Frequency stability of interconnected power systems using atom search optimization algorithm

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Abstract. This paper explores the dynamic controller design issue for load frequency control (LFC) of a practical interconnected power system model. In view of this, the three-degree-of-freedom proportional-integral-derivative (3DOF-PID) controller architecture and LFC performance analysis for the proposed atom search optimization (ASO) is presented. The consistency of the form and acceptability of the well-known PID controller's responses ultimately enforces to use in this work. The proposed ASO algorithm efficiently combines search space discovery and exploitation that yield promising solutions at the termination condition. The test system investigated is a four-area model with each region consisting of identical thermal unit. The system is also connected in one area with an interline power flow controller. The simulation results presented showed the superiority of ASO based 3DOF-PID controller in terms of settling time, peak variance, and magnitude of oscillation.

Keywords. frequency stability, evolutionary optimization; three-degree-of-freedom PID controller, interline power flow controller.

1. Introduction
The growth in size, complexity, the increasingly demand and linking energy systems for electricity are a major problem for the power utility company. The key reasons for linking energy systems are efficiency and economy [1]. The failure of a system part like a major transmission line or generator has a limited effect on the system with a large, interconnected grid. Reliability means that another device compensates for the failure when one device fails [2]. More than one path to connect a load to each generator is available in a realistic grid. Economy means that the energy from which it is cheap can be produced. The operation of large generating stations 24 hours a day at maximum capacity, which cater not to individual loads but pools power into the grid and is used for multiple linked loads,
is more economical. In respect to the above interactions, the interconnections of power utility companies led to the standardization of frequency. Also, there is a need for better utilisation and operation of AC transmission systems using high-power electronic converters. Several such converters are in operation in present time. A large power system can be plugged into neighbouring power systems via AC transmission lines or DC connections. In general, such neighbours are subject to the control exchange. This requires a better strategy for controller/optimization, than an additional mechanism for the operation of the power system.

In the previous work done, it has been clearly shown that the 2DOF controller has outlined the advantages of the classical 1DOF controller in the application of LFC problem [3]. It shows that if tuning buckles are in a controller framework, even better results might be possible. In [3] the higher DOF allows system oscillations to be dampened. In this work done, the significance of adding degree of freedom (DOF) to the conventional proportional-integral-derivative (PID) controller has shown. The 3DOF-PID controller therefore has the same possibility to further extend in the research work. The controller more conveniently controls the non-linearities and the disturbances in the dynamic system. In this work, important physical constraints such as time delay ($T_d$), governor dead band (GDB), boiler dynamics (BD), reheat turbine and generation rate constraint (GRC) has been added in the plant dynamics having interconnected four areas. The potential use of the LFC in the presence of flexible alternating current transmission system (FACTS) devices [4-6] is an important area of discussion in power system discussion. In [7], the output of a few FACTS units such as static synchronous compensation unit, thyristor-controlled series capacitor, thyristor-controlled phase shifter and IPFC was compared. Performance basis, dynamic IPFC responses are found to be better than the above-mentioned units.

Moreover, the IPFC device can transfer real power to any other and, thereby, facilitate real power transfer among the line. Thereby, in the studied test system, the IPFC controller is installed and its effectiveness is investigated. In the studied system, the control strategy work is done in the presence of PID and IPFC based damping controller designed by the very powerful optimization method. Thereby, all the variables of interest are optimized by using atom search optimization (ASO) approach. The details of ASO can be studied in [8-9]. The application of some of the application of power system through optimization techniques can be seen in [10-13].

In the following pages, the remainder of the paper is recorded. Section 2 includes brief explanations of the evaluated test system and the associated controller. The problems related to LFC are defined in Section 3. Section 4 describes a short preface for the ASO as an optimising method. Section 5 analyses the simulation results. In Section 6, the resulting findings are finalised.

