DESIGN OF MOEA BASED DECENTRALIZED LOAD-FREQUENCY CONTROLLERS FOR INTERCONNECTED POWER SYSTEMS WITH GDB NONLINEARITY

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Abstract: *A new design of Multi-Objective Evolutionary Algorithm (MOEA) based decentralized load-frequency controller for interconnected power systems with Governor Dead band (GDB) Nonlinearity is proposed in this paper. The proposed controller fulfills two main objectives, namely minimum Integral squared error of the system output and maximum closed loop stability of the system. The proposed design procedure is applied to an interconnected two-area thermal power system. The simulation results reveal the effectiveness of the proposed controller to provide better dynamic response with less transients and quick settling time with improved stability margin when compared to a conventional controller.*

Key words: *Power Systems, Load-Frequency Control, Multi-Objective Evolutionary Algorithm, Governor Dead Band Nonlinearity*

1. Introduction

The continuous growth in size and complexity of interconnected power systems, along with increase in power demands has attributed to the vital importance of Load-frequency control (LFC) in electric power system design and operation. The normal operation of an interconnected power system requires that each area maintain the load and generation balance. LFC tries to achieve this balance by maintaining the system frequency and the tie-line flows at their scheduled values. Many control strategies for LFC of power systems have been proposed and investigated by many researchers over the past several years [1]. However, in most of the LFC studies, the effect of the Governor dead band (GDB) nonlinearity is neglected for simplicity. But for a realistic analysis of the performance of the system, this should be included as it has a considerable effect on the amplitude and settling time of the oscillations [2].

The simple classical proportional plus integral controllers are still popular with the power industry because of their inherent simplicity, easy realization, robust and decentralized nature of the control strategy [3]. The Integral Squared Error (ISE) criterion is used for obtaining proper controller gain settings. However, the frequency deviations and tie-line power deviations persist for a long duration even though zero steady state errors are ensured. Controllers designed on the basis of ISE criterion are often of practical significance because of the minimization of control effort. But the system has poor relative stability. Hence, to obtain the decentralized controllers with improved stability margin, they are designed on the basis of Maximum Stability Margin (MSM) criterion using Lyapunov method. However, Controllers designed on the basis of MSM criterion do not posses the inherent good properties of the controller designed on the basis of ISE criterion even though there is improvement in stability [4]. Therefore, it is expected that an appropriate multi-objective control strategy will be able to give a better solution for this problem.

Many Evolutionary Techniques have been extensively used for the design of LFC for isolated as well as interconnected power systems [5]. But, they have been mainly applied to LFC problems treated as single-objective optimization problems. Hence, a new design of proportional plus integral controllers using Multi-Objective Evolutionary Algorithm (MOEA) is proposed in this work, for the decentralized load-frequency control of interconnected power systems with GDB nonlinearity to achieve a better transient, as well as steady state response and closed loop stability of the system. The LFC problem is formulated as a Multi-Objective Optimization problem where ISE criterion and MSM criterion are treated as competing objectives. The proposed controller has been applied to an interconnected two-area thermal power system

with two thermal generating units and Governor dead band nonlinearity in each area.

2. Statement of the problem

The block diagram representation of a two area interconnected thermal power system is shown in Fig.1. Each of the area in the interconnected power system consists of two thermal generating units and includes GDB nonlinearity. GDB is defined as the total magnitude of a sustained speed change within which there is no change in valve position. A describing function approach is used to incorporate the GDB nonlinearity [2].

The dynamic behaviour of the LFC system is described by the state space equation

$$\dot{x} = Ax + Bu + \Gamma d \tag{1}$$

where

$$x = \begin{bmatrix} \Delta F_1 \ \Delta P_{g11} \ \Delta X_{e11}' \ \Delta P_{g12} \ \Delta P_{g12}' \ \Delta X_{e12}' \ \Delta P_{e1} \\ \Delta F_2 \ \Delta P_{g21} \ \Delta X_{e21}' \ \Delta P_{g22} \ \Delta P_{g22}' \ X_{e22}' \end{bmatrix}^T$$

$$u = \begin{bmatrix} \Delta P_{c1} \ \Delta P_{c2} \end{bmatrix}^T \text{ and}$$

$$d = \begin{bmatrix} \Delta P_{d1} \ \Delta P_{d2} \end{bmatrix}^T$$

are the state, control and disturbance vectors and A, B and Γ are respectively system state matrix, control input matrix and disturbance input matrix of appropriate dimensions. The corresponding co-efficient matrices are obtained using the nominal system parameter values given in Appendix B. A step load disturbance of 1% has been considered as a disturbance in the system.

