DIFFERENTIAL EVOLUTION OPTIMIZATION OF PD-PID CONTROLLER FOR A TWO AREA POWER SYSTEM INCORPORATING SOLAR THERMAL RENEWABLE GENERATION AND STORAGE

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ABSTRACT:
This paper presents a two-area thermal system integrating solar thermal power plant in both areas for automatic generation control (AGC). The performance of the cascaded proportional-derivative-proportional-integral-derivative controller is assessed within the modelled system. A redox flow battery is incorporated in area 1 for better control of responses under dynamic conditions. The capability of redox flow battery is analysed for minimizing frequencies and tie-line power of the two-area power system. A replacement technique known as differential evolution algorithm is employed for the improvement of secondary controller gains in automatic generation control. Research disclose that differential evolution technique was capable of optimizing the performance of the controller with battery in area-1 is best than without battery regarding subsiding time, peak overshoot and magnitude of oscillations inside the system.

Keywords: AGC, differential evolution, redox flow battery, solar thermal power plant, renewable energy.

I. INTRODUCTION
Deregulation of the power industry paved many opportunities for independent power producers, private transmission operators and private utilities to take up operations concerning power grids. Renewable energy generation was encouraged to the maximum possible extent and their integration was found at various locations in the grid. While deregulation encouraged more generation through private participation and consumer level renewable power generation it is not without drawbacks. If not controlled properly, it can lead to generation load imbalance, transmission congestion and other technical difficulties. In this situation, it is extremely important to control generation according to system requirements [1, 2]. According to demand, the generation should also be controlled. However, it is highly challenging to stabilize the ever changing load requirement. As a consequence, disparity always exists amongst generated power and requirement of the load. As a result of this, frequency of the system (Δf) and power flow in the tie line deviate from their normal operating values. The scheduled frequency and the power flow in the tie line have to be retained inside approved boundaries posed by regulations; else system is likely to become unstable [3]. It is the function of the Automatic Generation Control (AGC) to maintain the Area Control Error (ACE) value at zero automatically by retaining the frequency of the system and power flow in the tie line within limits. This is necessary for effective and dependable power system operation. The frequency and the tie-line power of the system is retained by the AGC at their prescribed limits and also preserves the power generated at every unit at its optimum point in view of economic operation. AGC operates via two control modes, the main and the auxiliary control. The main control is a swift control mechanism while the auxiliary control is a slow one. Generally governors take care of main control and additional controllers are required for auxiliary control. At present, significant research concerning AGC has been focussed on the development of auxiliary controllers [4].

Owing to environmental issues and fast dwindling fossil fuel based energy resources, it is essential to explore other substitute sources in order to meet the future load demand effectively. Solar and wind power sources are most sought after alternate energy sources. Vast prospective are available with solar power and consistent with contemporary research, it is regarded to become future power source. In this regard, it is intended to study the effects of incorporating these systems in conventional power grids. Hence, a two area system integrating Solar
Thermal (ST) Power Plant will be studied for AGC in this paper for analysing the effects of these alternative sources on the frequency and tie line power of the grid [13]. Literature survey proposed many techniques for controlling and optimizing of auxiliary controller parameters for AGC. In this context, the present paper Differential Evolution (DE) optimization approach is carried out to fine tune the auxiliary control parameters in the system considered.

II. SYSTEM MODELLING

In the present study, a two area four unit power system consisting of a thermal and solar thermal generation in each area is considered and is appropriately designed in MATLAB/Simulink. The system dynamics are attained by considering one percentage step load perturbation (SLP) in area-1. The essential parameters including gain of the controller is optimized using DE technique. Figure 1 shows the block diagram of area 1 incorporating thermal and ST generations. Figure 2 shows the block diagram of area 2 consisting of thermal and ST generation system with Redox Flow Battery (RFB). Step load of 1% is given as input to the ST system in both the areas. The input of the controller is sum of feedback of the system and gain. The output of the controller is given as input in addition with gain to the ST and thermal power systems in both the areas [5, 6].

