Multi-Source Power System LFC Using the Fractional Order PID Controller Based on SSO Algorithm Including Redox Flow Batteries and SMES

H.A. Shayanfar *
Department of Elec. Engineering
College of Technical & Engineering,
South Tehran Branch,
Islamic Azad University

H. Shayeghi
Department of Electrical Engineering,
University of Mohaghegh Ardabili,
Ardabi, Iran

A. Molaee
Department of Electrical Engineering,
University of Mohaghegh Ardabili,
Ardabi, Iran

hashayanfar@gmail.com, hshayeghi@gmail.com, amolaee.a@gmail.com

Abstract- Load Frequency Control (LFC) of two-area interconnected power system using Fractional Order Proportional-Integral-Derivative (FOPID) controller based on Social Spider Optimization (SSO) algorithm is investigated in this paper. The FOPID controller is a non-integer order controller that improves the performance of the integer order PID controller. The difference between the FOPID and PID controller is fractional order of integrator and derivative in FOPID that make two degree of freedom in designing. In other word, the FOPID controller has five parameters to be tuned for exact performance. Hence, SSO algorithm is chosen to optimal tune the FOPID controller parameters in this paper. The test system is the two area multisource interconnected power system including reheat thermal, hydro, gas and diesel power plants. The proposed objective function consists of Integral of Time multiply Absolute Error (ITAE) plus sum of settling times of frequency deviation of each control area and tie-line power flow deviation that are associated with proper weighted coefficients. Also, to show the stability of FOPID controller the generation rate constraint is considered in this study and the Redox Flow Batteries (RFBs) and Super Magnetic Energy Storage (SMES) is used to improve the dynamics of the system response under the load disturbances and system nonlinearity. The simulation results reveal the good performance of the SSO based on FOPID controller in LFC problem.

Keyword: FOPID controller, Three-area power system, SSO algorithm, GRC, SMES, RFB.

1. Introduction

One of the most important issues in power system operation and protection is keeping the frequency and voltage in the nominal value or in predetermined limitation. The reliability and quality of generation power depend on balance between the power generated and power demand plus power losses in all over the power system. When this balance is disrupted causes deviation in frequency and tie-line power. Also, the loads are changed randomly. Hence using a proper control method it is necessary to prevent the power system to go to an unstable state. So far, different control method have been used to control the power system frequency in various type of power system.

Until now, some review articles in the LFC issue have been published [1]. In Ref. [2] the Proportional-Integral (PI) based on fuzzy gain scheduling considering generation Rate Constraint (GRC) has been proposed for a four-area interconnected power system. The fuzzy PID type controller for load frequency control of two-area power system has been investigated in [3]. Two-degree-of-freedom PID load frequency controller in presence of GRC at the power generation unit is performed in [4]. In [5] the robust PID controller is tuning based on maximum peak of response specification for Automatic Generation Control (AGC) in multi-machine power system. An adaptive PID has been tuned for LFC problem using Neuro Fuzzy Inference System (ANFIS) and Artificial Neural Network (ANN) based on Genetic Algorithm (GA) [6]. Recently, the researchers have used an improved form of PID controller called FOPID controller at the various research works. In [7] the FOPID controller parameters has been optimized using CNC-ABC algorithm for Automatic Generation Regulator. The FOPID controller is applied for stability analysis and compensation of reactive power in a micro-grid [8].

The FOPID controller has two extra parameters more than PID controller that makes two degree of freedom in controller design and application. Hence, the FOPID controller has been applied to load frequency control of two area multi-source interconnected power system.
considering GRC and the Flexible Alternating Current Transmission System (FACTS) devices such as SMES, in this paper. Also, optimal tuning of controller parameters to achieve the good performance and dynamics response is necessary. The SSO algorithm is one of the heuristic algorithm that is being used to solve the optimization problem. This algorithm can balance exploration and exploitation of solutions in the search space and prevent the premature convergence. Hence, the SSO algorithm is used for optimizing the FOPID controller to obtain the suitable dynamics response. The FOPID based on SSO algorithm has been applied on the two area multi-source interconnected power system. The simulation results show the good performance of this approach to damp the frequency and tie-line deviation in the presence of load disturbances and nonlinearities. Also, the effect of SMES on improvement of disturbance reduction can be seen in the results.