It is known that, by incorporating an integral controller, the steady state requirements can be achieved. In order to introduce integral function in the controller, the system equation (1) is augmented with new state variables defined as the integral of $ACE_i \left(\int v_i \, dt \right), i = 1, 2$.

The augmented system of the order $(2 + n)$ may be described as

$$\dot{\bar{x}} = \bar{A}\bar{x} + \bar{B}u + \bar{\Gamma}d \tag{2}$$

$$\bar{x} = \begin{bmatrix} \int v dt \\ x \end{bmatrix} \begin{matrix} \}2 \\ \}n \end{matrix}$$
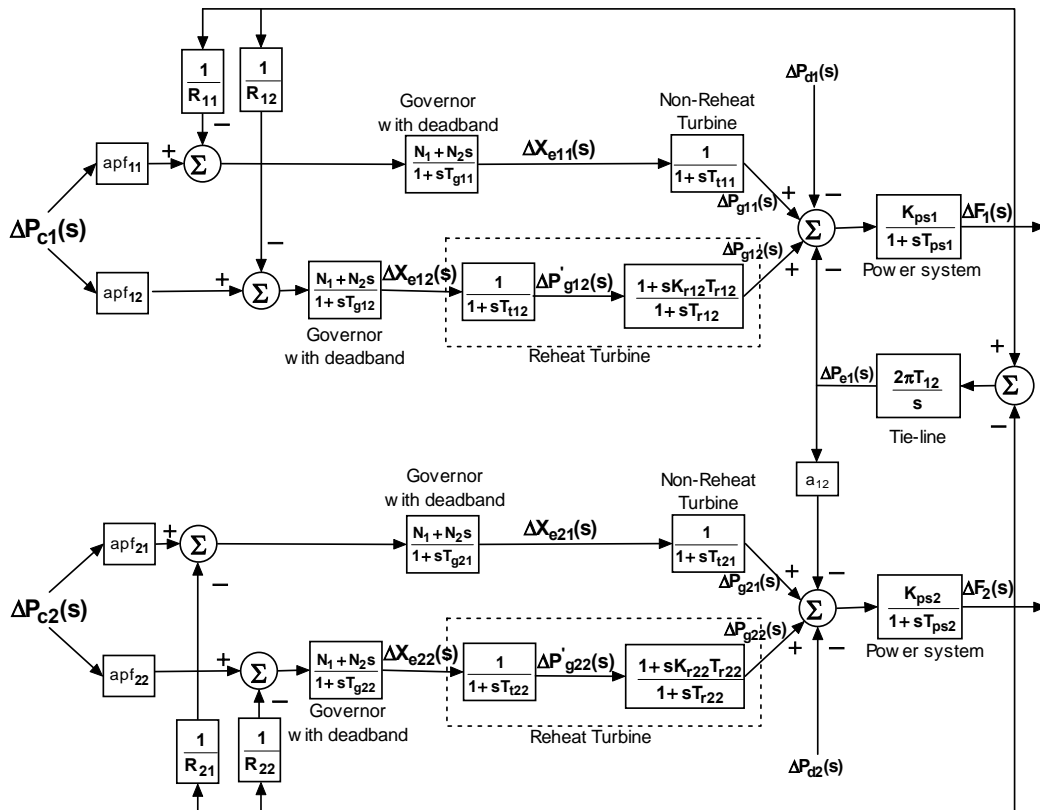

Fig. 1 Block diagram representation of a two area interconnected thermal power system with GDB nonlinearity

$$\overline{A} = \begin{bmatrix} 0 & C \\ 0 & A \end{bmatrix} \overline{B} = \begin{bmatrix} 0 \\ B \end{bmatrix} \text{ and } \overline{\Gamma} = \begin{bmatrix} 0 \\ \Gamma \end{bmatrix}$$

The decentralized feedback control law may be written in-terms of v_i as [6]:

$$u_i = -k_{i1} \int v_i dt - k_{i2} v_i , \quad i = 1,2 \qquad (3)$$

where $k_i^T = \begin{bmatrix} k_{i1} & k_{i2} \end{bmatrix}$ is a 2-dimensional integral and proportional feedback gain vector.

