Optimal AGC regulator for multi-area interconnected power systems with parallel AC/DC links

Omveer Singh1* and Ibraheem Nasiruddin2

Abstract: The problem of simultaneous tuning of the automatic generation control (AGC) regulator’s gains of multi-area interconnected power system is carried out in this manuscript. Based on the types of area interconnections, a power system model consisting of reheat turbines is investigated by two test cases for the AGC study. In one of the test case AC link is used as area interconnection, whereas the parallel combination of AC/DC links is used as area interconnection in other test case. Each test case control area is consisting of plants with reheat thermal turbines. Genetic algorithm (GA) is used to globally optimize the gains of proportional integral-based AGC regulators with simultaneous optimization of frequency bias coefficient and tie-line power flows. The dynamic response curves are obtained for various system states with the implementation of designed GA-based AGC regulators considering 1% load perturbation in one of the areas. The conventional AGC regulators are also developed using the popularly known Ziegler–Nichols technique. The investigations carried out demonstrate the superiority of proposed regulators over the conventional AGC regulators. The incorporation of DC link in parallel with AC link as an area interconnection has also exhibited favorable effect on dynamic response of the system.

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PUBLIC INTEREST STATEMENT

The management of AGC is a great challenge for power system operators, and is becoming more challenging these days owing to the increasing size and complexity of interconnected multi-area power system for the efficient and successful operation. The prime focus of the power system operators is the retention of an electrical power system characterized by nominal frequency configuration. Development of an efficient AGC scheme with parallel AC/DC transmission links ensures the needs and also DC link enhances the dynamic stability of the power system. Genetic algorithm-based optimal AGC scheme exhibits its excellent flexibility to great extent in the areas of power system.
1. Introduction

With the increasing trends in overall developments and enormous growth in population, the demand for electrical energy has been increasing exponentially over the years. Consequently, new power plants with higher generating capacity have been installed all over the country and compatible transmission and distribution systems are commissioned accordingly to feed the consumers located at far away from generating stations. The entire power industry is put to operate in interconnected fashion due to sharing the various benefits out of pool operation of power systems. However, over the last few decades, many critical areas are selected in the operation and control of such huge structured power systems. Therefore, the efforts have been put forward by the power engineers to make the operation and control of the interconnected power systems more reliable, economic, and effective.

Automatic generation control (AGC) of power systems has been identified as one of the most important entities in overall operation and control perspective of power systems. It has been dealt effectively and efficiently by power engineers by developing better and more effective AGC schemes over the years (Arya, Kumar, & Ibraheem, 2016; Bevrani & Hiyama, 2011; Elgerd & Fosha, 1970; Ibraheem, Hasan, & Hussein, 2014; Ibraheem & Kumar, 2004; Singh & Ibraheem, 2013). AGC has evolved rapidly from the time when the function was performed manually, through the days of analog systems to the present application of sophisticated direct digital control systems. Most of the works have considered net interchange tie-line bias control strategy using area control error (ACE) as a parameter to be mitigated after the disturbances. The existence of ACE means that there is excess or deficient of spinning stored energy which is required to restore the system frequency to scheduled value.

One of the major developments in the area of transmission system is the emergence of high-voltage direct current (HVDC) transmission systems on power scenario in India in the last phase of twentieth Century. Due to inherent technical and economic merits of DC transmission system over AC transmission systems, HVDC transmission systems have gained momentum for their development in India. The DC transmission systems are available up to a voltage level of 800 kV and more HVDC transmission systems are envisaged for the future (Singh & Ibraheem, 2013). Therefore, it needs proper attention of power engineers to include the dynamics of DC transmission system while carrying out the modeling of power system for their AGC studies (Arya et al., 2016; Ibraheem et al., 2014).

