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# ADRC for Two-Area LFC

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***Abstract*— Load Frequency Control (LFC) is a major problem of power systems which results due to mismatch between real power generation and consumption as the power consumption changes every minute. Consequently the frequency of the power system may not be at rated value resulting in power quality problems. Power system network is very complex and divided into number of areas. A two-area LFC is the basic structure for a multi-area LFC. Here we apply Active Disturbance Rejection Controller (ADRC) to alleviate the problems of LFC. Also we compare its performance with standard PID controller.**

***Keywords*— Load frequency control, two-area power system, area control error, active disturbance rejection controller, extended state observer, PID controller***

## I INTRODUCTION

An interconnected electrical power system needs to work in steady state condition. Under this condition power system bus voltages and frequency are to be maintained at prescribed nominal values. This requires reactive and real power balance in the system. Under reactive power imbalance, voltages of the system deviate from nominal values. This comes under voltage control [1,2] which was studied in [14]. When there is imbalance of real powers, frequency deviates from the rated frequency (50 Hz). Frequency decreases when power generation is less than the load and vice versa. By using different controllers we will study these frequency control problems [1-4].

The frequencies of the interconnected areas and tie-line power exchanges deviate from the scheduled values when active power of load changes. Hence performance of power system could be degraded. Then primary controls, like local governors of the power system, adjust the generator output to compensate the load power changes. This compensation is partial only. Therefore a secondary (supplementary) control is essential for the power system to maintain the system frequency at nominal values even with small load changes. This secondary control is called as load frequency control (LFC) or automatic generation control (AGC). To run the power system in stable operation frequency and tie-line power are maintained constant at prescribed values.

The growth of interconnected power systems increases the importance of LFC to operate the interconnected systems in steady state healthily. Hence objectives of LFC loop are to maintain the rated system frequency in an inter connected system economically and reliably by maintaining frequency deviations to zero, the tie-line power exchange according to schedule and good tracking of load demands even under small and slow load perturbations. To solve this kind of problems we have a number of control strategies like conventional PID and artificial intelligence techniques. Now we are using robust controller like ADRC to solve this type of problems. This new approach applies to nonlinear and time varying systems with single input and single output (SISO) or multiple–input and multiple-output (MIMO) systems.

Active Disturbance Rejection Controller (ADRC) is a novel robust approach [5-14] which was firstly proposed by Jing-Qing Han. It can estimate and mitigate uncertainties internal as well as external in real time. Also it is robust against structural uncertainties which are commonly presented in power systems. For the design of ADRC it requires only two tuning parameters like order of plant and high frequency gain $b_o$ of the system. The ADRC controller has been widely applied in many areas such as aerospace, aviation, electricity, chemical industry and other fields with many merits with simple algorithm, small settling time and little overshoot. The fundamental idea of ADRC is to implement an extended state observer (ESO) that provides an estimate of disturbance (internal plus external) d(t) present, such that it can be used to compensate the impact of $d(t)$. All that remains to be handled by the actual controller will then be a process with approximately integrating behavior which can be easily done by a simple proportional controller.

Using LFC we can maintain the nominal frequency and tie-line powers of a power system. Now we study the LFC problem using ADRC and PID controllers for a two-area power system. Firstly the design of ADRC is briefly introduced for an nth-order minimum phase system represented by transfer function. Proposed ADRC technique is applied to a decentralized LFC for a two area interconnected power system. Also a PID controller is designed for the same system. Both systems are simulated and their performances are compared.

## II LFC OF TWO AREA POWER SYSTEM

Inter connected power system is a very big electric network. Hence it has been divided into different groupings known as “operating areas”. A coherent group is formed by a group of generators that are closely coupled internally and swing in unison. This is known as single area and can be represented by a single equivalent system. Each single area represents power system network under the control of one state (utility). Nowadays electrical power systems can be considered as a number of control areas interconnected by means of high voltage transmission lines or tie-lines.

*Two-Area LFC modeling*

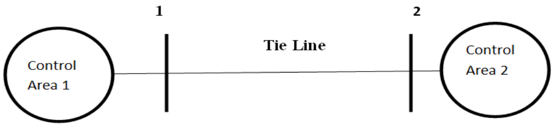


Fig 1 Two Areas with Tie-Line Connection

Consider a two area system represented by an equivalent generating unit interconnected by a lossless tie line with reactance $X_{tie}$. Each area is represented by a voltage source behind an equivalent reactance as shown Fig 1.