2. Fractional calculus

There are different definitions for Fractional calculus and the Caputo’s definition [9] is chosen here and formulation is as follows:

\[
\alpha D_{a}^{\mu}f(t) = \frac{1}{\Gamma(\mu-n)} \int_{a}^{t} \frac{f(\xi)}{(t-\xi)^{\mu-n+1}} d\xi
\]  

(1)

The above equation is the fractional Differential operator and the \( \mu \) is the fractional order, \( m \) is an integer, \( \Gamma(.) \) is the Euler’s gamma function, \( n-1 \leq \mu < n \) and the other details is described in [10]. For usage of fractional operator in application study, it is necessary that the approximation in integer order transfer function form be obtained. In this paper the Oustaloup’s approximation [10] is used for approximation and its formulation is as follows:

\[
s^\mu = K \prod_{i=-p}^{p} s + \omega_i^{*}
\]

(2)

\[
\omega_i^{*} = \omega_i \left( \frac{\omega_i}{\omega_i^*} \right)^{i+\frac{0.5(1+\mu)}{2P+1}}
\]

(3)

\[
\omega_i = \omega_i \left( \frac{\omega_i}{\omega_i^*} \right)^{i+\frac{0.5(1+\mu)}{2P+1}}
\]

(4)

\[
K = \left( \frac{\omega_i}{\omega_i^*} \right)^{\mu} \prod_{i=-p}^{p} \omega_i
\]

(5)

Where, \( \mu \) is the fractional order of derivative, \( 2P \) is the number of zeros and poles, \( \omega_i^{*} \) and \( \omega_i \) is the \( i \)th zero and pole in range of \([\omega_a, \omega_b]\), respectively.

3. FOPID Controller

Definitely, the PID controller is one of the most applicable controller that is used in industrial applications [11]. In the [12] an improved form of PID controller is proposed by converting the integer order of derivative and integrator into the fractional order. This controller is known as FOPID \((PFID^\mu)\) controller. Hence, the only difference between the PID and FOPID controller is the order of calculus operators that make more degree of freedom and flexibility in design and practice. The mathematical formulation of FOPID controller is as follows:

\[
C(s) = K_p + \frac{1}{s^{\mu}} + K_D s^\mu
\]

(6)

Where, the \( K_p, K_i \) and \( K_D \) are proportional, integral and differential gains and the \( \lambda \) and \( \mu \) are fractional order of integrator and derivative, respectively. The structure of FOPID controller is given in Fig. 1.

4. SSO Algorithm

The SSO algorithm is a swarm intelligence based algorithm that is proposed by Erik Cuevas et.al [13] in 2013. This algorithm simulate the cooperative behavior of the social spiders and its mechanism is based on two different search agent known as female and male spider. The SSO has a special structure to find the solutions in the search space, so that it make the balance between exploration and exploitation and also, prevents falling into the local optimum. It’s assumed that the all spiders communicate with each other by the communal web that makes the search space in this algorithm. Actually, the communal web is the link that the spiders transform information through it and the information is transferred using the produced vibration by the spiders. The three different types of vibration inspired by biological principles of the social spiders are modeled and described following. Here, a brief of the algorithm is explained and in detail expressed in [13]. The vibration realized by ith spider as a result of the information transformed by jth spider and is as follows:

\[
Vib_{i,j} = w_i e^{-d_{i,j}}
\]

(7)

Where, the \( d_{i,j} \) is the Euclidian’s norm between the spiders i and j. Similarly, \( Vib_{c} \) is the vibration realized by ith spider as a result of the transformed information by the cth spider that has two major characteristics as following: it is the nearest spider to ith spider and has a higher weight in comparison to i \( (w_c > w_i) \). \( Vib_{f_i} \) is the
vibration realized by \( i \)th spider as a result of the transformed information by the \( b \)th spider that has highest weight in whole population. \( V_{ibf} \) is the vibration realized by \( i \)th spider as a result of the transformed information by the \( f \)th spider that is the nearest female spider to the \( i \). The formulations of above definition about different type of vibration are given following:

\[
V_{ibc} = w_i e^{-d_{ic}} 
\]

\[
V_{ibb} = w_i e^{-d_{ib}} 
\]

\[
V_{ibf} = w_i e^{-d_{if}} 
\]

The flowchart of the SSO algorithm is shown in Fig. 2.