For modelling of the two area system the following transfer functions (TF) are considered.

For solar thermal power system:
The TF of solar field is \( \frac{K_s}{T_s s + 1} \)
The TF of governor is \( \frac{1}{T_g s + 1} \)
The TF of turbine is \( \frac{1}{T_t s + 1} \)

For thermal power system:
The TF of governor is \( \frac{1}{T_g s + 1} \)
The TF of turbine is \( \frac{1}{T_t s + 1} \)
The TF of reheat turbine is \( \frac{K_r T_r s + 1}{T_r s + 1} \)

The overall TF of the power system is \( \frac{K_p}{T_p s + 1} \)

Where
$K_s$ is the solar field constant
$T_s$ is the solar field time constant
$T_{gs}$ is speed governor time constant of solar thermal
$T_{ts}$ is steam turbine time constant of solar thermal
$T_g$ is the speed governor time constant of thermal
$T_t$ is the steam turbine time constant of thermal
$K_r$ is the steam turbines reheat constant
$T_r$ is the steam turbine reheat time constant
$K_p$ is the power system gain
$T_p$ is the power system time constant

At present for an extensive variety of applications requiring storage redox flow batteries are being utilized. These batteries are a combination of sulphuric acid entailing vanadium ions which are utilized as +ve and –ve electrolytes. These electrolytes are preserved in their corresponding storage containers and are further distributed to battery for operation. The main characteristics of these batteries are: modest working principle and lengthy life, no reserve loss, environmental friendly and superior recyclability, quick response, flexible layout, long life cycle, low maintenance and state of charge determination is easy and therefore delay in response does not occur. In order to reduce large fluctuations in customer demand, the battery is used for secondary control in power system. In order to improve the system response of small load disturbances in load frequency control (LFC) scheme RFBs have been integrated. These are applicable for Load balancing, Electric vehicles, UPS, where battery is used if main power fails to provide an uninterrupted supply, standalone power system, in solar micro grid applications and suitable for medium and large scale energy storage. [7,8,12]. RFB has to be installed in any one of the area to improve the transient response of the system i.e., the peak overshoot and undershoot of the system will be reduced and the system will settle in less time and it will reduce the change in system frequency and change in tie line power thus aiding AGC in a power system [7]. The transfer function of RFB is represented by

$$G_{RFB} = \frac{K_{RFB}}{1+T_{RFB}} \quad (1)$$

Where $K_{RFB}$ is the gain of RFB and $T_{RFB}$ is the time constant of RFB.

For the purpose of AGC, a cascaded PD-PID controller has been designed and implemented. Due to its inherent simplicity PID controller is the best choice, but to enhance the control action of the system and for AGC in multi area power system a PD controller is connected in cascade with the PID controller giving rise to PD-PID cascaded controller. The main drawback of PID controller is that their performance is highly dependent on an appropriate tuning of their coefficients. It has two control circles: inner control circle and outer control circle [9]. PID controller is implemented in the inner circle. It is also known as secondary circle or slave circle and it mainly involves in attenuation of the input disturbances. PD controller is realized in the outer circle. It is also known as primary loop or master circle. This loop is mainly to control the final response of the system. Figure 3 shows the PD-PID cascade controller model.

![PD-PID cascade controller model](image)

**III. DIFFERENTIAL EVOLUTION OPTIMIZATION**

The Integral of Time multiplied by Absolute Error (ITAE) is used as a cost function in this optimization is and it is given as

$$J = ITAE = \int_0^T (|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}|). t. dt \quad (2)$$

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The frequency deviations in area 1 and area 2 are $\Delta f_1$ and $\Delta f_2$, the tie-line power deviation between area 1 and 2 is $\Delta P_{tie}$. Minimize the value of objective function $J$, within the constraints

$$\begin{align*}
K_{p_{\text{min}}} & \leq K_p \leq K_{p_{\text{max}}} \\
K_{I_{\text{min}}} & \leq K_I \leq K_{I_{\text{max}}} \\
K_{D_{\text{min}}} & \leq K_D \leq K_{D_{\text{max}}}
\end{align*}$$

These constraints reduce settling time, peakovershoot and undershoot which cannot be achieved by Integral of Squared Error (ISE) or Integral of Absolute Error (IAE). Hence, ITAE is a superior objective function for optimizing AGC parameters.