During normal operation, the real power transferred over the tie line is given by

$$P_{12} = \frac{E_1 E_2}{X_{12}} sin\delta_{12} \quad (1)$$

where $X_{12} = X_1 + X_{tie} + X_2$, and $\delta_{12} = \delta_1 - \delta_2$ (2)

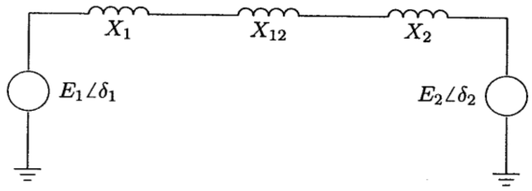


Fig 2 Equivalent network of two area power system

LFC modeling is based on a small perturbation in power system operating condition. The block diagram of two-area power system is shown in Fig 3. Here we employ tie-line bias control to keep frequency at nominal value and maintain tie-line flow at scheduled value. ACE is area control error. Tie-line bias control makes ACE = 0

$$ACE_i = \sum_{j=1;\, j\neq i}^{n} \Delta P_{ij} + K_i\, \Delta\omega_i \quad (3)$$

where $K_i$ – Area i bias factor.

Area bias $K_i$ determines the amount of interaction during a disturbance in the neighboring areas. For satisfactory performance, $K_i = B_i$, where $B_i = D_i + \frac{1}{R_i}$

with $B_i$ - Frequency bias factor

$D_i$ - Frequency sensitive load coefficient

$R_i$ − Speed Regulation in p.u.

For a two-area system

$ACE_1 = \Delta P_{12} + B_1\Delta\omega_1$ (4)

$ACE_2 = \Delta P_{21} + B_2\Delta\omega_2$ (5)

where $\Delta P_{12}$ and $\Delta P_{21}$ changes in scheduled interchanges. Frequency and tie-line power errors can be brought to zero by bringing the ACE to zero in steady state. In steady state $\Delta P_{12} = 0 = \Delta\omega = \Delta\omega_1 = \Delta\omega_2$.

Practically several generating units operate in parallel in the same area. For analysis sake an equivalent generator will be used to represent each area. If a number of generating units operating in parallel then equivalent of generator inertia constant ($H_{eq}$), frequency sensitive load coefficient ($D_{eq}$) and frequency bias factor ($B_{eq}$) can be represented as follows.

$$H_{eq} = \sum_{i=1,2\ldots n} H_i \quad (6)$$

$$D_{eq} = \sum_{i=1,2\ldots n} D_i \quad (7)$$

$$B_{eq} = \sum_{i=1,2\ldots n} D_i + \sum_{i=1,2\ldots n} \frac{1}{R_i} \quad (8)$$

AGC block diagram for two-area system is given below.

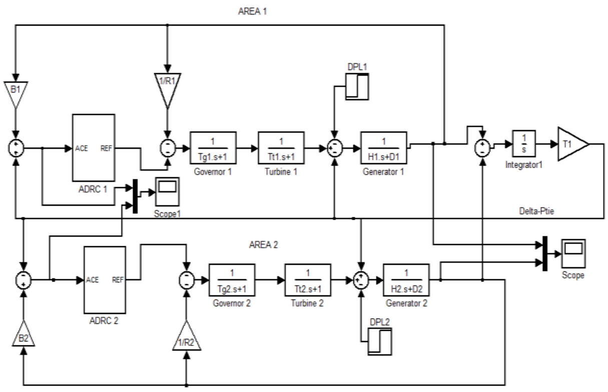


Fig 3 AGC block diagram for two-area system

## III DESIGN OF ADRC

*Structure of ADRC*

The heart of ADRC design is an observer who jointly treats actual disturbances and modeling uncertainties, such that only a very coarse process model is necessary in order to design a control loop, which makes ADRC an attractive choice for practitioners and promises good robustness against process variations. Here the states of nth-order system along with disturbances (internal and external) are estimated by (n+1)th-order Extended State Observer (ESO). ESO is a dynamical system with n+1states. The extended state in ESO is used to estimate the total action of the uncertain models and the system disturbances and then is applied to compensate the disturbances.