**5. FOPID Design for LFC Problem**

In this paper, the FOPID controller based on SSO algorithm has been investigated for LFC in the two area multi-source interconnected power system including three generation power in each control area that can be seen at Fig. 3. The control area-1 is consist of thermal reheat, hydro and gas power plant and control area-2 including thermal reheat, hydro and diesel power plant [14, 15]. Each plant need to be controlled by a controller, as a result, there are six FOPID controller and each controller has five parameters that should be tuned using SSO algorithm to achieve acceptable response. High performance of the proposed controller has been shown by applied on the tested system in the presence of nonlinearity and uncertainties in the power system parameters. Furthermore, in order to improve the damping of the frequency deviation the RFB and SMES are considered in simulation. To evaluate the performance of the SSO based FOPID controller it is need to discuss some error criterion such as ITEA and performance indices such as settling time and peak overshoot of power system response to load disturbances in different operation conditions. The proposed objective function is considered as follows:

\[
J = a_1 ITAE + a_2 (OS) + a_3 (ST) 
\]

\[
ITAE = \int_0^{t_{\text{sim}}} \left( |\Delta f_1| + |\Delta f_2| + |\Delta P_{\text{Tie-line}}| \right) dt 
\]

\[
OS = os_1 + os_2 + os_3 
\]

\[
ST = st_1 + st_2 + st_3 
\]

Where, \( \Delta f_1 \) and \( \Delta f_2 \) are the frequency deviation in control area-1 and area-2, respectively and \( \Delta P_{\text{Tie-line}} \) is tie-line power deviation. \( os_1 \), \( os_2 \) and \( os_3 \) are the peak overshoot and \( st_1 \), \( st_2 \) and \( st_3 \) are the settling time of the frequency deviation of area-1, area-2 and tie-line power deviation, respectively. The \( a_i \) coefficients are adjusted so that the all terms of Eq. (11) be in the same range.

The GRC and SMES model that have been used in this paper are shown in Fig. 4 [15, 16]. The GRC is considered 3% per min at the thermal unit in each control area and the power system parameters are given in Appendix. The SMES parameters must be optimized to improve the power system performance. The simulation is performed for three case studies as following:

**Case 1.** The FOPID controller has been applied on the two area multi-source interconnected power system considering GRC, only.

**Case 2.** The power system frequency has been controlled in the presence of GRC and considering the RFB in area-1 and SMES in area-2.

The FOPID controller parameters are optimized using SSO algorithm. The SSO and optimized controller parameters are given in Tables 1 and 2 and the SMES parameters optimized by SSO are shown in the Table 3. Also, the frequency deviation of area-1 and area-2 and tie-line power deviation are seen in Figs. 5 to 7. The ITAE and performance indices such as settling time and peak overshoot of frequency and tie-line power deviation related to both of cases are given in the Table 4.
Table 1. Value of SSO algorithm parameters for LFC problem

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population size</td>
<td>50</td>
</tr>
<tr>
<td>Iteration</td>
<td>50</td>
</tr>
<tr>
<td>Female Percent</td>
<td>64</td>
</tr>
<tr>
<td>Male percent</td>
<td>6</td>
</tr>
<tr>
<td>Upper limit of K, K, and Kf</td>
<td>+10</td>
</tr>
<tr>
<td>Lower limit of K, K, and Kf</td>
<td>-10</td>
</tr>
<tr>
<td>Upper limit of K_SMES</td>
<td>2</td>
</tr>
<tr>
<td>Lower limit of K_SMES</td>
<td>0</td>
</tr>
<tr>
<td>Upper limit of λ and μ</td>
<td>0</td>
</tr>
<tr>
<td>Lower limit of λ and μ</td>
<td>1</td>
</tr>
<tr>
<td>Upper limit of T, T, T, T, and T_SMES</td>
<td>1</td>
</tr>
<tr>
<td>Lower limit of T, T, T, T, and T_SMES</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2. Value of optimized FOPID controller parameters using SSO algorithm

<table>
<thead>
<tr>
<th>Control Parameters</th>
<th>Thermal</th>
<th>Hydro</th>
<th>Gas</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kp</td>
<td>-8.5607</td>
<td>8.8461</td>
<td>-1.7102</td>
<td></td>
</tr>
<tr>
<td>Ki</td>
<td>-7.1027</td>
<td>-0.6398</td>
<td>-9.5962</td>
<td></td>
</tr>
<tr>
<td>Kf</td>
<td>2.3955</td>
<td>1.1184</td>
<td>0.5135</td>
<td></td>
</tr>
<tr>
<td>λ</td>
<td>0.8147</td>
<td>0.2370</td>
<td>0.6390</td>
<td></td>
</tr>
<tr>
<td>μ</td>
<td>0.3827</td>
<td>0.5080</td>
<td>0.6390</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Value of SMES parameters optimized by SSO algorithm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>K_SMES</td>
<td>1.9039</td>
</tr>
<tr>
<td>T_S</td>
<td>0.6596</td>
</tr>
<tr>
<td>T_R</td>
<td>0.5762</td>
</tr>
<tr>
<td>T_D</td>
<td>0.1250</td>
</tr>
<tr>
<td>T_SMES</td>
<td>0.2931</td>
</tr>
<tr>
<td>T_DSMES</td>
<td>0.5194</td>
</tr>
</tbody>
</table>

