ISSN (Online) 2395-2717

International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
Vol 3, Issue 3, March 2017

Load Frequency Control in Two-Area Interconnected Power System Using Multi-Objective Differential Evolution

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Abstract: — **In this paper, the Multi-objective optimization of Load Frequency Control (LFC) problem of a Two-area interconnected Power system is discussed. The proposed power system consists of two Thermal Generating units. The Multi-objective Differential Evolution (MODE) algorithm is applied to the LFC problem to obtain the control parameters for the optimum performance of the system. Maintaining the Frequency and the Tie-line power in the standard values is the main objective for solving the LFC problem. This problem is solved using the Differential Evolution algorithm where the results obtained are better when compared with the actual Integral and Proportional Integral controller performance in the proposed power system.**

***Index Terms:*— Multi-objective Optimization; Two area interconnected Power System; Differential Evolution (DE); Load Frequency Control (LFC); Integral Controller; Proportional Integral (PI) Controller.**

I. INTRODUCTION

A typical large-scale power system consists of many control areas interconnected together and power is exchanged between control areas through tie-lines. In such systems, frequent changes occur due to the imbalance between the electrical load and the power supplied by the system connected generators. Thus a control system is essential to offset the random load changes and to keep the frequency and the voltage at the constant values[1]. The active power and the frequency control is referred to as Load Frequency Control (LFC), which is also responsible for supplying sufficient and reliable electrical power with good quality[2]. The main objectives of load frequency control (LFC) are to keep the system frequency at the scheduled value and regulate the generator units based primarily on Area Control Error (ACE). During the early stage, the LFC is based on centralized control strategy [3] but it has complex computation and storage complexities. To overcome the mentioned difficulties, decentralized LFC has been developed [4]. Several approaches have been reported to improve the performance of power system under dynamic condition by choosing the variable gain values of the PI controller.

Fuzzy gain scheduled proportional and integral (FGPI) controller [5] for two-area interconnected power system has been reported. A new robust load frequency control using fuzzy logic has been suggested [6], to control the valve position limits and the parametric uncertainties. Differential Evolution Algorithm based fuzzy logic controller is employed [7] to LFC in two-area interconnected power system by considering the effects of governor dead band and generation rate constraints. Designing of an Optimal PI controller for LFC in two-area interconnected thermal power system using real coded DE has been discussed in this paper. One of the population based stochastic search optimization algorithm such as, Particle swarm optimization is applied [8] for automatic generation control (AGC) problem in three-area interconnected thermal units to obtain the optimal gains of PI controller. A new algorithm of Bacteria foraging optimization algorithm (BFOA) is presented [9] for optimal designing of PI controller for LFC in two area interconnected power system to damp out the system oscillations and to overcome the premature convergence problem. Similar population based optimization algorithm of Artificial Bee colony [10] is applied to the interconnected reheat thermal power

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system in order to tune the parameters of PI controllers which are used for AGC. From the literature survey it concludes that, a secured, reliable and stable operation of the power system depends on the proper selection of the controller parameters and the above mentioned approaches are based on single objective optimization.

The practical control problems are characterized by several objectives, such as small overshoot, fast response, minimum steady state error, fast settling time and also it has to provide economical control action. The objectives are conflicting with each other, which must be satisfied simultaneously. In this work, the LFC synthesis is formulated as a Multi-objective optimization problem and is solved using Global Ranking Multi-objective Differential Evolution (GRMODE). The two-area interconnected power system consists of identical Thermal-Thermal units.

II. LFC OF TWO-AREA SYSTEM

2.1 Load Frequency Control

For understanding of control action of LFC, consider the non-reheat Thermal power system shown in Fig. 1. The basic block of power generating unit consists of combination of governor, turbine and generator. As the load varies, the speed or frequency of the generator changes. The speed governor helps to meet active power generation with the demand by controlling the throttle valves which monitor the steam input to the turbine. The turbine unit is used to transform the natural energy, such as the energy from the steam or water, into mechanical power which is supplied to the generator. The generator unit of the power systems converts the mechanical power received from the turbine into electrical power. But for LFC, the focus is on the rotor speed input i.e., the frequency of the power system, of the generator instead of the energy transformation. The linear model of the LFC is shown in Fig. 1 where the blocks are: non-reheat steam turbine= $\frac{1}{(T_t s+1)}$; load and machine= $\frac{K_p}{(T_p s+1)}$; governor= $\frac{1}{(T_g s+1)}$;

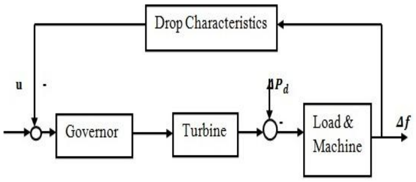

Fig.1 Model of Single area power system

In the above configuration, T_g and T_t are the the governor time constants. K_p= 1/D and Tp= 2H/fD where D is the ratio of load changes percentage to the frequency changes percentage and H is the Inertia coefficient of generator[11]. u is the load reference and ΔPd is the load change.