After compensating the disturbance, the resulting systems will be in the typical structure of nth-order cascaded integrators, which is easy to control without derivative action. The technology of linearization via dynamic compensation is the most important in the ADRC technique. ADRC assumes a certain canonical model regardless of the actual process dynamics and leaves all modeling errors to be handled as a disturbance.

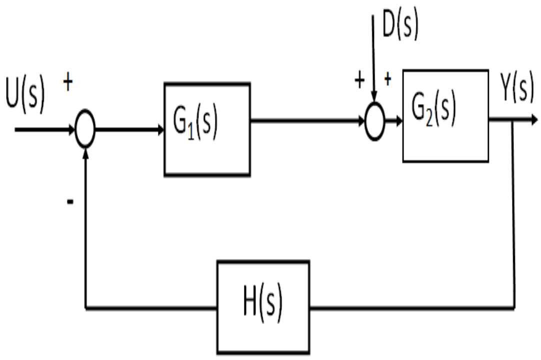


Fig 4 Block Diagram of the basic system

*Design of ADRC for a nth-order process*

STEP 1: Plant Remodeling

In this section, the design strategy of ADRC is developed for a general transfer function model of a physical system with primary loop as shown in Fig 4. The design involves both time-domain and frequency–domain representations. Our aim is to develop ADRC for a higher-order system.

Hence we introduce the design idea of ADRC for a nth-order system. General form of plant with finite zeros represented by a minimum phase transfer function is

$$G_p(s) = \frac{Y(s)}{U(s)} = \frac{b_{m+1}s^m + b_m s^{m-1} + \ldots + b_2 s + b_1}{a_{n+1}s^n + a_n s^{n-1} + \ldots + a_2 s + a_1}, n \geq m \quad (9)$$

where U(s) and Y(s) are input and output of the plant respectively. $a_i$ and $b_j$ $(i = 1,2,\ldots,n+1; j = 1,2,\ldots,m+1)$ are the coefficients of the transfer function. After performing the longhand division of (9), the plant model may be shown as

$$s^{n-m} Y(s) = b_0 U(s) + D(s) \quad (10)$$

with $b_0 = b_{m+1}/a_{n+1}$

D(s) includes both internal and external disturbances.

After remodeling, the plant has two important characteristics. One is the order of the remodeled plant (= n-m) and the other is the high frequency gain $b_0$. These two are the essential parameters for the ADRC design.

The fundamental idea of ADRC is to implement an extended state observer (ESO) that provides an estimate of $d(t)$, such that it compensates the impact of $d(t)$, on the process by means of disturbance rejection. All that remains to be handled by the actual controller will then be a process with approximately integrating behavior which can be easily realized by a simple proportional controller. Hence the generalized disturbance is observed and cancelled by ADRC. The uncertainties involved in the disturbance will also be canceled.

STEP 2: Estimation of generalized disturbance

After remodeling the plant, we need to cancel the generalized disturbance d(t). A practical method is to treat the generalized disturbance as an extra state of the system and use an observer to estimate its value. This observer is known as an Extended State Observer (ESO).

The state space model of plant represented as follows

$$sX(s) = AX(s) + BU(s) + E(s)D(s) \quad (11)$$

$$Y(s) = CX(s) \quad (12)$$

where $X(s) = \begin{bmatrix} X_1(s) \\ X_2(s) \\ \vdots \\ X_{n-m}(s) \end{bmatrix}_{(n-m)}$;

$$A = \begin{bmatrix} 0 & 1 & 0 & \ldots & 0 \\ 0 & 0 & 1 & \ldots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \ldots & 1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{(n-m)*(n-m)}; B = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ b_o \\ 0 \end{bmatrix}_{(n-m)}$$

$$C = [1 \quad 0 \quad \ldots \quad \ldots \quad 0]_{(n-m)}; E = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \vdots \\ 1 \end{bmatrix}_{(n-m)}$$

In order to derive the estimator, a state space model of the disturbed process can be represented as follows.