Fig. 3. Multi-source tow area interconnected power system

Fig. 4. (a) The GRC model for thermal unit (b) The SMES model
The settling time of frequency deviation of area 1 for case 1 is 3.5262 s and case 2 is 1.2943 s, same time for frequency deviation of area 2 is 3.9261 s for case 1 and is 1.7276 s and for case 2, the settling time of tie-line power deviation is 3.3334 s for case 1 and is 1.3298 s for case 2. It can be seen the high efficiency of the FOPID controller based on SSO algorithm in LFC problem and power system dynamics response has improved with considering RFB and SMES.

**Case 3.** To illustrate the robustness of the SSO based FOPID controller, uncertainties in the power system parameters are considered with changing in range of [-25%, +25%] from the nominal value of some parameters including \( T_t \), \( T_w \), \( T_{cd} \) and \( T_{ps} \). The \( T_t \), \( T_w \), \( T_{cd} \) and \( T_{ps} \) is the time constant of reheat turbine, time constant of hydro turbine, gas turbine compressor discharge volume-time constant and power system time constant, respectively. The results of simulation are shown in Figs. 8 to 10.

![Fig. 5](image-url)  
**Fig. 5.** Frequency deviations of area 1 for 1% step load disturbance in area 1; Solid (without FRB and SMES) and Dashed (with FRB and SMES)

![Fig. 6](image-url)  
**Fig. 6.** Frequency deviations of area 2 for 1% step load disturbance in area 1; Solid (without FRB and SMES) and Dashed (with FRB and SMES)

![Fig. 7](image-url)  
**Fig. 7.** Tie-line power deviations for 1% step load disturbance in area 1; Solid (without FRB and SMES) and Dashed (with FRB and SMES)

![Fig. 8](image-url)  
**Fig. 8.** Frequency deviations of area 1 for 1% step load disturbance in area 1 with RFB and SMES, Dashed (-25% of nominal value), Solid (nominal value) and Dotted (+25% of nominal value)

![Fig. 9](image-url)  
**Fig. 9.** Frequency deviations of area 2 for 1% step load disturbance in area 1 with RFB and SMES, Dashed (-25% of nominal value), Solid (nominal value) and Dotted (+25% of nominal value)

![Fig. 10](image-url)  
**Fig. 10.** Tie-line power deviations for 1% step load disturbance in area 1 with RFB and SMES, Dashed (-25% of nominal value), Solid (nominal value) and Dotted (+25% of nominal value)
Table 5. Value of ITAE, settling time and peak overshoot in presence of ±25% change in system parameters

<table>
<thead>
<tr>
<th>Parameters Change</th>
<th>-25%</th>
<th>Nominal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITAE</td>
<td>0.0235</td>
<td>0.0194</td>
</tr>
<tr>
<td>$T_{1}$, Settling Time (0.2%) Overshoot</td>
<td>2.9222</td>
<td>2.2943</td>
</tr>
<tr>
<td>$T_{2}$, Settling Time (0.2%) Overshoot</td>
<td>0.0441</td>
<td>0.0144</td>
</tr>
<tr>
<td>$M_{P}^{\text{peak}}$, Settling Time (0.2%) Overshoot</td>
<td>4.3252</td>
<td>2.7276</td>
</tr>
<tr>
<td>$M_{C}^{\text{peak}}$, Settling Time (0.2%) Overshoot</td>
<td>0.0043</td>
<td>0.0045</td>
</tr>
</tbody>
</table>

Based on the obtained results of Table 5 and Figs. 8-10 and comparison of ITAE index, settling time and overshoot for frequency deviations of each control area, the good performance damping of the proposed controller against various uncertainties is achieved. These outcomes show that the SSO based FOPID controller has a high ability in improvement the dynamics performance of the two area multi-source interconnected power system in presence of different operation conditions and nonlinearities such as GRC and uncertainties in the power system parameters.