2.2 System Under Study

As an example of multi area power system, we have considered two area interconnected power system for LFC analysis. In multi-area power system, the primary objectives of the LFC are to keep the system frequency at the standard value, to provide load sharing between the generators proportionately and to maintain the tie-line power exchange at schedule value. For an interconnected system, each area connected to others via tie-line which is the basis for power exchange between them. When there is change in power in area 1, that will be met by the increase in generation in all the areas associated with a change in the tie-line power and a reduction in frequency. But the normal operating state of the power system is that the demand of each area will be satisfied at a normal frequency and each area will absorb its own load changes. There will be area control error (ACE) for each area and this area will try to reduce its own ACE to zero. The ACE of each area is the linear combination of the frequency and the tie-line error, i.e.

ACE=Frequency error + Tie-line error ⟶ (1)

The block diagram of the two-area Thermal power system is depicted in Fig.2. This proposed system is simulated in two types which are, LFC of two area system without controller and the LFC of two area system with controller. The Mathematical modeling can be seen in Appendix section. The below figure represents the Two-area interconnected Thermal power system connected via a Tie-line:

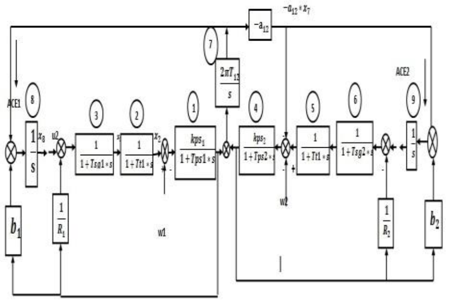

Fig.2 Two-Area Thermal Power System

III. MULTI-OBJECTIVE DIFFERENTIAL EVOLUTION ALGORITHM

By maintaining a population of solutions, Differential Evolution (DE) can search for many non-inferior solutions in parallel. This characteristic makes DEs very suitable for solving Multi-objective problems. Unlike single objective optimization, the solution to point is not a single point, but a family of solution known as the Pareto-optimal set [12]. A Pareto optimal set is a set of solutions that are non-dominated with respect to each other [13]. Pareto-based fitness assignment suggested by Goldberg [14], assigns rank 1 to the non-dominated individuals and removes them from competition, then finds a new set of non-dominated individuals, with rank 2, and so on.

3.1 *Problem formulation*

To apply the optimization techniques to any problem, basically objective function and limitations are to be formulated[15]. A general form of the multi-objective optimization problem (MOOP) subjected to set of equality and inequality constraints is given as follows

Minimize/Maximize $f_k(x)$ $k = 1, 2, \dots, K$
Subjected to $p_i(x) \geq 0$ $i = 0, 1, 2, \dots, I$
$q_j(x) = 0$ $j = 0, 1, 2, \dots, J$

where f_k is k^{th} objective function; parameter x is a design or decision vector that represents a solution:K, I and J are number of objective functions, equality and inequality constraints respectively.

Let x_1 and x_2 are two solutions of MOOP, a solution x_1 is said to dominates x_2 if it satisfies the following two conditions.

i. The solution $x_1$is not worst than x_2 for all objectives i.e.,

$$\text{for all } i \in \{1, 2, \dots, K\}: f_i(x_1) \leq f_i(x_2) \longrightarrow (2)$$

ii. The solution $x_1$is firmly better than x_2 for at least one objective i.e.,

$$\text{there exists } j \in \{1, 2, \dots, K\}: f_j(x_1) < f_j(x_2) \longrightarrow (3)$$

3.2 *Crowding Distance*

The crowding distance is a measure of how close an individual is to its neighbors. The aim of evaluating crowding distance is to obtain a uniform spread of solutions along the best known Pareto front using a fitness sharing parameter. The procedure for evaluating crowding distance is as follows [16] :

Step 1: Rank the population and identify the non-dominated fronts $F_1, F_2, \dots\dots F_r$.

For each front j=1,2,…., r. repeat Step 2.

