Performance Comparison of Load Frequency Control for Power System by ADRC Approach and PID Controller

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Abstract. Load Frequency Control (LFC) is the main problem of power networks which outcomes because of mismatch between real power generation and consumption as the power consumption changes every period. Therefore, the frequency of the power system may not be at rated value resulting in power quality problems. Hence, the aim of LFC is to reduce the transient changes of area frequency and tie-line power transfer maintaining them at steady state. Moreover, the external disturbances and uncertainty factors, as well as parameters of the power system, causes a big problem for controller design in LFC. Therefore, this research describes a comparative consideration for Active Disturbance Rejection Control (ADRC) based LFC as an operational control strategy, which requires few information from the plant model and being robust against disturbances and uncertainties. Two intelligent controllers Particle Swarm Optimization (PSOA) Algorithm, Bacterial Foraging Optimization (BFO) mechanism are used for tuning Proportional Integral Derivative (PID) controller based LFC to acquire optimal values, taking into consideration single-area power system. The simulation results exhibit that the ADRC can obtain better performance than PID tuned by BFO and PSO in terms of frequency deviation and settling time.

1. Introduction

An interconnected electrical energy system is required to run in the zero steady-state conditions. In a power plant, the voltage and frequency must be kept according to the rated values in a specific condition. Reactive and real power balance are thus required in the system. Voltages of the system tend to deviate from nominal values under reactive power imbalance. In case of control of voltage stability presented in [1, 2]. There are many ways to adjust the PID controllers for the study of Multi-Power Systems. To maintain system stability in the estimated value Researchers need to control the system frequency and the automatic voltage regulator by Automatic generation control. Thus, Researchers try to take advantage of simulation tools and suggest a method to adjust PID controllers using simulations. There are three main points namely; determining the gain parameter; the transient performance and the performance of the stable state [3]. Performance comparisons with the traditional stabilizers and a three-area power system with the PID-based Power System Stabilizer have shown an improvement in a region’s oscillation system [4]. Intelligent Proportional Integral (PI) control using model-free sliding mode controllers regulate pitch positions and the azimuth. [5] for many years, PI was widely used as a frequency control unit in industries. Three-area interconnected power network.
controlled by a PI controller is presented in [6], where the controller parameters of the PI controller are tuned using a trial-and-error approach for a centralized method for an entire power system model based on LFC scheme. The centralized mechanism is provided by multiple-zone power system to implement an optimization algorithm on the entire model. Many researchers working a lot on various artificial intelligence (AI) based controllers such as decentralized controllers sliding mode control (ANN) [7] has been used as a new powerful Radial Basis Function load controller to improve the performance and make the power system stable. The reason is the parametric uncertainties with different operating conditions. In this work, the problem was resolved using the ANN controller [8], fuzzy logic (FL) controller [9] and neuro-fuzzy controller [10]. There are numerous optimization mechanisms applied to tune the control parameters; Differential Evolution [11], Genetic Algorithms Technique, Particle Swarm Optimizations Algorithm [12], Ant Colony Optimization Method (ACOM) is modern methodology to LFC problem solving that takes inspiring from the social behaviours of Ants [13]. If a variation happens in the active power of the load, the frequencies will deviate from their nominal values while the power exchange will occur in the tie-line interconnected area. Because of this, there will be a degradation of power system performance. The elementary control from the output of the generator to compensate for the changes in the load can be applied though incomplete compensation. The secondary control is capable of maintaining the system frequency at rated values when the changes happen in the load. There are many examples of secondary control such as LFC, PID, ANN, FL, etc. In case the power system is under unstable operation, the frequency and tie-line power have to be maintained at their rated values, therefore the LFC is required. There is need for economical and reliable methods to maintain frequency deviations to be close to zero. There are a number of control strategies and techniques, including conventional PID and AI to solve these kinds of problems [8]. ADRC is a new robust controller used to manipulate several problems in power systems. This powerful and brand-new technique is usable in non-linear systems with multiple-input multiple-output and single-input single-output Systems. Jing-Qing Han proposed the ADRC technology to serve as an alternative to the PID controller, which proved to be very effective in control systems [14, 15]. Optimization of PID controller using two intelligent controllers such as PSO and BFO for LFC to control single area power system [16] was proposed. Afterward, a new method was realized due to the incompatibility between real power generation and consumption as energy consumption changes every minute. Thus, the power system frequency may not be at the estimated value, leading to energy quality problems. The standard PID performance was compared with the ADRC in two areas. A comparative study was conducted between ADRC and the PID in the case of one region and multiple areas in power systems in [17]. The study examined the effects of changing the ADRC parameters in the LFC unit to regulate the Area Control Error (ACE), frequency deviations and the tie-line in the single-area and multi-area and comparative with PID. It is observed that for ADRC based LFC, a controller bandwidth of 4 rad/sec for both power systems and observer bandwidth of four times the controller bandwidth gives good results for a single area power system in [18]. ADRC can calculate and estimate disturbance and uncertainties in real-time. It is also robust for the uncertainties in the model system, which are associated with energy systems. The ADRC application requires two factors namely the order of the system and high-frequency gain and can be applied in several areas such as aerospace field, electricity power plant, chemical industry, etc. [19]. ADRC is a simple algorithm with short settling time and small overshoot. The main idea of the ADRC is to benefit from the Extended State Observer (ESO), which evaluates all existing d(t) disturbances so that it can be used to compensate problems. All that remains to be taken care of by the actual controller will then be a process with approximately integrating behavior, which can be done easily by a simple proportional controller [17]. This research presents a solution to the LFC problem for a single area power system. The study uses ADRC and PID tuned by PSO and BFO. In the beginning, the transfer function is used to represent the model of ADRC, which is a synopsis for an nth-order minimum phase system. For a single area power system, a proposed ADRC technique is applied to LFC and compared with PID. The PID was tuned by PSO and BFO as well. The simulation was done for the two systems and their performances were achieved.
The rest of this article is organized as follows: Item 2 represents the Problem Formulation and illustrates the system modelling in a single area. In Section 3, the ADRC technique based LFC model is displayed. The simulation results as shown in Section 4. Therefore, the conclusions are included in Section 5.