A variety of optimization problems incorporate DE technique which belong to a class of evolutionary algorithms used for optimization. Overall, three main advantages encompass DE (1) capable of converging to global optimum regardless of the input estimates required at beginning of the process (2) has fast convergence (3) employs minimal parameters for control and hence its use is easy and modest. In each iteration, the computation process encompasses crossover/recombination, mutation and selection operators. At the start of the process population is set randomly and then the algorithm employs mutation as an operator for exploration and selection as an operator to examine the search space for potential regions to identify global optimum. This algorithm is programmed on the basis of numerous stages which are summarized below.

A. **Initialization**

Assume a function has to be optimized with realistic parameters. Population size, $N$, should be set to be a minimum of four. The probable candidate solution for the vector of parameters for four-dimensional improvement issues have the shape $X_{i,Q} = [X_{1,i,Q}, X_{2,i,Q}, \ldots, X_{4,i,Q}]$ wherever $i=1,2,\ldots,N$ and $Q$ are the unit numbers of the generation. The initial price is haphazardly designated for every candidate within the $[X_{L},X_{H}]$ interval, wherever $X_{L}=\{X_{1,L},X_{2,L},\ldots,X_{D,L}\}$ and $X_{H}=\{X_{1,H},X_{2,H},\ldots,X_{D,H}\}$ is the lower and higher bounds of search area, respectively:

$$X_{j,i,0} = X_{L} + \text{rand}[0,1](X_{H} - X_{L})$$

B. **Mutation**

Three vectors $(X_{r1,Q},X_{r2,Q},X_{r3,Q})$ are randomly selected within the range $[1,NP]$ when a given parameter vector is $X_{i,Q}$ so that the indices $i$, $r1$, $r2$ and $r3$ differ. A donor vector $V_{i,Q}$ is proposed by adding to the third (called base) vector a weighted difference between two vectors

$$V_{i,Q} = X_{r1,Q} + F(X_{r2,Q} - X_{r3,Q})$$

Where the factor for mutation scaling is $F$, and generally has a range of $[0,1]$.

C. **Recombination**

$V_{i,Q}+1$ which is the donor vector and $X_{i,Q}$ which is considered as target vector are assorted to result in a pilot vector

$$U_{j,i,Q} = \begin{cases} 
V_{j,i,Q} & \text{if } \text{rand} \leq CR \text{ or } j \leq j_{\text{rand}} \\
X_{j,i,Q} & \text{otherwise}
\end{cases}$$

Recombination using binomial method is considered in this present work. This is described as

$$U_{j,i,Q} = \begin{cases} 
V_{j,i,Q} & \text{if } \text{rand} \leq CR \text{ or } j \leq j_{\text{rand}} \\
X_{j,i,Q} & \text{otherwise}
\end{cases}$$

Where $J=1,2,\ldots,D$, $I=1,2,\ldots,N$. $CR$ is known as the crossover rate and its role is to control alternate DE parameters parallel to $F$. $J$ rand $[1,2,\ldots,D]$ is a arbitrarily chosen index to certify whether $U_{i,Q}$ achieves at least one dimension of $V_{i,Q}$ or not.