$$sZ(s) = AZ(s) + BU(s) + L(Y(s) - \hat{Y}(s)) \quad (13)$$

where

$\hat{Y}(s) = CZ(s)$; $Z(s) = [Z_1(s) \; Z_2(s) \; \ldots . Z_{n-m}(s)]^T_{(n-m)}$

and

$$L = [l_1 \; l_2 \; \ldots \; l_{n-m}]^T_{(n-m)}. \quad (14)$$

In order to locate the all eigenvalues of the ESO to $-\omega_o$(observer bandwidth), the observer gains are chosen as

$$l_i = \binom{n-m+1}{i} . \omega_o^i, i = 1,2,\ldots,n-m+1. \quad (15)$$

By proper designing of ESO, $Z_i(s)$ will be estimating the values of $X_i(s)$ closely (i=1, 2 … n-m). Then $Z_{n-m} = \hat{D}(s) \approx D(s)$

The basic idea of ADRC design is based on the assumption that the transfer function of the plant has no finite zeros. In case the transfer function has finite zeros, then convert the model into a transfer function without finite zeros. The error between the two models can be included into the generalized disturbance term. A well tuned ESO outputs $\hat{x}_i$ will track $x_i$ closely. Then we have

$\hat{x}_{n+1} \approx x_{n+1} = D.$

The generalized disturbance $d(t)$ can be removed by the

time domain estimated value $x_{n+1}$.

Now the control law $U(s) = \frac{U_o(s) - Z_{n-m}(s)}{b_o}$, (16)

Now the system is reduced to a pure integral plant by substituting

$$s^{n-m}Y(s) = b_o . \frac{U_o(s) - Z_{n-m}(s)}{b_o} + D(s)$$

$$= U_o(s) - \hat{D}(s) + D(s) \approx U_o(s)$$

The control law for the pure integral plant is

$$U_o(s) = K_1(R(s) - Z_1(s)) - K_2 Z_2(s) - \cdots - K_{n-m-1} Z_{n-m-1}(s) \quad (17)$$

To simplify the tuning process, all the closed-loop poles of the controller are set to $-\omega_c$. Then the controller gains have to be selected as

$$k_i = \binom{n-m}{n-m-i+1} \omega_c^{n-m-i+1}, i = 1,2,\ldots,n-m. \quad (18)$$

Placing all the observer poles at one location is known as Bandwidth Parameterization. $\omega_c$ represents the bandwidth of the controller. Increasing $\omega_c$ the tracking speed of the output of ADRC controlled system will increase. In other words the tracking error, overshoot and settling time of the output will decrease. Generally, $\omega_c$ varies from 3~10 rad/s.

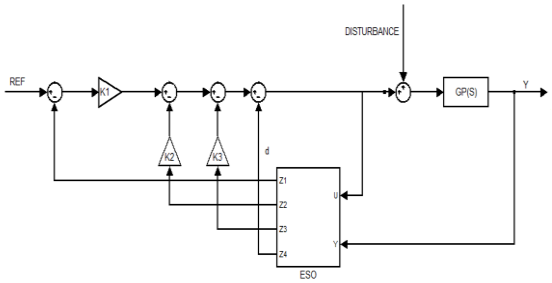


Fig 5 ADRC structure with state feedback

The proposed ADRC control for decentralized system is shown in Fig 3. In this figure an ADRC is placed in each area acting as a local LFC under decentralized control strategy. These two decentralized areas are connected through tie line. The detailed structure of ADRC is given in Fig 5. For this LFC problem, $ACE_1$ and $ACE_2$ are the reference inputs and load changes $\Delta PL_1$ and $\Delta PL_2$ are the external disturbances in areas 1 and 2 respectively. The parameter values for both areas of the system are shown in Table 1.

Table 1. LFC Data

| | | |
|---|---|---|
| Inertia constant | H (p.u.sec.) | 10 |
| Frequency sensitive load coefficient | D (p.u./Hz) | 1 |
| Turbine time constant | $T_t$ (sec) | 0.3 |
| Governor time constant | $T_g$ (sec) | 0.1 |
| Governor speed regulation | R (Hz/p.u.) | 0.05 |
| Synchronizing coefficient | T (p.u./rad.) | 22 |
| ADRC bandwidth | $\omega_c$(rad/sec) | 10 |
| Observer bandwidth | $\omega_o$(rad/sec) | 20 |
| Load change in area 1 | $DPL_1$ (p.u.) | 0.1 |
| Load change in area 2 | $DPL_2$ (p.u.) | 0.08 |