2. Problem formulation
In an integrated power system, the uncertainty in the demand for energy load in both the frequency deviation and the tie-line has an essential task of exchanging energy across a single-area system. The aims of LFC are to reduce the transient changes of area frequency and tie-line power transfer, and maintain them at a steady state. The external disturbances and uncertainties factors of the model and parameters of the power system cause a big problem for controller design in LFC.

A single-area power system is revealed in Figure 1. It comprises of one generator, one governor, and one turbine unit. The electric power system (EPS) inputs are controller input, \( U(s) \), \( D(t) \) is load disturbance and tie-line power error. System outputs are Area Control Error \( y(s) \), and Generator Output (GO) \( \Delta f \). In Figure 1, is denoted as valve position change \( \Delta P_r \), electrical power \( \Delta P_e \), and mechanical power \( \Delta P_m \).

![Figure 1. The diagram of the single-area power-generating unit.](image)

Let the transfer function (TF) from \( \Delta P_r(s) \) to \( \Delta P_e(s) \) be \( G_{\Delta f}(s) = \frac{\text{Num}_{\Delta f}(s)}{\text{Den}_{\Delta f}(s)} \) in which \( \text{Num}_{\Delta f}(s) \) is numerator and \( \text{Den}_{\Delta f}(s) \) is denominator change with generating units. \( G_{\Delta f}(s) \) is the non-reheat turbine, \( T_s \) is Governor time constant, \( T_{se} \) is Turbine time constant. The unit is determined by (1).

\[
G_{\Delta f}(s) = \frac{\text{Num}_{\Delta f}(s)}{\text{Den}_{\Delta f}(s)} = \frac{1}{(T_s s + 1)(T_{se} s + 1)}
\]  

The transfer function of the generator is defined as:

\[
G_{g(s)} = \frac{1}{\text{Den}_g(s)} = \frac{1}{M s + D}
\]  

Where \( M, D \) are Area inertia constant and area load damping constant

The output \( Y(S) \) for each and every area can be described by:

\[
Y(s) = G_{f}(s) U(s) + G_{i}(s) \Delta P_r(s) + G_{c}(s) \Delta P_f (s)
\]  