2. Test system dynamics

2.1. System dynamics

The investigated test device is a four-area (all thermal reheaters) with the same area capability. Nonlinear physical constraints like, GDB, BD or GRC are well known to have major implications for transient oscillations. To make the analysis more relevant, the test system contains these limitations. The 3DOF-PID controller, one single turbine unit of 50.0 ms, 0.06 percent GDB (0.036 Hz), 3 % BD and GRC per minute are scheduled for each zone [14] (Refer to Appendix section for the related model parameters (for example, the device configuration and device parameters). The model has followed the boiler dynamics configuration taken from [15]. The simplified diagram and the ith area configuration of the studied test system are depicted in Fig. 1(a) and Fig. 1(b), respectively.
2.2. Studied controller: 3DOF-PID controller
The power system needs continuous surveillance and control. In other way, the power system operator must, like many other engineering systems, constantly track a power system’s health and carry out control measures if appropriate. A large number of automatic control systems have been installed in the systems. These controllers can require manual steps to be supplemented. The basic 3DOF design structure for a plant model is illustrated in Fig. (2a). The same applies to 3DOF-PID controller structure design and is shown in Fig. (2a). The 3DOF-PID controller’s closed loop expression can be defined in (1) [16-17].

$$Y(s) = \left[ \frac{C(s)P(s)}{1+C(s)P(s)} R_c(s) \right] R(s) + \left[ \frac{P(s)-C(s)P(s)FF_c(s)}{1+C(s)P(s)} \right] D(s)$$ (1)
In (1), $R(s)$ is the input reference signal, $Y(s)$ is the system output, $P(s)$ corresponds to plant model, $C(s)$ is the 1DOF controller, $D(s)$ is the load disturbance, $R_e(s)$ is the input reference controller and $FF_c(s)$ is the feed-forward controller. As concerned to $C(s)$ controller, $K_{Pi}$, $K_{Ii}$ and $K_{Di}$ are its PID gains, respectively. $N_i$ is the filter coefficient for derivative controller. $R_e(s)$ consists of $b_i$ and $c_i$ which are the PD set point weight for the reference signal whereas $FF_c(s)$ has $G_{iff}$ as the gain parameter (refer Fig. 2 (b)).

![Diagram](image)

**Figure 2.** Studied 3DOF-PID controller: (a) controller structure and (b) block diagram [16].

3. LFC problem formulation

3.1. Objective function

In the present LFC optimization task, ITAE (also named as figure of demerit (FOD)) is used as the objective function for the design of constrained optimization task. The same may be stated in (2).

$$FOD = ITAE = \int_{0}^{t_{sim}} \left[ \Delta f_i + \left| \Delta P_{tieij} \right| \right] dt \quad (2)$$

In (2), $\Delta f_i$ is the frequency deviation profile of $i$th area; $\Delta P_{tieij}$ is the net tie-line power deviation plot connecting between the $i$th and the $j$th area and $t_{sim}$ is the simulation time.
3.2. Problem constraints

The problem conceived in this section is called a restricted optimization task. Thus, 3DOF-PID control gains and the IPFC time-constant are the optimizing parameters of this tuning task. The limits of these restrictions can be defined in (3).

\[
\begin{align*}
K_{pk}^{\text{min}} & \leq K_{pk} \leq K_{pk}^{\text{max}}, & k = 1 \text{ to } 4 \\
K_{ik}^{\text{min}} & \leq K_{ik} \leq K_{ik}^{\text{max}}, & k = 1 \text{ to } 4 \\
K_{dk}^{\text{min}} & \leq K_{dk} \leq K_{dk}^{\text{max}}, & k = 1 \text{ to } 4 \\
b_k^{\text{min}} & \leq b_k \leq b_k^{\text{max}}, & k = 1 \text{ to } 4 \\
c_k^{\text{min}} & \leq c_k \leq c_k^{\text{max}}, & k = 1 \text{ to } 4 \\
G_{eff}^{\text{min}} & \leq G_{eff} \leq G_{eff}^{\text{max}}, & k = 1 \text{ to } 4 \\
N_k^{\text{min}} & \leq N_k \leq N_k^{\text{max}}, & k = 1 \text{ to } 4 \\
T_{ipfc}^{\text{min}} & \leq T_{ipfc} \leq T_{ipfc}^{\text{max}}, & k = 1 \text{ to } 4
\end{align*}
\]

In the present optimization task, the minimum and the maximum values of PID gains are 0.001 and 10, respectively; the range of $N$ is 0.001 to 100 and the range of $b_k$, $G_{eff}$, $T_{ipfc}$ and $c_k$ is 0.001 to 1.