D. **Selection**

Operators required for selection can be realized as
\[ X_{i,Q} +1 = U_{i,Q}, \text{ if } J(U_{i,Q}) < (X_{i,Q}); =X_{i,Q}, \text{ otherwise} \]

The fitness function to be optimized is \( J(X) \). The fitness function is an IAE which demands that \( J(X) \) has to be minimized. Therefore, if a replacement pilot vector chooses a poorer fitness function value, the corresponding target vector is exchanged within subsequent generation; otherwise the target vector stays at the identical value. The population will, therefore, regain efficiency or stay as a preceding fitness value [10,11].

### IV. SIMULATION AND RESULTS

The simulation model of two area power system model under study is represented Figure 4. Cascade PD-PID controller is chosen as auxiliary controller to reinforce the performance of the system. RFB is positioned in area-1 for improving the transient response. The minimum and maximum values of \( K_p, K_i \) and \( K_d \) are chosen as 0 and a couple of respectively. The simplest end solutions obtained within the 100 runs and objective function ITAE are: the controller parameter values are presented in Table 1.

#### Table 1: Controller parameter values

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PD-PID controller without RFB</th>
<th>PD-PID controller with RFB</th>
</tr>
</thead>
<tbody>
<tr>
<td>KP1</td>
<td>0.1676</td>
<td>1.4206</td>
</tr>
<tr>
<td>KP2</td>
<td>1.9618</td>
<td>1.6059</td>
</tr>
<tr>
<td>KI1</td>
<td>0.1441</td>
<td>1.8204</td>
</tr>
<tr>
<td>KI2</td>
<td>1.9652</td>
<td>1.8242</td>
</tr>
<tr>
<td>KD1</td>
<td>0.2356</td>
<td>1.2591</td>
</tr>
<tr>
<td>KD2</td>
<td>0.5200</td>
<td>0.2630</td>
</tr>
<tr>
<td>K_1</td>
<td>1.2199</td>
<td>0.1243</td>
</tr>
<tr>
<td>K_2</td>
<td>0.5672</td>
<td>1.5551</td>
</tr>
<tr>
<td>K_3</td>
<td>0.5929</td>
<td>1.4843</td>
</tr>
<tr>
<td>K_4</td>
<td>1.6558</td>
<td>1.2519</td>
</tr>
<tr>
<td>ITAE</td>
<td>0.2094</td>
<td>0.3442</td>
</tr>
</tbody>
</table>

Fig. 4. Two area power system model
For area-1 at t=0 sec a 1% step load is applied and the values regarding indices performance are shown in Table 2. It can be seen from Table 2, that the PD-PID controller's performance with RFB is better than other techniques. The related transient responses are shown in Fig.5 (a-c). The system responses with and without RFBs are compared in Fig.6 (a-c).

Table 2: Performance index values

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PD-PID without RFB</th>
<th>PD-PID with RFB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settling Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta f_1$</td>
<td>19</td>
<td>16.5</td>
</tr>
<tr>
<td>$\Delta f_2$</td>
<td>19.2</td>
<td>16.6</td>
</tr>
<tr>
<td>$\Delta P_{tie}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\Delta f_1$</td>
<td>0.47</td>
<td>0.25</td>
</tr>
<tr>
<td>$\Delta f_2$</td>
<td>0.23</td>
<td>0.22</td>
</tr>
<tr>
<td>$\Delta P_{tie}$</td>
<td>0.08</td>
<td>0.1</td>
</tr>
<tr>
<td>Peak Overshoot $\times 10^{-3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta f_1$</td>
<td>-7.84</td>
<td>-3.11</td>
</tr>
<tr>
<td>$\Delta f_2$</td>
<td>-6.02</td>
<td>-2.92</td>
</tr>
<tr>
<td>$\Delta P_{tie}$</td>
<td>-1.93</td>
<td>-0.9</td>
</tr>
<tr>
<td>Undershoot $\times 10^{-3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta f_1$</td>
<td>-7.84</td>
<td>-3.11</td>
</tr>
<tr>
<td>$\Delta f_2$</td>
<td>-6.02</td>
<td>-2.92</td>
</tr>
<tr>
<td>$\Delta P_{tie}$</td>
<td>-1.93</td>
<td>-0.9</td>
</tr>
</tbody>
</table>