Where \( G_{f}(s), G_{i}(s) \) and \( G_{c}(s) \) are the Transfer Functions between the three inputs and ACE consecutively and described as:

\[
G_{f}(s) = \frac{\text{RBNum}_{\Delta f}(s)}{\text{Num}_{\Delta f}(s) + \text{RDen}_{\Delta f}(s) \text{Den}_{\Delta f}(s)}
\]

\[
G_{i}(s) = \frac{-\text{RBDen}_{\Delta f}(s)}{\text{Num}_{\Delta f}(s) + \text{RDen}_{\Delta f}(s) \text{Den}_{\Delta f}(s)}
\]

\[
G_{c}(s) = \frac{\text{Num}_{\Delta f}(s) + \text{RDen}_{\Delta f}(s) \text{Den}_{\Delta f}(s) - \text{RBDen}_{\Delta f}(s)}{\text{Num}_{\Delta f}(s) + \text{RDen}_{\Delta f}(s) \text{Den}_{\Delta f}(s)}
\]
where R and B are speed regulation coefficient, frequency bias parameter Replace the values of the parameters into (4) for the single area with the non-reheat turbine $G_{PN}(s)$, as shown in (7).

$$G_{PN}(s) = \frac{297.6}{s^2 + 16.13s + 45.54s + 2.48}$$

(7)

3. ADRC approach based LFC model

The scheme diagram of the ADRC-LFC is illustrated in Fig. 2. The Plant block represents a single area of a power system. Outputs of this schematic diagram are tie flow deviations and frequency that are gathered to form ACE. The ADRC mechanism takes the ACE and yields the input $u$ for the plant. Frequency deviation is also fed-back to the plant through the speed droop coefficient.

$$Y(s) = G_p(s)U(s) + W(s)$$

(8)

Where $Y(s)$, $U(s)$, $W(s)$ are the Output (O), the Input (I), the General Disturbance (GD), respectively. The general physical plant $G_p(s)$ is modeled as

$$G_p(s) = \frac{Y(s)}{R(s)} = \frac{h_{11}s^{n-1} + h_{12}s^{n-2} + \cdots + h_{1j} + h_1}{a_{i1}s^n + a_{i2}s^{n-1} + \cdots + a_{im} + a_i}$$

(9)

Where $R(s)$ is the reference input and $a_i = (i = 1, \ldots, n)$, $b_j = (j = 1, \ldots, m)$ is the coefficient of the TF.

The essential idea of the ADRC method is based on the TF of the plant without zeros. Thus, in order to use ADRC for the system indicated by (8), it is important to develop an equivalent model of (9) so that the transfer function only has poles. In order to improve the nonzero equivalent model of (9), the following polynomial long division is conducted on $\frac{1}{G_p(s)}$ .

$$\frac{1}{G_p(s)} = \frac{a_{i1}s^n + a_{i2}s^{n-1} + \cdots + a_{im} + a_i}{b_{j1}s^n + b_{j2}s^{n-1} + \cdots + b_{jm} + b_j}$$

$$= C_{i0}s^{n-m} + C_{i1}s^{n-m-1} + \cdots + C_{im} + C_i$$

(10)

In (10), $C_i = (i = 1, \ldots, n-m)$ are coefficients of polynomial division result, and the $G_{red}(s)$ is a remainder, which can be represented by:

$$d_{j1}s^{n-j} + d_{j2}s^{n-j-1} + \cdots + d_{jm} + d_j$$

$$= b_{j1}s^{n-j} + b_{j2}s^{n-j-1} + \cdots + b_{jm} + b_j$$

(11)

In (11), $d_j = (j = 0, \ldots, m-1)$ are the numerator coefficients of the remainder for TF. Substituting (10) into (8) gives,

$$[C_{i0}s^{n-m} + C_{i1}s^{n-m-1} + \cdots + C_{im} + C_i + G_{red}(s)]Y(s)$$

$$= U(s) + W'(s)$$

(12)
n-m \right)
\end{equation}

and

\begin{equation}
\text{Consequently, an ESO needs to be developed to estimate } D(s) \text{ in real-time.} \tag{13}
\end{equation}

Finally, we obtain this,

\begin{equation}
s^n Y(s) = \frac{1}{C_w} D(s) \tag{14}
\end{equation}

where in:

\begin{equation}
D(s) = -\frac{1}{C_w} b C_{w-n} s^{n-m} + \ldots + C_i s + C_0 + G_r(s) Y(s) + \frac{1}{C_w} W'(s) \tag{15}
\end{equation}