3.3. Calculation of performance indices

The current work has stressed the accuracy of the developed controller's output to build an adaptive plant model. Quality indexes like ISE, ITSE and IAE are considered to demonstrate this. To describe these three performance indexes, (4) - (6) can be defined.

\[
\begin{align*}
\text{ISE} & = \int_{0}^{t_{\text{sim}}} \left\{ (\Delta f_i)^2 + (\Delta P_{\text{tieij}})^2 \right\} dt \quad (4) \\
\text{ITSE} & = \int_{0}^{t_{\text{sim}}} \left\{ (\Delta f_i)^2 + (\Delta P_{\text{tieij}})^2 \right\} t \, dt \quad (5) \\
\text{IAE} & = \int_{0}^{t_{\text{sim}}} \left\{ |\Delta f_i| + |\Delta P_{\text{tieij}}| \right\} dt \quad (6)
\end{align*}
\]

4. ASO algorithm

Zhao et.al [8] presented, in 2018, a new physics-based optimization approach called ASO based on atomic dynamics. This ASO algorithm is taken from the atomic motion model, which follows the standard molecular mechanics. All substances consist of atoms, bound by covalent bonds, and converted to molecules. Moreover, the interaction between these atoms is attractive or repulsive based on the gap. The repulsion power between atoms increases sharply as the gap decreases. In comparison, with increasing the distance between the atoms the frequency of attraction increases. Therefore, the acceleration of atom $i$ can be calculated based on Newton’s second law and is given below [9].
\[ a_i = \frac{F_i + G_i}{m_i} \quad (7) \]

where, \( a_i \) represents the acceleration of \( i^{th} \) atom, \( F_i \) denotes the interaction force, \( G_i \) signifies the constraint force, and \( m_i \) indicates the mass of \( i^{th} \) atom. The details of this algorithm can be found in [8-9].

5. Simulation results and analysis

This study aims to change the conventional PID controller to increase DOF's and show the dynamic performance. DOF is the number of closed loop transfer functions that can be individually modified depending on the form of problem to be solved [18]. The design of control systems is a multi-variable problem. In the Fig. 3, the studied load disturbance profiles are shown. The test device studied was simulated to assess the efficiency of the updated controller for example and comparison. For the simulation work, the following scenarios are considered to study the system dynamic performance.

Scenario (a): System dynamic performance study with SLP

Scenario (b): System dynamic performance study with RLP

![Figure 3. Studied load perturbation profiles: (a) SLP and (b) RLP [19].](image)

5.1. Scenario (a): Test system dynamic performance analysis with SLP

The dynamic output of the device with the use SLP magnitude 0.01 p.u.MW is investigated in this case. The optimized control gain values for the investigated control type are arranged with this charge disturbance in Table 1. This table shows the utility benefit of ASO-based 3DOF-PID controllers. Table 2 calculates device FOD values which include three performance indices produced by ASO-optimized controllers are calculated in Table 2. Fig. 4 displays the load alarming complex responses. An examination of Fig. 4 showed that improvement in dynamic responses of frequency deviation of area-1 (\( \Delta f_1 \)) and area-2 (\( \Delta f_2 \)), tie-line power deviation profiles such as (\( \Delta P_{tie12} \)) and (\( \Delta P_{tie23} \)) as well as \( ACE_1 \) may be observed with the proposed ASO-3DOF-PID technique.

The convergence profile of FOD with iteration cycle is also recorded in Fig. 5. In this figure, comparative convergence mobility of the FOD value, obtained by the proposed ASO has been plotted. This figure shows the superiority of ASO technique in terms of tuning process while viewing the FOD value.
Figure 4. ASO based response profiles for 0.01 p.u.MW SLP: (a) $\Delta f_1$, (b) $\Delta f_2$, (c) $\Delta P_{tie12}$, (d) $\Delta P_{tie23}$.

Figure 5. ASO based profile of FOD.
Table 1. Optimized PID controller gains for the investigated controller types pertaining to Scenario (a)