6. CONCLUSION

In this paper, the FOPID controller based on SSO algorithm is proposed to solve the LFC problem in a multi-source two-area interconnected power system. The objective function is combination of ITAE and sum of settling times of the frequency deviations of each control areas and tie-line power deviations. The results demonstrate that the SSO based FOPID controller associated with RBF and SMES have a high ability in damping the frequency deviation of control areas and tie-line power deviation. The control parameters has been tuned using SSO algorithm that is capable at obtaining the optimum solutions in optimization problems. The proposed method has been applied on power system considering nonlinearity such as GRC and parameters uncertainties in power system. The results reveal high ability of the proposed control method to balance the power system frequency deviations in the presence of uncertainties, nonlinearity in power system structure and load disturbance.

APPENDIX

The value of under study system parameters in Fig. 2 are given below:

- $f = 60$ Hz, $B_{1} = B_{2} = 0.4312$ pu MW/Hz; PR = 2000MW (rating), $P_{L} = 1840$ MW (nominal loading); $T_{cs1} = T_{cs2} = 10$ s; $K_{11} = K_{12} = 0.3$; $T_{p1} = T_{p2} = 2.2943$ s; $R_{s1} = R_{s2} = R_{g} = 2.4$ Hz/pu MW; $T_{ms1} = T_{ms2} = 0.035$ s; $K_{m1} = K_{m2} = 0.543478$; $K_{d1} = K_{d2} = 0.326084$; $K_{i1} = K_{i2} = 0.130438$; $T_{i1} = T_{i2} = 0.2$ s; $T_{ni1} = T_{ni2} = 28.75$ s;
- $T_{ms1} = T_{ms2} = 11.49$ s; $K_{ps1} = K_{ps2} = 0.0433$ pu.
- $T_{00} = 0.0027$; $T_{01} = 0.027$; $T_{02} = 0.2067$.

REFERENCES


BIographies

Heidar Ali Shayanfar received the B.S. and M.S.E. degrees in electrical engineering in 1973 and 1979, respectively. He received the Ph.D. degree in electrical engineering from Michigan State University, East Lansing, MI, USA, in 1981. Currently, he is a Full Professor with the Department of Electrical Engineering, Iran University of Science and Technology, Tehran, Iran. His research interests are in the application of artificial intelligence to power system control design, dynamic load modeling, power system observability studies, voltage collapse, congestion management in a restructured power system, reliability improvement in distribution systems,
smart grids and reactive pricing in deregulated power systems. He has published more than 520 technical papers in the international journals and conferences proceedings. Dr. Shayanfar is a member of the Iranian Association of Electrical and Electronic Engineers.

Hossein Shayeghi received the B.S. and M.S.E. degrees in Electrical and Control Engineering in 1996 and 1998, respectively. He received his Ph.D. degree in Electrical Engineering from Iran University of Science and Technology, Tehran, Iran in 2006. Currently, he is a full Professor in Technical Engineering Department of University of Mohaghegh Ardabili, Ardabil, Iran. His research interests are in the application of robust control, artificial intelligence and heuristic optimization methods to power system control design, operation and planning and power system restructuring. He has authored and co-authored of 5 books in Electrical Engineering area all in Farsi, one book and two book chapters in international publishers and more than 330 papers in international journals and conference proceedings. Also, he collaborates with several international journals as reviewer boards and works as editorial committee of three international journals. He has served on several other committees and panels in governmental, industrial, and technical conferences. He was selected as distinguished researcher of the University of Mohaghegh Ardabili several times. In 2007 and 2010 he was also elected as distinguished researcher in engineering field in Ardabil province of Iran. Furthermore, he has been included in the Thomson Reuters’ list of the top one percent of most-cited technical Engineering scientists in 2015 and 2016, respectively. Also, he is a member of Iranian Association of Electrical and Electronic Engineers (IAEEE) and senior member of IEEE.

Abdollah Molaee was born in Kermanshah, Iran, in 1988. He received the B.S. degree in Electrical Engineering from the Kermanshah University of Technology, Kermanshah, Iran, in 2013. He currently is M.S. Degree student in Electrical Engineering from University of Mohaghegh Ardabili, Ardabil, Iran. His areas of interest in research are the Power System Restructuring and application of heuristic optimization methods and robust control design to power system control.