This design assumes that, the two area interconnected power system consists of 2 - identical areas. Therefore, the decentralized integral feedback gains $(k_{11} = k_{21} = k_I)$ and the decentralized proportional controller feedback gains $(k_{12} = k_{22} = k_P)$ of the 2 - identical areas are assumed to be equal.

3. Design of Decentralized Proportional Plus Integral Controller Using ISE Criterion

The objective is to obtain the optimum values of the controller parameters that minimize the performance index,

$$J_i = \int_0^t \left(x_{ei}^T W_i \, x_{ei} \right) dt \quad , \quad i = 1,2 \qquad (4)$$

Where

$$W_i = diag \{ w_{i1} \; w_{i2} \} \text{ and } x_{ei}^T = \begin{bmatrix} \Delta f_i & \Delta p_{ei} \end{bmatrix}$$

w_{i1} and w_{i2} are weighting factors for the frequency deviation and tie–line power deviation respectively of area i and are chosen as unity. The decentralized proportional plus integral controller gains using ISE criterion are designed as discussed in [7] and the values obtained are $k_P = 0.32$ and $k_I = 0.135$.

4. Design of Decentralized Proportional Plus Integral Controller Using MSM Criterion

The controller designed on the basis of Integral Squared Error criterion tends to show a rapid decrease in the large initial error. Hence, the response is fast and oscillatory. Thus, the system has poor relative stability [8]. Therefore, the design of proportional plus integral controller with improved stability using MSM criterion by Lyapunov method [2] is discussed in this section.

The stability index to be minimized is

$$\eta = \overline{x}^T P \overline{x} \qquad (5)$$

Where P is a symmetric positive definite matrix obtained from the solution of

$$\hat{A} P + P \hat{A} = -Q \qquad (6)$$

where Q is a positive semi-definite matrix and $\hat{A}$ is augmented system matrix.

The weighting matrix Q is chosen as $Q = diag \{ 0,0,1,0,0, \; 0,0,0,1,1, \; 0,0,0,0,0 \}$.

The proportional controller feedback gain k'_P, corresponding to minimum value of stability index η, is obtained using the MSM criterion by plotting the stability curve for various values of k'_P against the stability index η [2]. The integral feedback gain k'_I is treated as zero throughout in this design. From the stability curve, the optimal proportional controller feedback gain $k'_P = -0.3$ is obtained. Next, the stability curve for various values of k'_I is obtained by simulating the closed loop system and keeping $k'_P = k'_{P (opt)}$. From the curve, the optimal integral controller feedback gain $k'_I = 0.8$ is obtained.

5. Design of Proposed Decentralized Proportional Plus Integral Controller

Controllers designed on the basis of MSM criterion do not posses the inherent good properties of the controller designed on the basis of ISE criterion except for improvement in stability. Therefore, a new controller design needs to be developed based on a compromise between the ISE design criterion and MSM design criterion in order to obtain satisfactory closed loop system performance and stability [4].

An attempt has been made in this section to design a decentralized controller using Multi-Objective Evolutionary Algorithm.

5.1 Multi-Objective Evolutionary Algorithm

Multi-objective optimization methods deal with finding optimal solutions to problems having multiple objectives. These objectives often conflict each other so that improving one of them will deteriorate another objective function. Therefore, the solution to a Multi-objective optimization problem is normally not a single value but instead a set of values called the "Pareto-Optimal Set". No solution from this set of optimal solution can be said to be better than another solution. This procedure is practical because the user gets an opportunity to investigate a number of other trade-off solutions before choosing one particular optimal solution.