Generally, the undesirable effects which disturb the scheduled power exchange and frequency are mitigated using the various types of controllers like integral (I), proportional–integral (PI), and proportional–integral–derivative (PID) controllers. These are probably the most commonly used controllers in the power systems. This is due to its simple structure and ease of use in addition to robustness and their wide range of applicability. Among these controllers, integral controller offers higher maximum overshoot than the PI and PID controller (Nagarath & Gopal, 2001). Therefore, PI and PID controllers are preferred for AGC of power systems. However, PID controllers add the noise level in the communication signals. As PI controllers are free from these drawbacks, they are preferred for designing AGC schemes for power systems.

The classical AGC regulators design based on Ziegler–Nichols (ZN) concept have been found better in many aspects as compared to manually tuned AGC regulators in power systems. The implementation of ZN-based AGC schemes improve steady-state error simultaneously allowing a dynamic response with reduced magnitude in the overshoot. Moreover, a ZN-based scheme adds some
probability to the definite control, and is a better option. The classical control schemes were found inadequate to cope with the desired effective, economic, reliable, and secured operation of AGC of large multi-variable power systems. The application of modern control theory to develop AGC schemes has solved the problems associated with classical concept-based AGC regulators to a great extent. Moreover, the use of microprocessors and computers for online monitoring and control of modern large-scale power systems has motivated the engineers to propose modern and intelligent AGC schemes for fast and more effective control of power systems. The last lap of twentieth century has witnessed many AGC regulator designs using intelligent techniques. Since then many modified and advanced versions of AGC regulator design have been reported in literature (Bevrani & Hiyama, 2011; Singh & Ibraheem, 2013).

In most of these works, dynamic performance of two-area power systems are obtained with the implementation of AGC regulators designed using various control techniques, which are compared to establish the superiority of one technique over the others. Apart from bacteria foraging optimization algorithm (Ali & Abd-Elazim, 2011), grey wolf optimization (Guha, Roy, & Banerjee, 2016), ant colony optimization, artificial neural network, and fuzzy logic concepts (Singh & Ibraheem, 2013), many power researchers have applied genetic algorithm (GA)-based AGC schemes for effective control of power systems.

The GA-based control scheme has played a significant role in its use in AGC of interconnected power systems (Daneshfar & Bevrani, 2012; Dwivedi, Ray, & Sharma, 2016; Ibraheem, Singh, & Hasan, 2009; Mahdavian et al., 2012; Milani & Mozafari, 2011; Rerkpreedapong, Hasanovic, & Feliachi, 2003; Selvakumaran, Rajasekaran, & Karthigaivel, 2014; Topno & Chanana, 2016). It circumvents the disadvantages associated with AGC schemes based on conventional control concept-based controllers which are generally tuned using trial and error methods. Furthermore, these controllers are not effective under certain operating conditions. Also, these are unable to tackle the complexity of the power systems such as nonlinear load characteristics and variable operating points effectively. The GA-based AGC has demonstrated as the right choice for achieving near global optimum values of the feedback gains of the regulators.

Keeping in view the foregoing discussions, AGC regulators based on PI control strategy for a multi-area power system are designed in MATLAB/SIMULINK version 13.1 environment. The GA is used to optimize the feedback gains of AGC regulators. For the sake of comparison, the AGC scheme based on ZN concept is also obtained. A multi-area interconnected power systems model consisting of reheat thermal plants has been selected for investigations. The area interconnections are considered for investigation as: (1) AC link only, (2) parallel AC/DC links. The DC link is considered to be operating in constant current control mode. The incremental power flow through turbine controllers is considered as an additional state variable in systems dynamic model. The designed optimal AGC regulators are tested in the wake of 1% load perturbations in one of the power system areas.

2. Power system model under investigation
A multi-area interconnected power system consisting of three identical power plants with reheat thermal turbines is considered for the present study. A power system model is identified which investigated through test case-I and test case-II. These test cases are depending upon the use of AC and parallel AC/DC links as area interconnection. In test case-I (model-1), AC link is used as area interconnection between all three power system areas, whereas in test case-II (model-2), DC link in parallel with AC link is used as an area interconnection between area 1 and 3, and areas 1–2 and 2–3 are interconnected via AC link only. The power system model test cases are shown in Figures 1 and 2, respectively.