| Optimized controller gains (For SLP load) | ASO-3DOF-PID | ASO-3DOF-PID For random load perturbation |
|------------------------------------------|--------------|-----------------------------------------|
| $K_{p1}$                                 | 7.9442       | 0.0100                                  |
| $K_{i1}$                                 | 0.1304       | 0.2596                                  |
| $K_{d1}$                                 | 8.7762       | 0.0100                                  |
| $b_1$                                    | 0.0100       | 0.0247                                  |
| $c_1$                                    | 0.0569       | 0.5200                                  |
| $G_{ff1}$                                | 0.0101       | 0.7807                                  |
| $N_1$                                    | 0.0113       | 98.7671                                 |
| $K_{p2}$                                 | 0.0101       | 0.0100                                  |
| $K_{i2}$                                 | 0.0164       | 0.1413                                  |
| $K_{d2}$                                 | 0.0100       | 0.0102                                  |
| $b_2$                                    | 0.9783       | 0.0515                                  |
| $c_2$                                    | 0.0121       | 0.7996                                  |
| $G_{ff2}$                                | 1.0000       | 0.5858                                  |
| $N_2$                                    | 0.0774       | 33.1252                                 |
| $K_{p3}$                                 | 0.0100       | 0.2254                                  |
| $K_{i3}$                                 | 0.0232       | 0.4375                                  |
| $K_{d3}$                                 | 0.0110       | 0.0167                                  |
| $b_3$                                    | 1.0000       | 0.4230                                  |
| $c_3$                                    | 0.1522       | 0.1379                                  |
| $G_{ff3}$                                | 0.8411       | 0.0102                                  |
| $N_3$                                    | 0.0101       | 100.0000                                |
| $K_{p4}$                                 | 0.0280       | 0.7941                                  |
| $K_{i4}$                                 | 0.0264       | 0.0388                                  |
| $K_{d4}$                                 | 0.0100       | 0.7700                                  |
| $b_4$                                    | 0.0100       | 0.7544                                  |
| $c_4$                                    | 1.0000       | 0.0373                                  |
| $G_{ff4}$                                | 0.5508       | 0.9060                                  |
| $N_4$                                    | 0.0152       | 9.8413                                  |
| $T_{ipfc}$                               | 0.1017       | 0.0157                                  |
Table 2. Comparative FOD and the studied performance indices values pertaining to Scenario (a)

| Controller type | FOD (=ITAE) | ISE  | ITSE | IAE  |
|-----------------|-------------|------|------|------|
| ASO-3DOF-PID    | 8.9527      | 0.0065 | 0.0649 | 1.0920 |
| (For SLP load)  |             |      |      |      |
| ASO-3DOF-PID    | 27.1613     | 0.0007 | 0.0445 | 0.5508 |
| (For random load perturbation) | | | | |

5.2. Scenario (b): Test system dynamic performance analysis with RLP
The load disturbance differs randomly in the narrative in this scenario. The same system is tested in the same problem formulation as in Scenario (a). The system is separately tested as secondary controls by ASO-3DOF-PID. Each controller’s gains are optimized by ASO simultaneously. The value of the specified controller is provided in Table 1 for each controller. Table 2 displays the FOD values along with the values of the output indices analyzed. The area frequencies, the power deviation response of the tie-line and the quantity of area error, subject to RLP in area-1, are shown in the figure after the execution of the simulation work (refer Fig. 6). It can be observed that the oscillations are damped, and their constant state has nearly been restored. Thus, it can eliminate the damped oscillation by applying the RLP in the proposed MVO-3DOF-PID controller.
6. Conclusion
The dynamic performance of a four-area thermal test system with important physical constraints under 3DOF-PID controller has been shown in this manuscript. The controller design methodology is based on the tuning performance ASO. The primary contribution of this work done is the implementation of a powerful optimization technique in the large interconnected four-area power system with relevant system constraints that depicts the behaviour of power system. The simulation work showed that the ASO technique that was applied to the test system showing prominent results subjected to LFC task. It also indicates improved tuning abilities that can be observed from the measure of performance study. In the event of random load disturbance, the dynamic response for the 3DOF-PID controller centred on the ASO is better in the presence of non-linearity of device dynamics. Better results can be observed because it is parameter-free and simple to build, is very accurate, offers quicker versatility to converge.

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Appendix

Nominal data of the studied four-area test system [14]

System configuration: 
\[ f = 60 \text{ Hz}, P_{r1} = P_{r2} = P_{r3} = P_{r4} = 2000 \text{ MW}, \text{ Total area load}=1000 \text{ MW}, \text{ Base rating}=2000 \text{ MW}, \text{ Initial loading}=50\% .\]

System parameters: 
\[ a_{ij} = -1, B_i = 0.425 \text{ p.u.MW/Hz}, K_{ri} = 0.5, K_{pi} = 120 \text{ Hz/p.u.MW}, R_{ti} = 2.4 \text{ Hz/p.u.MW}, T_{ij} = 0.086, T_{gi} = 0.08 \text{ s}, T_{pi} = 20.0 \text{ s}, T_{ri} = 10 \text{ s}, T_{ti} = 0.3 \text{ s}, \]