Step 2: For each objective function, sort the solutions in F_j in the ascending order.

Let L = $|F_j|$ and $f_{(i,m)}$ represent the i^{th} solution in the sorted list with respect to the objective function m. Assign crowding distance ranges as, $cd_m f_{(1,m)}$ = ∞ and $cd_m f_{(L,m)}$ = ∞ and for i= 2,….. , L-1 as:

$$cd_m f_{(i,m)} = \sum_{i=1}^{m} \frac{f_{(i+1,m)} - f_{(i-1,m)}}{f_i^{max} - f_i^{min}} \longrightarrow (4)$$

Where m is the number of objectives, f_i^{max} and f_i^{min} are the maximum and minimum values of i^{th} objective function respectively.

3.3 *Structure of MODE*

A random population of N size is generated. The objective values of each individual are evaluated and then the fitness functions are calculated based on Global fitness assignment. By using the binary tournament selection [17], the parents are selected are based on their global rank values. In this study, the size of the selected parents are chosen as N/2 (half of original population size). The selected population generates off springs (N size) by crossover and mutation operations. In this work, simulated binary crossover scheme and polynomial mutation are used. This new population along with parents are combined and sorted according to the dominance rank and the crowding distance in elitism. By application of these two sorting mechanisms, a population of N size is produced as a new generation. Now the initial population is replaced with the new population, and then the above mentioned procedure is repeated until the termination condition is met. The structure of MODE is shown in below figure:

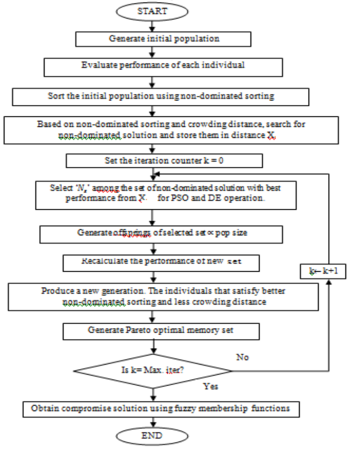

Fig. 3 Flowchart of Multi-objective Differential Evolution

IV. INTEGRAL CONTROLLER

In this study, Integral controller is used as a supplementary control for LFC. The Integral controllers are widely used in industry because of its clear functionality, easy implementation, applicability, robust performance and simplicity. The transfer function of an Integral controller is:

$$G_I(s)= \frac{-K_i}{s} \qquad (5)$$

Here Ki is the Integral gain. In an Integral controller, the integral part minimizes the steady state error. To get the optimum performance of the considered system, the Ki of the Integral controller must be tuned in such a way that, the close loop system produces desired result. The desired result should have minimum settling time, no overshoot and zero steady state error. The parameters of the Integral controllers have been designed using developed Differential Evolution (DE) algorithm.

V. PROPORTIONAL INTEGRAL (PI) CONTROLLER:

Now-a-days, PI controller is most widely adopted in industrial application due to its simple structure, easy to design and low cost. PI controller will eliminate forced oscillations and steady state error resulting in operation of on-off controller and P-controller respectively. However, introducing Integral mode will have a negative effect on speed of the response and overall stability of the system. Thus, PI controller will not increase the speed of the response. It can be expected since PI controller does not have means to predict what will happen with the error in near future. This problem can be solved by introducing derivative mode which has ability to predict what will happen with the error in the near future and thus to decrease a reaction time of the controller. PI controllers are very often used in the industry, especially when speed of the response is not an issue. PI controller fails when the controlled object is highly non-linear and uncertain.

$$G(s)= -k_p - \frac{k_i}{s} \qquad (6)$$

VI. SIMULATION RESULTS AND DISCUSSIONS:

The system model is simulated under dynamic condition. A variety of test cases are considered such as by considering a 10% step increase in load demand in area 1 and area 2 and also by considering 20% changes in the system parameters (k_{pi}, T_{pi} and T_{12}). The population of DE is taken as 20 individuals and the maximum number of generations of 100 is chosen as stopping criteria. The performance of DE generally depends on the Crossover and mutation probabilities. The best result of DE was obtained in this work with the following selection parameters: No. of generations: 100, population size: 50, Crossover possibility: 0.6, Mutation probability: 0.03. The upper and lower limits of PI controller gain values K_p and K_I are selected as (-10,10) and (-5,5) respectively. Once the generation has reached the stopping criteria; it was found that there was no change in the fitness value of all individuals. It concludes that, the single objective optimization has reached the optimum solution.