A Multi-objective optimization problem can be mathematically defined as [9]:

Minimize/ Maximize $f_m(X)$, $m=1,2,...M;$ (7)

Subject to J inequality constraints
$g_j(X) \geq 0,$ $j = 1,2,...J;$
and K equality constraints
$h_k(X) = 0,$ $k = 1,2,...K;$
$x_i^{(L)} \leq x_i \leq x_i^{(U)},$ $i = 1,2,......n.$

The last set of constraints are called variable bounds, restricting each decision variable x_i to take a value within a lower $x_i^{(L)}$ and an upper $x_i^{(U)}$ bound.

There are M objective functions $f(X) = (f_1(X), f_2(X),...f_M(X))^T$ considered in the above formulation. A solution X is a vector of n decision variables. $X = (x_1, x_2,......x_n)^T$.

Evolutionary Algorithms (EAs) are a natural choice for solving multi-criterion optimization problems because of their population-based nature. A number of Pareto-optimal solutions can, in principle, be captured in an EA population, thereby allowing a user to find multiple Pareto-optimal solutions in one simulation run. Different approaches of MOEA have been used by different researchers for multi-objective optimization, each one having its merits and demerits. Among various MOEAs, ε – MOEA has shown the best performance.

Hence, in this study, a steady state Multi-Objective Evolutionary Algorithm based on ε-dominance concept is used [10].

Here, two populations (EA and archive) are evolved simultaneously and independently. Using one solution each from both populations, two off-spring solutions are created through mating. Each off-spring is then used to update both parent and archive populations. The archive population is based on the ε-dominance whereas a usual dominance concept is used to update the present population. The final archive members after a specified number of iterations are reported as the obtained solutions [10]. The algorithm for ε – MOEA is given in [11].

5.2 Design of proposed decentralized controller using MOEA

An attempt has been made in this section, to apply MOEA to the LFC problem with ISE criterion and MSM criterion as conflicting objectives.

The LFC problem can be formulated as

Minimize
$$f_1(X) = f_1(x_1, x_2) = f_1(k_{Pm}, k_{Im}) = J_1$$
$$f_2(X) = f_2(x_1, x_2) = f_2(k_{Pm}, k_{Im}) = \eta$$

Subject to
$$k_{Pm}^{(L)} \leq k_{Pm} \leq k_{Pm}^{(U)}$$
$$k_{Im}^{(L)} \leq k_{Im} \leq k_{Im}^{(U)}$$ (8)

The proportional controller feedback gains obtained by ISE and MSM criteria, namely $k_P = 0.32$ and $k'_P = -0.3$, are treated as the upper and lower bounds for the decision variable k_{Pm} in the MOEA. Similarly, the integral controller feedback gains obtained by MSM criterion and ISE criterion, namely, $k'_I = 0.8$ and $k_I = 0.135$, are treated as the upper and lower bounds for the decision variable k_{Im}. The proposed controller feedback gains are obtained as $k_{Pm} = 0.16$ and $k_{Im} = 0.27$ using MOEA. This design ensures that, the controller feedback gains will always be within the ranges of the gains obtained from the ISE criterion and the MSM criterion. Therefore, the controller will guarantee the stability. Further the controller possesses improved stability when compared to the controller obtained using ISE criterion. The overall performance of these controllers will be better than that of the controller designed on the basis of MSM criterion. The choice of ε-MOEA parameters was done according to general guidelines available in the literature. A population size of 100, the real-parameter Simulated Binary Cross-over (SBX) recombination operator with a crossover probability of 1 and a distribution index of 15 for crossover, and a polynomial mutation operator with a mutation probability of 1/n (n = number of decision variables) and a distribution index of 20 for mutation, have been used. The recommended values of $\varepsilon_1 = 0.05$ and $\varepsilon_2 = 0.05$ are found to be robust enough and are used in our study.