Using above data, we obtain for (D(s)=0)

$$G_p(s) = \frac{Y(s)}{U(s)} = \frac{1}{0.3s^3+4.03s^2+10.4s+21} \qquad (19)$$

Here n=3, m=0, $a_4$ =1, $b_o$=1;
Hence $b_0 = b_1 / a_4 = 3.33$;
From (10), controller design equation
$s^3Y(s) = 3.33\,U(s) + D(s)$
The model of ESO is obtained as

$$\begin{pmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{pmatrix} = \underbrace{\begin{pmatrix}0&1&0&0\\0&0&1&0\\0&0&0&1\\0&0&0&0\end{pmatrix}}_{A}\cdot\begin{pmatrix}x_1\\x_2\\x_3\\x_4\end{pmatrix} + \underbrace{\begin{pmatrix}0\\0\\3.33\\0\end{pmatrix}}_{B} u + \underbrace{\begin{pmatrix}0\\0\\0\\1\end{pmatrix}}_{E} \dot{d}$$

$$y = \underbrace{\begin{pmatrix}1&0&0&0\end{pmatrix}}_{C}\begin{pmatrix}x_1\\x_2\\x_3\\x_4\end{pmatrix} \qquad (20)$$

From (14), ESO may be written in terms of observer gains as

$$\begin{pmatrix}\dot{\hat{x}}_1\\ \dot{\hat{x}}_2\\ \dot{\hat{x}}_3\\ \dot{\hat{x}}_4\end{pmatrix} = \begin{pmatrix}0&1&0&0\\0&0&1&0\\0&0&0&1\\0&0&0&0\end{pmatrix}\cdot\begin{pmatrix}\hat{x}_1\\ \hat{x}_2\\ \hat{x}_3\\ \hat{x}_4\end{pmatrix} + \begin{pmatrix}0\\0\\3.33\\0\end{pmatrix}.u(t) + \begin{pmatrix}80\\2400\\32000\\160000\end{pmatrix}.(y-\hat{y})$$

$$= \underbrace{\begin{pmatrix}-80&1&0&0\\-2400&0&1&0\\-32000&0&0&1\\-160000&0&0&0\end{pmatrix}}_{A-LC}\begin{pmatrix}\hat{x}_1\\ \hat{x}_2\\ \hat{x}_3\\ \hat{x}_4\end{pmatrix} + \underbrace{\begin{pmatrix}0\\0\\3.33\\0\end{pmatrix}}_{B}.u(t) + \underbrace{\begin{pmatrix}80\\2400\\32000\\160000\end{pmatrix}}_{L}.y(t) \qquad (21)$$

The ESO is derived for observer bandwidth $\omega_o = 20$ rad/s. Next controller gains are computed from (18) for controller bandwidth $\omega_c = 10$ rad/s, as

$$k_1 = 1000,\ k_2 = 300,\ k_3 = 30$$

## IV TUNING OF PID CONTROLLER

The basic structure of a PID controller is

$G_C(s)=K_P + \frac{K_I}{s} + K_D\, s$

where $K_P$, $K_I$ and $K_D$ are proportional, integral and derivative gain constants. Proportional control results in decrease of rise time but also results in oscillatory performance. Derivative control reduces the oscillations by providing proper damping which results in improved transient performance and stability. Integral control reduces the steady state error to zero. Theoretically $K_P$, $K_I$ and $K_D$ are to be selected from infinite combinations. Proper selection ensures the bull's eye. In MATLAB, the transfer function of PID controller is

$$G_C(s)=K_P + \frac{K_I}{s} + \{K_D Ns/(s+N)\} \qquad (22)$$

where N sets the pole location of derivative noise filter. Default value of N is 100.PID controller tuning can be achieved in three steps using MATLAB SIMULINK [3]. In Step 1 we select $K_P$ that results in a highly oscillatory stable response with $K_D = K_I = 0$. In Step 2 we fix the parameter $K_D$, for $K_P$ selected in Step1, to take care of transient performance. In Step 3 we fix the parameter $K_I$, for $K_P$ and $K_D$ selected in Steps 1 and 2, to take care of steady state performance. Actually this selection converges to set of values of $K_P$, $K_I$ and $K_D$. This completes the tuning of PID controller. Following this tuning method the resulting parameters of PID controller are

$K_P = 0.5$, $K_I = 0.83$ and $K_D = 0.5$

## V SIMULATION RESULTS

We simulate the above two-area system first without any secondary controller and then with ADRC and PID controllers. The results are shown in the following figures.