From (3), \( C_{n-m} \) can be explained as

\begin{equation}
C_w = \frac{a}{b} \tag{16}
\end{equation}

For the improvement process of the ADRC controller, D(s) is dealt with as the generalized disturbance and assessment of the time domain so that the precise expression for \( c_i \) and \( d_j \) are neglected. In its place using the order of plant n, the relative order \( n-m \) may be used as the order of the controller system and equation (14) can be written as

\begin{equation}
s^n Y(s) = b U(s) + D(s) \tag{17}
\end{equation}

Where \( b = \frac{1}{C_w} \)

3.2. Design of ADRC.

ADRC controller can be defined as a gathering of ESO and a state feedback controller. The ESO unit is applied to observe the generalized disturbance \( D(t) \), which is also used as extended state variables, and the state feed-back controller is utilized to regulate the tracking error between the output and a reference signal for the physical system [7]. ESO the performance of ADRC technique is depending on its precise estimation of the generalized disturbance D(s). Consequently, an ESO needs to be developed to estimate D(s) in real-time.

Now the state-space model of (14) is,

\begin{equation}
\begin{bmatrix}
S X(s) = A X(s) + B U(s) + E(s) D(s) \\
Y(s) = C X(s)
\end{bmatrix} \tag{18}
\end{equation}

Where

\begin{align*}
X(s) &= \begin{bmatrix} X_1(s) \\ X_2(s) \\ \vdots \\ X_{n-m}(s) \end{bmatrix} \\
A &= \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \\
B &= \begin{bmatrix} b_0 \\ \vdots \\ b_{n-m} \end{bmatrix} \\
C &= \begin{bmatrix} 1 & 0 & \cdots & 0 \end{bmatrix} \\
E &= \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}
\end{align*}

The ESO of the plant is,

\begin{equation}
s Z(s) = A Z(s) + B U(s) + L[Y(s) - Y(s)] \tag{19}
\end{equation}

Where \( Z(s) \) is the rated state vector chosen as

\begin{equation}
Y(s) = C Z(s); \tag{20}
\end{equation}

\begin{equation}
Z(s) = \begin{bmatrix} Z_1(s) \\ Z_2(s) \\ \vdots \\ Z_{n-m}(s) \end{bmatrix} \tag{21}
\end{equation}

L is the observer gain vector given by

\begin{equation}
L(s) = \begin{bmatrix} l_1(s) \\ l_2(s) \\ \vdots \\ l_{n-m}(s) \end{bmatrix} \tag{22}
\end{equation}

In order to determine all the eigenvalues of the ESO to \( \omega_n \), L are chosen as
\[
l_i = \binom{n-m+1}{i} a_{i}^{n} i=1,2,\ldots,n-m+1
\]

With a good-tuned ESO, \( Z(s) \) we will be able to estimate the amount of \( x_i(s) \) carefully at the value of changing \( i (i=1,2,\ldots,n-m+1) \). at last come this:
\[
Z_{\omega} = D(s) = D(s)
\]

3.3. Feedback Controller.
If the control input is designed as
\[
U(s) = \frac{U_{o}(s) - Z_{\omega}(s)}{b_{c}}
\]
Equation (10) will reduce to a pure integral part, i.e.
\[
S^{+}Y(s) = b_{c} \frac{U_{o}(s) - Z_{\omega}(s)}{b_{c}} + D(s) = U_{o}(s) - D(s) + D(s) = U_{o}(s)
\]

The control law for the pure integral plant model is:
\[
U_{o}(s) = K_{R}(R(s) - Z_{\omega}(s) - K_{Z}Z_{\omega}(s) - \ldots - K_{Z_{\omega}}Z_{\omega}(s))
\]

Where, \( R(s) \) is a reference input signal \( U_{o}(s) \) is the control law, \( Y(s) \) is the output will be a drive to \( R(s) \), which is null-value for the LFC. To simplify the process model, the feed-back loop poles values of the PD controller are set to \(-\omega_{0} \). Then the controller gain in (23) has to be selected as
\[
K_{i} = \binom{n-m}{n-m-i+1} a_{i}^{n} i=1,2,\ldots,n-m
\]

4. Simulation Results and Discussion
The ADRC based Load Frequency Control (LFC) performance was compared between PSO and BFO, which have been utilized to define the optimal values of the PID controller based LFC, by implementing them in the single area power system.

The ACE, frequency, and tie-line power flow errors have been considered as the output of the LFC. The value of 0.1 p.u. represents the change in the load of the step and has been applied as a disturbance.

