 & 1 & 0 & \cdots & 0 \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
0 & 0 & 0 & \cdots & 1
\end{bmatrix},
B = \begin{bmatrix}
0 \\
\vdots \\
0 \\
1
\end{bmatrix},
E = \begin{bmatrix}
0 \\
\vdots \\
0 \\
1
\end{bmatrix}
\]

We assume that \( D(s) \) has the local Lipschitz continuity and \( SD(S) \) is bounded within domains of interests. Then the ESO is

\[
sZ(s) = AZ(s) + BU(s) + L(Y(s) - \hat{Y}(s))
\]

\[
\hat{Y}(s) = CZ(s)
\]

where \( Z(s) = \begin{bmatrix} Z_1(s) \\ Z_2(s) \\ \vdots \\ Z_{n-1}(s) \end{bmatrix} \) and \( L = \begin{bmatrix} \beta_1 & \beta_2 & \cdots & \beta_{n-m} \end{bmatrix} \). In order to locate all the eigenvalues of the ESO to \(-\omega_o\), the observer gains are chosen as

\[
\beta_i = \left( \frac{n-m}{i} \right) \omega_o, \quad i = 1, \ldots, n-m.
\]

Therefore, we can change the observer gains through tuning the unique parameter \( \omega_o \), which is also the bandwidth of the observer. With a well-tuned ESO, \( Z(s) \) will be able to estimate the value of \( X_i(s) \) closely \((i = 1, \ldots, n-m)\). Then we have

\[
Z_{\omega-o}(s) = \hat{D}(s) = D(s)
\]

where \( \hat{D}(s) \) represents estimated \( D(s) \).

C. Design of ADRC

If the control input is designed as

\[
U(s) = (U_i(s) - Z_{\omega-o}(s))/b,
\]

the original system (21) will be reduced to a pure integral plant. This process can be demonstrated by (28), where \( U_i(s) \) is the control law for regulating the ACE output \( Y(s) \).

\[
s^{-\omega-o}Y(s) = b(U_i(s) - Z_{\omega-o}(s))/b + D(s)
\]

\[
U_i(s) - \hat{D}(s) + D(s) \approx U_i(s)
\]

Our control goal of the LFC is to regulate the ACE to zero. A traditional PD controller can reach this goal. So the control law \( U_i(s) \) is chosen as (29), where \( R(s) \) is a reference input.

\[
U_i(s) = k_i(R(s) - Z_i(s)) - k_2Z_2(s) - \cdots - k_{n-1}Z_{n-1}(s)
\]

To further simplify the tuning process, all the closed-loop poles of the PD controller are set to \(-\omega_c\). Then the controller gains in (29) have to be selected as

\[
k_i = \left( \frac{n-m-1}{n-m-i} \right) \omega_c, \quad i = 1, \ldots, n-m-1.
\]

IV. SIMULATION RESULTS

According to the discussions in Section III, the ADRC for area 1 can be designed and represented by the following equations.

\[
sZ(s) = (A - LC)Z(s) + BU(s) + LY(s)
\]

\[
U_o(s) = k_i(R(s) - Z_i(s)) - k_2Z_2(s) - k_3Z_3(s)
\]

(32)

\[
U_o(s) = \frac{U_i(s) - Z_e(s)}{b}
\]

(33)

where

\[
\begin{bmatrix}
Z_e(s) \\
Z_e(s) \\
Z_e(s)
\end{bmatrix} = \begin{bmatrix}
0 & 1 & 0 \\
0 & 1 & 0 \\
0 & 0 & 0
\end{bmatrix},
B = \begin{bmatrix}
0 \\
\vdots \\
0
\end{bmatrix},
L = \begin{bmatrix}
4\omega_o \\
6\omega_o \\
4\omega_o
\end{bmatrix},
k_i = \omega_c^3
\]

The performance of ADRC is tested for two cases. In these two cases, a 0.1 p.u. (per unit) step load change is applied to the three different areas at \( t = 2, 7, \) and 12 seconds respectively. In different cases, the parameter values of the non-reheat unit in area 1 will have variant values. However, the controller parameter values of the ADRC, as listed in Table II, remain unchanged in the following two cases.