Fig 5(a) shows the graph for the circuit without considering RFB, taking change in frequency of area1 on X-axis and time on Y-axis. The graph starts at zero, from there it falls to negative and the undershoot occurs at -7.84 Hz, from there it rises to positive and the peak overshoot occurs at 0.47 Hz and it settles at a value of 19.0 Sec. Fig 5(b) shows the graph for the circuit without considering RFB, taking change in frequency of area2 on X-axis and time on Y-axis. The graph starts at zero, from there it falls to negative and the undershoot occurs at -6.02 Hz, from there it rises to positive and the peak overshoot occurs at 0.23 Hz and it settles at a value of 19.2 Sec. Fig 5(c) shows the graph for the circuit without considering RFB, taking change in tie line power on X-axis and time on Y-axis. The graph starts at zero, from there it falls to negative and the undershoot occurs at -1.93 pu, from there it rises to positive and the peak overshoot occurs at 0.08 pu.

Fig 6(a-c) shows the variations of graph for the circuit without RFB (shown by blue line) and considering RFB in area 1 (shown by red line). The red line in fig 6(a) shows the graph for the circuit considering RFB in area1, taking change in frequency of area1 on X-axis and time on Y-axis. The graph starts at zero, from there it falls to negative and the undershoot occurs at -3.11 Hz, from there it rises to positive and the peak overshoot occurs at 0.25 Hz and it settles at a value of 16.5 Sec. The red line in fig 6(b) shows the graph for the circuit considering RFB in area1, taking change in frequency of area1 on X-axis and time on Y-axis. The graph starts at zero, from there it falls to negative and the undershoot occurs at -2.92 Hz, from there it rises to positive and the peak overshoot occurs at 0.22 Hz and it settles at a value of 16.6 Sec. The red line in fig 6(c) shows the graph for the circuit considering RFB in area1, taking change in tie line power on X-axis and time on Y-axis. The graph starts at zero, from there it falls to negative and the undershoot occurs at -0.9 Hz, from there it rises to positive and the peak overshoot occurs at 0.1 Hz. From the values of comparison with and without RFB, it is understood that the overshoot, undershoot and settling time values are better with RFB in area1 than without RFB. From these figures, it’s observed that the PD-PID controller with RFB provides excellent transient responses in terms of less settling time, less peak overshoot and fewer undershoot for frequency change in area-1, frequency change in area-2 and alter in tie-line power and it also reduces oscillations.

![Graph Image](5(a))
Fig 5(a-c): Dynamic responses for 1% SLP in area-1
V. CONCLUSIONS

In this paper, for a two equal-area automatic generation control system, a simplified model of an STPP was incorporated. A comparison of performance of cascaded PD-PID controller with and without RFB in area-1 is discussed. An analysis of the simulation result reveals that superior performance is achieved with the DE algorithm optimized PD-PID controller with the presence of RFB in area-1. It has been identified that the dynamic response of the system with the presence of RFB in area-1 is found to be superior in terms of settling time, peak overshoot, undershoot and oscillation magnitude justifying the use of RFB and optimization.

Appendix 1:

\[
\begin{align*}
&f = 60 \text{ Hz}; \quad T_{gs} = 1.0 \text{ s}; \quad T_{ts} = 3.0 \text{ s}; \quad T_{t} = 0.08 \text{ s}; \quad T_{r} = 10 \text{ s}; \quad K_{p} = 0.5; \quad K_{s} = 1.8; \quad K_{p} = 120 \text{ Hz/pu MW}; \quad T_{p} = 20 \text{ s}; \quad K_{RFB} = 1.87, \quad T_{RFB} = 0, \quad \text{SLP} = 1\% \text{ in area-1}. 
\end{align*}
\]

REFERENCES