4.1. Simulink of Single Area Power System.
The implementation of ADRC and PID tuned by PSO and BFO based LFC in a single area power system is shown in Figs. 3, 4 consecutively and Figs. 5, 6,7 shown the Comparison of Frequency, Tie-line power, ACE errors of PSO, BFO, and ADRC based LFC.

Figure 3. PID Tuning by PSO and BFO based LFC model of single area power system
Figure 4. The diagram of ADRC controller-based LFC of the single-area

Figure 5. Comparison of Frequency errors of PSO, BFO, and ADRC based LFC

Figure 6. Comparison of Tie-line power errors of PSO, BFO, and ADRC based LFC

Figure 7. Comparison of ACE errors of PSO, BFO, and ADRC based LFC
In this study, the generator represented by its mathematical equivalent model. Further, the non-reheat turbine model is deemed as illustrated in Figures. 3,4. From the table 1, it is observed that the error magnitude obtained by the ADRC based LFC is lower than the error magnitude obtained by PID tuned by PSO and BFO based LFC at the same value of load change as a disturbance. However, the responses and settling time is lower in the case of ADRC. A brief description of the system performance including settling time, peak and frequency deviation is measured for the single-area power system as indicated in Table 1. The turbine parameters, speed governor unit, and generator are shown in Table 2 [17]. The simulation was done in MATLAB to determine the performances of the approaches in terms of settling time, frequency deviation and the peak as well. As shown in Table 1, the PSO and ADRC relatively have the same peak as well as settling time at ACE and tie-line error, and they are better than BFO. With respect to the frequency error, the ADRC has the best performance for all cases. From table 1, the absolute peak of PSO and ADRC relatively has a lower peak than BFO for this system. In terms of settling time and frequency deviation, it is noted that ADRC has better performance than BFO and PSO, although it is a classical computational controller. ADRC is showing better performance than intelligent controllers.

5. Conclusion
In this research, a comparison of ADRC based LFC and PID based LFC (tuned by PSO and BFO) was conducted. The simulation was done in MATLAB to determine the performances of the approaches in terms of settling time, frequency deviation and the peak. The PSO and ADRC based LFC have relatively the same peak as well as settling time at ACE and tie-line error better than BFO based LFC. With respect to the frequency deviation, the ADRC has better performance in all cases although it is a classical computational controller whereas the PID tuned by PSO mechanism and BFO technique are intelligent controllers.

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Appendix

Table 1. The DYNAMIC performance of intelligent PID tuned by pso, bfo, and adrc

| TYPES ERROR | ADRC | PSO | BFO |
|-------------|------|-----|-----|
|              | $\Delta f (p.u)$ | $Ts (sec)$ | $Tp (p.u)$ | $\Delta f (p.u)$ | $Ts (sec)$ | $Tp (p.u)$ | $\Delta f (p.u)$ | $Ts (sec)$ | $Tp (p.u)$ |
| ACE         | 3.2769*10^{-5} | 0.9574 | 0.0710 | -6.509*10^{-5} | 2.932 | 0.0069 | -11.15*10^{-5} | 4.471 | 0.0176 |
| Tie-line Error | 1.7063*10^{-4} | 0.9574 | 0.0031 | -1.628*10^{-4} | 2.932 | 0.0029 | -1.782*10^{-7} | 4.471 | 0.0114 |
| Frequency error | -1.1228*10^{-4} | 0.9574 | 0.0039 | 0.6899*10^{-4} | 2.932 | 0.0038 | 4.714*10^{-4} | 4.471 | 0.0076 |

Table 2. The parameter values of the system

| Description | Parameter | Value |
|-------------|-----------|-------|
| Governor Gain | $K_g$ | 1 |
| Governor time constant | $T_g (sec)$ | 0.08 |
| Turbine Gain | $K_t$ | 1 |
| Turbine time constant | $T_t (sec)$ | 0.28 |
| Load model Gain | $K$ | 120 |
| Parameter                        | Value       |
|---------------------------------|-------------|
| Area inertia constant           | $M_i \text{ (p.u. sec.)}$ |
| Area load damping constant      | $D \text{ (p.u./Hz)}$     |
| Gain                            | $T_{i2}$     |
| Speed regulation coefficient    | $R \text{ (Hz/p.u.)}$      |
| ADRC bandwidth                  | $\omega_c \text{ (rad/sec)}$ |
| Observer bandwidth              | $\omega_o \text{ (rad/sec)}$ |