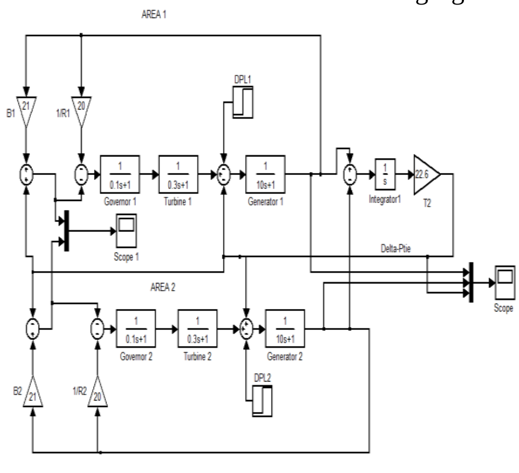


Fig 6 Two area power system without secondary controller

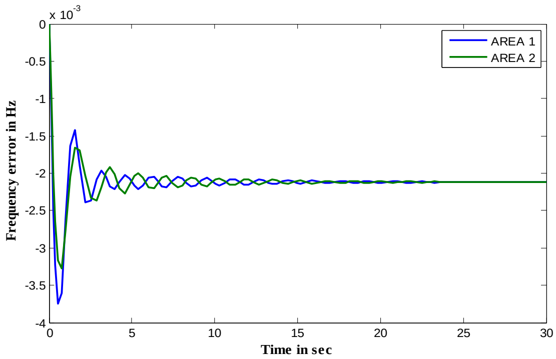


Fig 7 Frequency responses without secondary controller

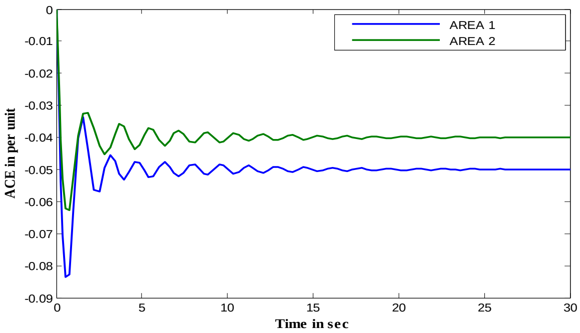


Fig 8 ACEs of two areas without secondary controller

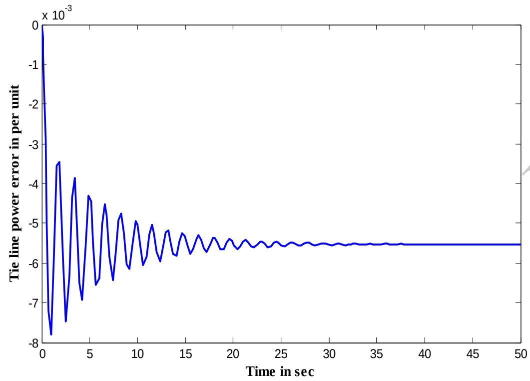


Fig 9 Tie line power error without secondary controller

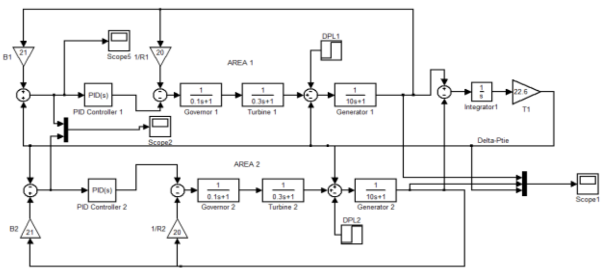


Fig 10 Decentralized LFC of two area system with PID controller

The proposed ADRC for a two area system is shown in Fig 11.An ADRC controller is placed in the each area acting as secondary control.