3. AGC parameter scheduling
AGC parameter scheduling is one of the very essential key factors of controlling power systems whose dynamics change due to uncertain operating conditions. It is normally used when the
relationship between dynamics of the system and operating conditions are known, and for which a single linear time-invariant model is insufficient.

In this article, implementation of GA technique to reschedule the parameters of the AGC regulators according to rate of change of the ACE of ith area is carried out. The scheme is depicted in Figure 3.

In conventional controlling systems, the turbine reference power of each area is set by PI controllers. Because a perturbation in either area affects the frequency in both the areas and a perturbation in one area is observed by the other area through a deviation in tie-line power flow. The AGC regulator of each area is not important only for the local frequency variation, but also for the tie-line power deviations. The AGC regulators used just these states as an input. Therefore, it must be combined into a single flat signal can be inputted in the regulator. The simplest path of doing this is to combine them, linearly, which are shown in the block diagram of an interconnected power system model. Model test cases considered ACE, in Figures 4 and 5, respectively. Symbol used with suffix “i” refer to area-1, those with suffix 2 refer to area-2, and those with suffix 3 refer to area-3. Mathematically, for area-1, area-2, and area-3, these can be represented by
After putting the numerical values for system parameters involved in the development of model test cases as given in Appendix A, the resulting transfer function models can be derived. The transfer functions of the power system model tests are shown below in Equations (4–6).

\[
ACE_i = B_i \Delta F_i + \Delta P_{tie_{ij}} 
\]

(1)

\[
ACE_2 = B_2 \Delta F_2 + \Delta P_{tie_{23}} 
\]

(2)

\[
ACE_3 = B_3 \Delta F_3 + \Delta P_{tie_{31}} 
\]

(3)

After putting the numerical values for system parameters involved in the development of model test cases as given in Appendix A, the resulting transfer function models can be derived. The transfer functions of the power system model tests are shown below in Equations (4–6).

\[
G_{gi} = \frac{K_{gi}}{1 + sT_{gi}} 
\]

(4)

\[
G_{ri} = \frac{1 + sK_{ri}T_{ri}}{1 + sT_{ri}} 
\]

(5)

\[
G_{ti} = \frac{K_{ti}}{1 + sT_{ti}} 
\]

(6)

An appropriate transfer function model is developed to study the problem of AGC. It is traditionally assumed that each control area can be represented by an equivalent governor, turbine, and generator system. These test cases are shown in Figure 6 for power system model test case-I (with AC links only) and test case-II (with parallel AC/DC links).
4. Tuning of conventional AGC parameters

The prime focus is to be addressed by AGC regulators to minimize ACE, to zero as a control variable (Dwivedi et al., 2016). The AGC regulators based on PI control structure have an output as a control signal represented by

\[ U_{\text{PI}}(t) = K_p e(t) + K_i \int_0^t e(t) \, dt \]  

where the \( U_{\text{PI}}(t) \) is the control inputs for the governors, \( e(t) \) the error, i.e. rate of change in ACE, of ith area interconnected power systems. \( K_p \) is the PI controller gain parameter. ACE, is the summation of change in frequencies and transmission link power flows.

\[ \text{ACE}_i = B_i \Delta F_i + \Delta P_{\text{tie-}i} \]  

Performance index \( J \) can be defined by adding the sum of squares of cumulative errors in ACE, and used as a fitness function for ZN technique. The \( J \) is given by

\[ J = \int_0^t \text{ACE}_i^2 \, dt \]  

where \( t \) is the power system model real simulation time.