6. Simulation Results and Observations

The decentralized controller with output feedback is designed using MOEA with multiple objectives, namely the ISE criterion and MSM criterion, and implemented in the interconnected two-area thermal power system with two units in each area. The system is simulated with the proposed controller for 0.01 p.u.MW step load change in area 1 and the corresponding frequency deviation Δf and tie-line power deviation ΔP_{e1} are plotted with respect to time. For easy comparison, the responses of Δf and ΔP_{e1} of the system are shown along with the responses obtained with the optimal decentralized proportional plus integral controller designed on the basis of ISE
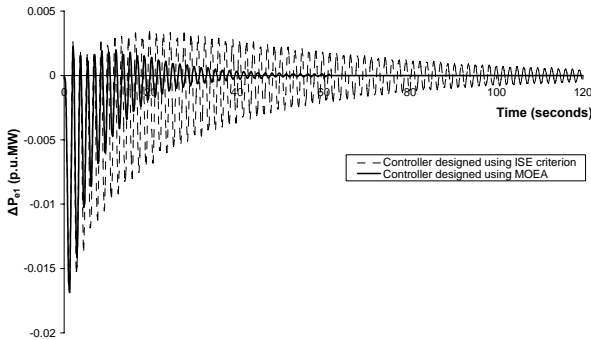
criterion in Fig. 2. It is observed that the proposed controller has good damping and reduced transient error and any further improvement in one of the design objectives will lead to degradation in the other objective.
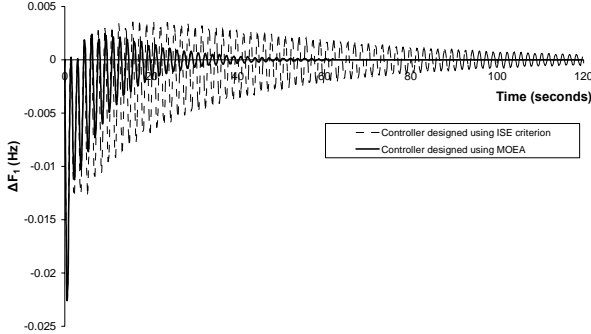
(a)Frequency deviation of area 1
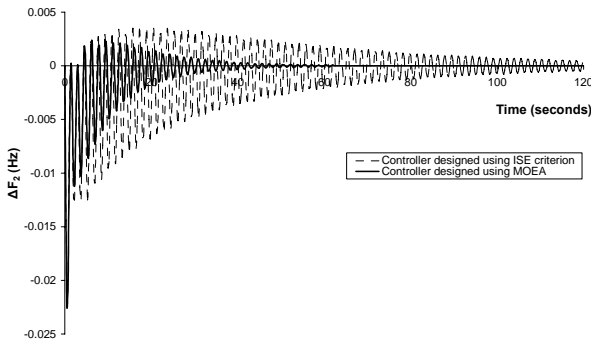
(b) Frequency deviation of area 2

(c) Tie-line power deviation of area 1

Fig. 2. Frequency deviations and tie-line power deviation for 0.01 p.u.MW step load change in area 1 with MOEA based decentralized controller

The cost function values of both the controllers are given in Table 1. It is observed from Fig. 2 and Table 1 that the proposed controller using MOEA has improved stability as well as reduced cost function value when compared to the controller designed on the basis of ISE criterion.

Table1: Comparison of cost function values

Type of proportional plus integral controller	Feedback gains	cost function value
Controller designed using ISE criterion	$k_P = 0.32$ $k_I = 0.135$	0.4652
Controller designed using MOEA	$k_{Pm} = 0.16$ $k_{Im} = 0.27$	0.2245

7. Conclusion

A design of Multi-Objective Evolutionary Algorithm based decentralized load-frequency controllers for interconnected power systems with GDB nonlinearity, is presented. This design has been successfully applied to an interconnected two-area thermal power system with two thermal generating units and Governor dead band in each area. Simulation results reveal that the proposed controller provides an improved dynamic response in addition to excellent closed loop stability.