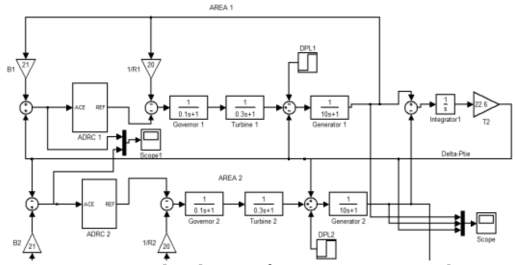


Fig 11 Decentralized LFC of two area system with ADRC

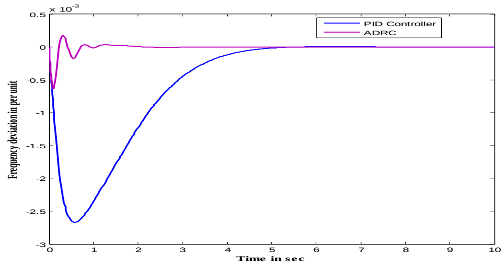


Fig 12 Frequency errors comparison of area 1

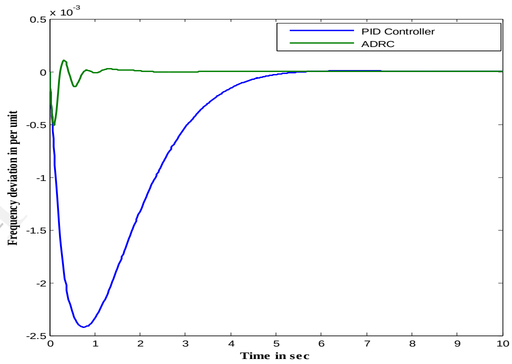


Fig 13 Frequency errors comparison of area 2

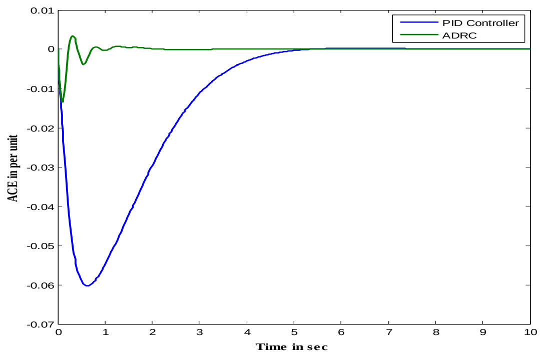


Fig 14 ACE of area 1

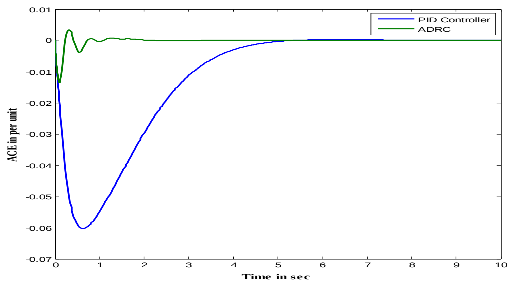


Fig 15 ACE of area 2

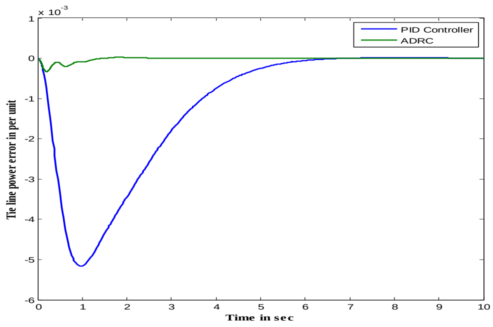


Fig 16 Tie-line power error of the two areas

## VI DISCUSSION

The two-area system without a secondary controller is unable to bring the steady state frequency errors, tie-line power errors and ACEs to zero. Also the settling times are large. Both ADRC and PID controllers brought the steady state frequency deviations, tie-line power errors and ACEs to zero with small settling times. Obviously from Figures 12-16, undershoot and settling time are less for ADRC compared to PID controller. In ADRC, selection of $\omega_c$ and $\omega_o$ is a trial and error process like the selection of $K_P$, $K_I$ and $K_D$ for PID controller.

## VII CONCLUSIONS

Power system network is divided into number of areas. Two- area power system is the basic model for the analysis of multi-area power system. LFC is a very major problem of power systems. The aims of LFC are to bring steady state frequency errors, tie-line power errors and ACEs to zero with small settling time. Active Disturbance Rejection Controller (ADRC) is a novel robust approach. It can estimate and mitigate both internal and external uncertainties in real time. An ADRC is designed for the LFC of two-area problem. Its performance is compared with a standard PID controller. The results show that the ADRC is superior. Next ADRC can be applied to multi-area power systems as an extension.

## VIII ACKNOWLEDGEMENTS

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