Based on tuned value of \( J \) calculation problem for a multi-area interconnected power systems can be stated as follows:

Minimize \( J \)

Subjected to the limitations:
The tuning process of the PI controller’s gains is generally performed by a heuristic ZN method. They described simple mathematical procedures for tuning classical PI controllers (Nagarath & Gopal, 2001). It is performed by setting the integral gain ($K_I$) to zero, the proportional gain ($K_P$) is increased (from zero) until it reaches the critical ultimate gain ($K_U$), at which the output of the loop starts to oscillate. $K_U$ and oscillation of ultimate time period ($T_U$) are used to set the proportional and integral gains depending on the regulators used as shown in the Table 1.

| Regulators | $K_P$ | $K_I$ |
|------------|-------|-------|
| P          | $K_I/2$ | -     |
| PI         | $K_I/2.2$ | 1.2$K_I/T_U$ |

$K_{Pl,j}^{min} \leq K_{Pl,j} \leq K_{Pl,j}^{max}$

$B_{Pl,j}^{min} \leq B_{Pl,j} \leq B_{Pl,j}^{max}$

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5. Designing of optimal AGC regulator

GA is an optimization method based on the routine technical aspects of natural selection (Goldberg, 1989; Grefenstette, 1986; Michalewicz, 1995; Miranda, Srinivasan, & Proença, 1998). In nature, weak and unfit species within their surrounding are faced with extinction by natural selection. The healthy ones have more chance to pass their genes to future generations. In the tedious steps, species carrying the right combination in their genes become leader in their population. During the slow movement of evolution, random transitions may present in genes for sometimes. If these transitions develop additional benefits in the challenge for survival, new species develop gradually from the old ones. Transitions which are not successful, they eliminated by natural selection.

Real-coded floating-point numbers are used in the GA representation which has a number of benefits over binary encoding (Michalewicz, 1995). The GA capability gets enhanced as there is no need to encode/decode the result variables into the binary type. The technique is frequently employed in the optimization problems and field of the power systems (Miranda et al., 1998). GA is developed for AGC using the following sequential steps in this investigation.

5.1. Chromosome structure

GA has an output vector known as species or a parent or a chromosome. Chromosomes are made of continuous units called genes. Every gene handles one or more qualities of the chromosome (Michalewicz, 1995). The chromosome string consists of $J$ of AGC encoded as a string of real numbers.

5.2. Fitness function evaluation

The objective here is to minimize the deviation in the frequency and tie-line power flows of all areas of the power system. These deviations are weighted together by a linear combination to a single variable called the ACE. The fitness function is taken as the integral square error (ISE) value of ACE, at every continuous time instant in the investigation (Selvakumaran et al., 2014). The $J$ is used to find the optimal $K_{Pl,j}$ and $B_{Pl,j}$. $J$ can be used as a fitness function for GA optimization technique.

5.3. Selection

This process handles the population of the parents to select the results that help in the creation of future generations. This technique imitates natural selection selected by biological environments. A newest population is created from the healthy members, and weak members (poor performers) are diminished. Healthy members are selected for the sake of passing qualities to future populations. Selection is a technique of selecting a parent which will survive and shift on to the next generation.
based on the fitness function from a population of parents in the GA. In the proposed technique, rank-based selection criterion is utilized for selection process of fit members.

The rank-based selection scheme is to select a group of parents randomly from the population. The parents in this group are then measured with each other, with the fittest among the group going to be the selected as parents. In the fitness task, the population is arranged according to the fitness values. The fitness defined to each parent depends only on its status in the parents rank, and not on the real fitness value. This selection strategy is shown in Figure 7.

5.4. Crossover
It is the key genetic operator, capable of evaluating new parents within the search space. It is an event of transferring qualities between parents. Random selection of two of the parents from the breeding pool is carried out. Following that, a crossover point is taken. The crossover process is also named as recombination.

This operator uses the quality according its need for a pair of parents to create two healthy children by replacing corresponding parts from the parents coding (Michalewicz, 1995). Crossover operation exhibition in the most popular uniform crossover is taken which is shown in Figure 8.

5.5. Mutation
Mutation is a path of involving random alteration of quality to put a new updated parent. It is the repair of search diversification for the parent in the assurance path. It is confidence to be a coming after previous operator which lengthens the search place. This algorithm is governed carefully and moderately. One or more of the gene of an existing parent; mutation generates latest children's and thus increases the variability of the population by updating. In the present algorithm, uniform mutation is adopted which is also exhibited in Figure 9.