The system performance under different loading conditions, where 10% increase in load demand is applied in area 1 (case I) and 10% increase in load demand is applied in area 2 (case II) and 10% increase in load demand is applied in area 1 and area 2 simultaneously (case III) are taken into consideration for comparative study analysis.

6.1 Case I: 10% Increased Step load Disturbance (SLD) applied in area 1

A heavy disturbance of 10% SLD is applied in area 1 at t=0sec, the system becomes highly oscillatory. The frequency variations in area 1 and area 2 (ΔF_1 *and* ΔF_2) are shown in Fig.1. It is found that the oscillations are greatly reduced by the proposed controller. Further it can be seen that the performance of the proposed GRMODE PI controller is superior to a conventional PI controller and Single objective DE PI controller by smaller overshoot and settling time. This case study concludes that the proposed GRMODE is better in terms of convergence characteristics. Hence, the proposed controller greatly enhances the system stability and also improves the dynamic characteristics of Power system. The Gain setting values which are the k_I and k_p values, that are obtained using the Pole placement technique have been reduced when the MODE controllers are applied to the area 1 power system i.e., k_I from 0.088 to 0.072. The Frequency response of the area 1 and 2 without controller, with Integral (I) and Proportional Integral (PI) Controllers is shown in Fig. 4.

6.2 Case II : 10% Increase Step Load Disturbance (SLD) applied in area 2

A severe load disturbance of 10% SLD is applied in area 2 at t=0 sec, but area 1 is operating at Nominal load. The Dynamic response of the system is shown in below figure. This illustrates that the system is unstable and becomes more oscillatory. The frequency deviation in area 2 has more overshoot and long settling time as compared to area 1. This is due to the severe disturbance applied in area 2. The stability of the system is maintained with the application of the controller. The effective performance of the proposed controller is also evidenced. This case study concludes that, the stability of the system is improved by the proposed GRMODE controller under disturbance condition. The change in Tie-line power flow to meet the demand is also verified. The proposed controller has small change in power flow and quickly reaches the steady state as compared to conventional and DE controller. The Gain setting values that are the k_I and k_p values have been reduced when compared to The original Pole placement technique to the MODE controllers which are applied to the area 2 power system i.e., $k_p$from -0.100 to -0.250 and k_i from 0.012 to 0.029. The improved response when the MODE is applied to the Power system, is shown in Fig. 5.

6.3 Case III : 10% Increase Step Load Disturbance(SLD) applied in areas 1 & 2

The effective performance of the proposed controller is also verified by applying increased load at both areas simultaneously. A step load disturbance of 10% increase in demand in areas 1 and 2 are applied simultaneously at time t= 0 sec. The response of system under the above disturbance condition is shown below. The heavy disturbance leads to more oscillations in conventional and DE controller as compared to the proposed controller. The stability of the system is greatly affected in the case of conventional controller. The system frequency variations does not reach the steady state within the simulation time of 100 sec, thus for this case the simulation run time has extended up to 120 sec to get the steady state response of conventional controller. From Fig.6 the Pareto Optimum solution was found to be around, ISE= 4.7 and minimum overshoot function =0.1706. Further, it can be seen that, the proposed GRMODE controller exhibits a better performance under heavy load disturbance conditions (increased in both areas) as compared to other two test cases.

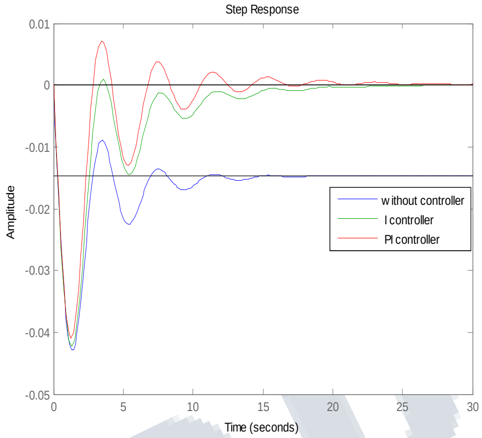

Fig. 4 Frequency Response of Without and With Controllers (Integral and PI) in both area 1 & 2