Acknowledgement

References
1. Shayeghi,H., Shayanfar, H.A., and Jalili, A.:*"Load frequency control strategies: A state-of-the-art survey for the researcher"*, Energy Conversion Management, Vol. 50(2), Feb.2009, pp.344-353.
2. Tripathy,S.C., Hope,G.S., and Malik,O.P.: *"Optimisation of load-frequency control parameters for power systems with reheat steam turbines and governor dead band nonlinearity",* IEE Proceedings, Vol. 129, Pt. C, No. 1, Jan. 1982, pp. 10-11.
3. Elgerd,.O.E., and Fosha, C.E.: *"Optimum megawatt-frequency control of multiarea electric energy systems"*, IEEE Transactions on Power Apparatus and Systems, PAS-89,No.2, 1970,pp.556-563.
4. Chidambaram,I.A., and Velusami,S.: *" Design of decentralized biased controllers for load-frequency control of interconnected power systems"*, Electric Power Components and Systems, Vol. 33, Issue 12, 2005,pp. 1313-1331.
5. Mathur,H.D., and Ghosh,.S.: *" A comprehensive analysis of intelligent controllers for load frequency control"*, Proceedings of IEEE Power India Conference, New Delhi, 2006, pp. 853-857.

6. Ramar,K., and Velusami,S.: *"Design of decentralized load-frequency controllers using pole placement technique",* Electric Machines and Power Systems, Vol. 16, 1989, pp. 193-207.

7. Nanda,J., and Kaul,B.L.: *" Automatic generation control of an interconnected power system",* IEE Proceedings, Vol. 125, No. 5, May 1978, pp. 385-390.

8. Ogatta,K.: *Modern control engineering,* Prentice-Hall, New Jersey, 1970.

9. Deb,K.: *Multi-objective optimization using evolutionary algorithms,* John Wiley, UK,2001.

10. Deb,K., Mohan,M., and Mishra,S.: *" A fast multi-objective evolutionary algorithm for finding well-spread pareto-optimal solutions",* kanGAL Technical Report No. 2003002, Kanpur Genetic Algorithms Laboratory, Indian Institute of Technology, Kanpur, India., 2003, pp.1-18.

11. Shin,S.-Y., Lee,I.-H., Zhang,B.-T.: *"Microarray probe design using ε-multi-objective evolutionary algorithms with thermodynamic criteria",* Proceedings of EvoWorkshops2006, LNCS 3907, Springer, 2006, pp.184-195.

Appendix

A. Nomenclature:

f	area frequency in Hz
P_{ei}	the total power exchange of area i in p.u. MW
P_d	area real power load in p.u. MW
P_c	area speed changer output in p.u.MW
X_E	governor valve position in p.u. MW
P_g	mechanical (turbine) power output in p.u MW
k_{ps}	gain associated with the transfer function of the area in Hz / p.u. MW.
T_{ps}	area time constant in seconds
R	steady state regulation of the governor in Hz / p.u.MW
T_g	time constant of the governing mechanism in seconds
k_r	reheat coefficient of steam turbine
T_r	reheat time constant of the steam turbine in seconds
T_t	time constant of the steam turbine in seconds
β_i	frequency bias constant in p.u. MW / Hz
apf	area participation factor
N	number of interconnected areas
N_1, N_2	Fourier Coefficients
Δ	incremental change of a variable

B. Data for the interconnected two-area thermal power system [2]:

Rating of each area = 2000MW, Base power = 2000MVA, $f° = 60$ Hz, $R_{11}=R_{12}=R_{21}=R_{22}=2.4$ Hz/p.u.Hz, $T_{g11}=T_{g12}=T_{g21}=T_{g22}=0.08$ s, $T_{t11}=T_{t12}=Tt_{21}=Tt_{21}=0.3$ s, $T_{r12}=T_{r22}=10$s, $K_{ps1}=K_{ps2}=120$ Hz/p.u.MW, $K_{r12}=K_{r22}=0.5$, $T_{ps1}=T_{ps2}=20$ s, $\beta_1=\beta_2=0.425$ p.u. MW/Hz, $2\pi T_{12}=0.545$ p.u. MW/Hz, $a_{12}=-1$, $\Delta P_{d1}=0.01$ p.u.MW, $apf_{11}=apf_{12}=apf_{21}=apf_{22}=0.5$

Biographies

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