5.6. Elitism
The probabilistic habit of adoption supports a probability that the fittest generation of the population is finished by the utilization of genetic operators. An elitist criterion is employed in order to remedy the situation. It makes the guaranty that the fittest generation is moved into the next
generation. The GA checks the expected replication of the best generation. Elitism is a method to save and use previously found best parents in subsequent generations of GA. The population of best parents can’t degrade with generation in an elitist GA. This speeds up the convergence operation to achieve global optima.

5.7. Convergence criteria
The processes stop as soon as the criterion of convergence is satisfied. This convergence criterion moves in between PI regulators feedback gains margins. An extensively used convergence criterion is that:

(i) Ending the algorithm when the average value of the fitness of the population becomes satisfactory.
(ii) Ending the algorithm after an assigned number of generations.
(iii) Ending the algorithm when the yielded parent does not present any improvement after a definite number of generations.

5.8. Pseudo-code for the proposed GA

Step 1: Initialization
Set gen = 1, randomly create $N$ generations to form the first population ($P_i$). Calculate the fitness of generations in $P_i$. Initialize the probabilities of crossover ($P_c$) and mutation ($P_m$). These parameters are assigned according to the structures of $J$ for optimization.

Step 2: Selection
Select the parents that help to the population at the next generation. Rank-based selection a criterion is defined to select the next level generation.

Step 3: Crossover
Create a population of child (healthy parent for next generation),

if $P_c > \text{random}$,

Select one best generation from $P_i$ based on the fitness values, and random generation from the population for crossover process. Using a crossover operator, create children and sum up them. Then, back into the population.

\[
\begin{align*}
\text{child}_1 &= r \text{ parent}_1 + (1 - r) \text{ parent}_2; \\
\text{child}_2 &= r \text{ parent}_2 + (1 - r) \text{ parent}_1;
\end{align*}
\]

end if

Step 4: Mutation
Mutation reschedules the parent, to create a single new child.

if $P_m > \text{random}$,

Mutate the selected generation with a pre-specified mutation rate.

end if
**Step 5: Fitness task**

The fitness function specified by Equation (9) is minimized for the feasible solution.

**Step 6: Elitism**

The selected number of elite parents (best parents) is saved in subsequent parents in the population.

**Step 7: Stopping criterion**

If the maximum number of generations have extended, then finish the search and return back to the fresh population, else, set generation = generation + 1 and go to Step 2.

end while

The GA is used here employs direct calculation of the parameters. The values of GA operator used for optimization are given in Appendix A and additionally its flow chart is described in Figure 10.

### 6. Results and discussion

The feedback gains of the AGC regulators and biasing constants of the power system model test cases are obtained using ZN and GA methods. For the study, a multi-area power system model is considered with different area interconnections. The values of $K_{PI_i}$ and $B_{PI_i}$ obtained for the AGC regulators are given in Table 2. To study the dynamic performance of power system models, the time response plots are plotted for various system operating conditions with the implementation of designed AGC regulators considering 1% load disturbance in one of the power system areas. The response plots are shown in Figures 11-22. The time domain characteristic specifications calculated from time response plots are given in Table 3.

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**Table 2. Feedback gains and frequency bias constants for ZN-tuned PI and optimal GA-based AGC regulators**

| Regulators | $K_p$ | $K_i$ | $B_1$ | $B_2$ | $B_3$ |
|------------|-------|-------|-------|-------|-------|
| PI         | 0     | 0.341 | 0.425 | 0.425 | 0.425 |
|            | 2.32  | 0.132 |       |       |       |
|            | 2.30  | 0.129 |       |       |       |
| GA         | 1.999 | 0.299 | 0.115 | 0.115 | 0.115 |
|            | 1.976 | 0.275 |       |       |       |
|            | 1.678 | 0.264 |       |       |       |
Figure 11. Dynamic response of $\Delta F_1$ for 1% load disturbance in area-1.