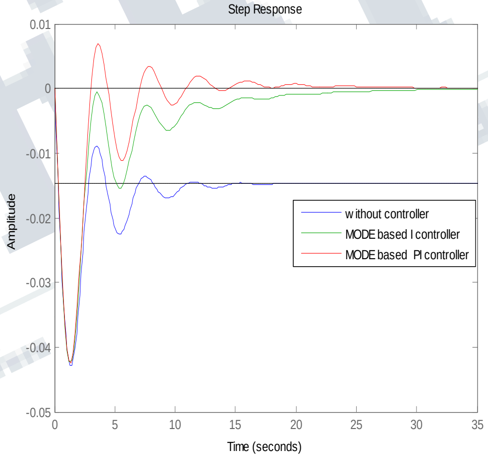

Fig. 5 Frequency Response when MODE is applied

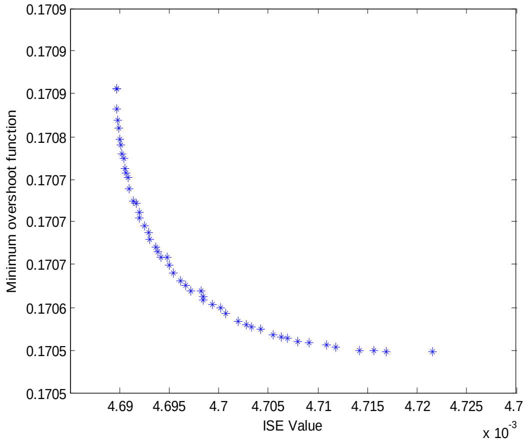

Fig. 6 Pareto Optimal Solution

S.No	Controller	Original System	
		Pole Placement	MODE
1	I	k_{I}= 0.088	k_{I}=0.072
2	PI	k_{p}=-0.100 k_{I}=0.012	k_{p}=-0.250 k_{I}=0.029

Tabular Form 6.1: Gain Setting values for Different Controllers for Original and Reduced order systems

S.No	Controllers	Outputs	I	PI
1	Δy_1	Pole Placement based Controllers	8.270	8.707
2	Δy_1	MODE based Controller	7.590	7.617

Tabular Form 6.2: Comparison of Settling time (in sec) values for output responses using different Controllers

VII. CONCLUSIONS

In this paper, the influence of Integral and proportional integral controller on two-area system is investigated. In implementation, Multi-objective optimization is very different than the single objective optimization. In Single objective optimization, one attempt to obtain the best design or decision, which usually is the Global minimum or the global maximum depending on optimization problem is that of minimization or maximization.

Here, we minimized multi-objective problems by using multi objective optimization. Many factors like settling time, Maximum overshoot, undershoot etc plays vital role in stabilizing the stability of the system. While comparing the Settling time values of the outputs, they have reduced when MODE controllers are applied to the power system i.e., for Integral controller, the Settling time value reduced from 8.270 to 7.59. For PI controller, the Settling time from 8.707 to 7.617.

Simulations by MATLAB programming show that the conventional approach does provide good performances but with long settling time. The proposed DE algorithm based controllers on the other hand provides less settling time, thus ensuring system stability.

Appendix:
Mathematical Modeling

For the above given Two-area interconnected system, the state space equations are formulated as:

$$x_1 = \frac{k_{ps1}}{1+T_{ps1}s}(x_2 - x_7 - w_1) \qquad (7)$$

$$x_2 = (\frac{1}{1+T_{ps1}s})x_3 \qquad (8)$$

$$x_3 = (u_1 - \frac{1}{R_1})(\frac{1}{1+T_{sg1}s}) \qquad (9)$$

$$x_4 = (\frac{k_{ps2}}{1+T_{ps2}s})(\text{-}(\text{-}a_{12}x_7)\text{-}w_2+x_5) \qquad (10)$$

$$x_5 = (\frac{1}{1+T_{t2}s})\, x_6 \qquad (11)$$

$$x_6 = (\frac{1}{1+T_{sg2}s})(\, u_2\text{-}\frac{1}{R_2}x_4) \qquad (12)$$

$$x_7 = \frac{2\pi T_{12}}{s}(x_1\text{-}x_4) \qquad (13)$$

$$x_8 = (1/s)(\, x_7+b_1x_1) \qquad (14)$$

$$x_9 = (1/s)(\, b_2x_4\text{-}a_{12}x_7) \qquad (15)$$

All the above 9 equations can be arranged in the following vector matrix form:

$$\dot{X} = AX + BU + FW \qquad (16)$$

Where the X, U and W are the State, Control and the Disturbance vectors and the A, B and F are the State, Control and Disturbance matrices respectively.

From the state space equations that are obtained by taking their Laplace transformations the State, Control and the Fault matrices are obtained. Then these matrices are converted into Transfer functions using the simulations for both with and without controller systems. Then these Transfer functions are implemented in the optimization of the Load frequency control problem.

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