In case 1, the parameters of the non-reheat unit in area 1 are chosen to have nominal values. The effectiveness of ADRC will be tested in this case by simulating the closed-loop control system in Fig. 9. In our simulation results, area 1 is denoted as the area with non-reheat unit (or non-reheat), area 2 the area with reheat unit (or reheat), and area 3 the area with hydraulic unit (or hydraulic). The system responses for three different areas are shown in Figures 3, 4, and 5. From the three figures, we can see that the ACEs, frequency errors, and tie-line power deviations have been successfully driven to zeros by ADRC in the presence of power load changes. The average settling time \( (T_s) \) in the system responses is around 3 seconds. The \( T_s \) is much shorter than the one in the PID controlled system [9-12]. The responses of area 3 have relatively large overshoot percentages compared to the other two areas. We believe this is because the hydraulic unit is inherently unstable. The instability could cause the big oscillation during the transient period.

In case 2, in order to test the robustness of ADRC, the variations of all of the parameters \((M_i, D_i, T_{ch1}, T_{g1}, R_1, \) and \( T_i)\) of the non-reheat unit in the first area are assumed to be \(-20\%\) and \(20\%\) of their nominal values respectively. However, the controller parameters of ADRC are not changed with the variations of the system parameters. The responses of area 1 are shown in Figures 6, 7 and 8 which illustrate the ACE outputs, frequency errors, and tie-line power errors of area 1 orderly with the variant parameter values for the non-reheat unit. From
the simulation results, we can see that despite such large parameter variations, the system responses do not show notable differences from the results in Figures 3, 4, and 5. Therefore the simulation results demonstrate the robustness of ADRC against system parameter variations. When we change the system parameters for reheat and hydraulic units, the same conclusion is obtained.

V. CONCLUDING REMARKS

This paper proposed an ADRC based decentralized LFC for an interconnected three-area power system. Our control objective is to regulate ACE, frequency errors, and net tie-line power deviations to zeros in the presences of power load changes and system uncertainties. The ADRC is designed for the power system containing both thermal and hydraulic turbines. The simulation results further verified the effectiveness of the ADRC.

In the future, we plan to consider singularities of speed governor such as rate limits on valve position and generation rate constraints. We will employ the ADRC to compensate the singularities. We are also going to construct the power system in Simplorer, a powerful CAD tool in modeling real power systems. The successful implementation of the ADRC on such a Simplorer based power system model will further ensure its feasibility in power industries.
APPENDIX

TABLE III: DEFINITIONS OF PARAMETERS

<table>
<thead>
<tr>
<th>Mi</th>
<th>Area Inertia Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Di</td>
<td>Area load damping constant</td>
</tr>
<tr>
<td>Td</td>
<td>Turbine time constant</td>
</tr>
<tr>
<td>Tl</td>
<td>Governor time constant</td>
</tr>
<tr>
<td>Rl</td>
<td>Speed regulation coefficient</td>
</tr>
<tr>
<td>Fhp</td>
<td>Tie-line synchronizing coefficient</td>
</tr>
<tr>
<td>Trh</td>
<td>Low pressure reheate time</td>
</tr>
<tr>
<td>Ti</td>
<td>Reset time for hydraulic unit</td>
</tr>
<tr>
<td>Tw</td>
<td>Water starting time</td>
</tr>
</tbody>
</table>

Note: The letter i represents the number of an area, and i=1, 2, 3.

TABLE IV: PARAMETER VALUES

<table>
<thead>
<tr>
<th>MI (p.u. sec.)</th>
<th>Non-reheat</th>
<th>Reheat</th>
<th>Hydraulic</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 ± 20%</td>
<td>M2 (p.u. sec.)</td>
<td>10.0</td>
<td>M3 (p.u. sec.)</td>
</tr>
<tr>
<td>D1 (p.u./Hz)</td>
<td>± 20%</td>
<td>D2 (p.u./Hz)</td>
<td>1.0</td>
</tr>
<tr>
<td>Tch1 (sec.)</td>
<td>0.3 ± 20%</td>
<td>Tch2 (sec.)</td>
<td>0.3</td>
</tr>
<tr>
<td>Tg1 (sec.)</td>
<td>0.1 ± 20%</td>
<td>Fhp</td>
<td>0.3</td>
</tr>
<tr>
<td>R1 (Hz/p.u.)</td>
<td>0.03 ± 20%</td>
<td>Trh (sec.)</td>
<td>7.0</td>
</tr>
<tr>
<td>T1 (p.u./rad)</td>
<td>22.6 ± 20%</td>
<td>Tg2 (sec.)</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R2 (Hz/p.u.)</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T2 (p.u./rad)</td>
<td>22.6</td>
</tr>
</tbody>
</table>

REFERENCES