![Graph](image1)

Figure 12. Dynamic response of $\Delta F_2$ for 1% load disturbance in area-1.

![Graph](image2)

Figure 13. Dynamic response of $\Delta F_3$ for 1% load disturbance in area-1.

![Graph](image3)
Figure 14. Dynamic response of $\Delta P_{tie12}$ for 1% load disturbance in area-1.

Figure 15. Dynamic response of $\Delta P_{tie23}$ for 1% load disturbance in area-1.

Figure 16. Dynamic response of $\Delta P_{tie31}$ for 1% load disturbance in area-1.
Figure 17. Dynamic response of ACE₁ for 1% load disturbance in area-1.

Figure 18. Dynamic response of ACE₂ for 1% load disturbance in area-1.

Figure 19. Dynamic response of ACE₃ for 1% load disturbance in area-1.
Figure 20. Dynamic response of $\Delta F_1$ for 1% load disturbance in area-1.

Figure 21. Dynamic response of $\Delta P_{tie31}$ for 1% load disturbance in area-1.

Figure 22. Dynamic response of ACE1 for 1% load disturbance in area-1.

Table 3. Time domain specifications of power systems model with GA-based AGC regulators

| Time domain specifications | First peak overshoot, $s$ (ACE1) | Settling time, $s$ (ACE1) | Fitness function (ISE) |
|---------------------------|---------------------------------|--------------------------|------------------------|
| Test case-I (without DC link) | $-0.0104$ | More than 10 | $6.5304e^{-04}$ |
| Test case-II (with parallel AC/DC links) | $-0.0057$ | 10 | $5.9522e^{-04}$ |
From the inspection of time domain specifications of ACE, for both test cases as given in Table 3, it is inferred that for power system model with parallel AC/DC links, there is an appreciable reduction in the swing of first overshoot and settling time of the ACE response plots in comparison to power system model without DC link. The similar conclusion is drawn for the values of fitness function ISE.

The patterns of Figures 11–13 show dynamic responses of the frequency deviations of all three areas of power model test cases under investigation. From these plots, it is revealed that the dynamics performance of GA-based AGC regulators is much better than uncontrolled and ZN-tuned AGC regulators. The analysis of plots of Figures 14–16 reveals that proposed AGC regulators are capable to mitigate the deviations in tie-line power flow of the control areas. However, there is an appreciable improvement in the peak overshoot of $\Delta P_{\text{tie}}$ by implementing proposed AGC regulators.

The response curves of Figures 17–19 are show that value of the amplitude of ACEs is reduced to zero within 4 s. of time. It is needless to say that design and implementation of AGC regulators are necessary to mitigate the persistent steady-state error which is present in the dynamic responses after the disturbance.

The fashion of the responses of Figures 20–22 present frequency deviation, tie-line power flow, and ACE in area-1 for both cases in power system model. These Figures show that there is an appreciable improvement in dynamic performance of the power system incorporating AC/DC links as area interconnection rather than using AC link only.

7. Conclusion
GA is proposed in this manuscript to optimize the parameters of PI regulators for AGC domain. AGC of a multi-area power system including thermal reheat turbines with parallel AC/DC links is considered to show the efficacy of proposed technique. The $J$ has been taken as the sum of squares of cumulative errors in ACE. Investigational results present that the developed GA-optimized controllers are robust in its operation and provides an excellent damping performance both for frequency and tie-line power variation compared to ZN-tuned PI regulators. Moreover, its dynamic performance is far better than that could be achieved by ZN-tuned controller. Also, these proposed regulators have a simple structure and the potentiality of implementation in real-time scenario.

The proposed model is derived based on difference between the frequency deviations at both ends of the DC link. It is desirable to carry out further study with a more rigorous and comprehensive model of incremental power flow through DC link to investigate the performance of interconnected power systems.

Abbreviations

\[
\begin{align*}
\Delta F_i & \quad \text{incremental change in frequency} \\
(i = 1, 2, 3) & \quad \text{subscript referring to area} \\
\Delta P_{di} & \quad \text{incremental change in load demand (p.u.MW/Hz)} \\
\Delta P_{di} & \quad \text{incremental DC power flow} \\
\Delta X_{gi} & \quad \text{incremental change in governor valve position} \\
\Delta P_{ci} & \quad \text{incremental change in speed changer position} \\
K_{gi} & \quad \text{speed governor gain constants} \\
T_{gi} & \quad \text{speed governor time constant, s} \\
K_{ri} & \quad \text{reheat thermal turbine gain constant} \\
T_{ri} & \quad \text{turbine time constants, s} \\
K_{ri}, T_{ri} & \quad \text{reheat coefficient's and reheat time's, s} \\
K_{pi} & \quad \text{electric system gain constants} \\
T_{pi} & \quad \text{electric system time constants, s} \\
B_i & \quad \text{frequency bias constant (p.u.MW/Hz)}
\end{align*}
\]
$R_i$ speed regulation parameter (Hz/p.u.MW)

$ACE_i$ area control errors

$U_i$ outputs of the regulator’s

$T_{ij}(\infty)$ synchronizing coefficient of AC tie-line

$T_{dc}$ time constant of DC link, s

$K_{dc}$ gain associated with DC link

$G_{gi}$ transfer function of governors

$G_{hi}$ transfer function of reheaters

$\Delta P_{(i,j)}$ transmission line power flows

**Funding**

The authors received no direct funding for this research.

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**Citation information**

Cite this article as: Optimal AGC regulator for multi-area interconnected power systems with parallel AC/DC links, Omveer Singh & Ibraheem Nasiruddin, Cogent Engineering (2016), 3: 1209272.

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Appendix A

Data
For reheat thermal plants (Ibraheem & Kumar, 2004): \( f = 50 \text{ Hz} \), \( P_{r1} = P_{r2} = P_{r3} = 2,000 \text{ MW} \), \( H_1 = H_2 = H_3 = 5 \text{ s} \), \( T_{t1} = T_{t2} = T_{t3} = 0.3 \text{ s} \), \( T_{g1} = T_{g2} = T_{g3} = 0.08 \text{ s} \), \( T_{r1} = T_{r2} = T_{r3} = 10 \text{ s} \), \( T_{p1} = T_{p2} = T_{p3} = 20 \text{ s} \), \( K_{r1} = K_{r2} = K_{r3} = 0.5 \), \( K_{t1} = K_{t2} = K_{t3} = 1.0 \), \( K_{g1} = K_{g2} = K_{g3} = 1.0 \), \( K_{p1} = K_{p2} = K_{p3} = 120 \), \( D_1 = D_2 = D_3 = 0.00833 \text{ p.u.MW/Hz} \), \( R_1 = R_2 = R_3 = 2.4 \text{ Hz/p.u.MW} \), \( B_1 = B_2 = B_3 = 0.425 \text{ p.u.MW/Hz} \), \( M_1 = M_2 = M_3 = 0.167 \text{ (p.u.MW)}^2 \), \( \alpha_i = -1, \Delta P_{i1} = 0.01 \text{ p.u.MW} \).

For AC link/ DC link: \( P_{\text{max}} = 200 \text{ MW} \), \( 2\pi T_{ij} = 0.545 \text{ p.u.MW} \), \( \delta_1 - \delta_2 = 30^\circ \), Subscript referring to area \((i = 1, 2, 3)\) and \((i \neq j)\).

\[ K_{dc} = 1.0, T_{dc} = 0.2 \text{ s}. \]

For GA Technique (Ibraheem et al., 2009): In all the test cases, the parameters of GA are kept same and are given below:

The number of population = 100
Number of parents = 10
Number of children = 100
The number of generation/iteration = 175
Crossover rate = 0.8
Mutation rate = 0.006

The mutation function is taken as Gaussian. The rank-based fitness scaling function is utilized. By minimizing the fitness function, achieve the optimal parameters of PI regulators.