Decentralized Load-Frequency Control of Interconnected Power Systems with SMES Units and Governor Dead Band using Multi-Objective Evolutionary Algorithm

S.Ganapathy† and S.Velusami*

Abstract – This paper deals with the design of decentralized controller for load-frequency control of interconnected power systems with superconducting magnetic energy storage units and Governor Dead Band Nonlinearity using Multi-Objective Evolutionary Algorithm. The superconducting magnetic energy storage unit exhibits favourable damping effects by suppressing the frequency oscillations as well as stabilizing the inter-area oscillations effectively. The proposed control strategy is mainly based on a compromise between Integral Squared Error and Maximum Stability Margin criteria. Analysis on a two-area interconnected thermal power system reveals that the proposed controller improves the dynamic performance of the system and guarantees good closed-loop stability even in the presence of nonlinearities and with parameter changes.

Keywords: Governor Dead Band Nonlinearity, Load-Frequency Control, Multi-Objective Evolutionary Algorithm, Power Systems, Superconducting Magnetic Energy Storage

1. Introduction

Load-frequency control (LFC) plays an important role in securing a satisfactory operation of interconnected power systems. The purpose of LFC is to maintain system frequency and tie-line power interchanges close to specified values. In the last few decades, many control techniques have been proposed by various researchers for the LFC problem [1]. Most of these techniques are based on the classical proportional plus integral (PI) control due to the simplicity, ease of implementation, robustness and decentralized nature of control strategy.

However, even in the case of small load disturbances and with the optimized gains for the PI controller, the frequency oscillations and tie-line power deviations persist for a long duration. In these situations, the governor system may no longer be able to absorb the frequency fluctuations due to its slow response. Thus, to compensate for the sudden load changes, an active power source with fast response such as a Superconducting Magnetic Energy Storage (SMES) unit is expected to be the most effective counter measure [2].

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 [3]. The effect of GDB nonlinearity is considered in this study, by describing function approach in the state space model.

The optimum parameter values of the conventional proportional plus integral (PI) controller have been obtained in the literature by minimizing the popular integral of the squared error (ISE) criterion [4]. 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 [5]. 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 [6]. 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 SMES units and including GDB to achieve a better dynamic 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 SMES units. Each area has two thermal generating units and includes GDB nonlinearity.

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2. 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 the 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

3. SMES System

The schematic diagram in Fig.1 shows the configuration of a thyristor controlled SMES unit. The SMES unit contains a DC superconducting coil and a 12-pulse converter which are connected by Y–Δ/Y–Y transformer. The superconducting coil is contained in a helium vessel. Heat generated is removed by means of a low-temperature refrigerator. The energy exchange between the superconducting coil and the electric power system is controlled by a line commutated converter [2].

The superconducting coil can be charged to a set value from the grid during normal operation of the power system. Once the superconducting coil gets charged, it conducts current with virtually no losses, as the coil is maintained at extremely low temperatures. When there is a sudden rise in the load demand, the stored energy is almost released through the converter to the power system as alternating current. As the governor and other control mechanisms start working to set the power system to the new equilibrium condition, the coil current changes back to its initial value. Similarly, during sudden release of loads, the coil immediately gets charged towards its full value, thus absorbing some portion of the excess energy in the system and as the system returns to its steady state, the excess energy absorbed is released and the coil current attains its normal value. The control of the converter firing angle provides the dc voltage E_d appearing across the inductor to be continuously varying within a certain range of positive and negative values.

In LFC operation, the dc voltage E_d across the super-

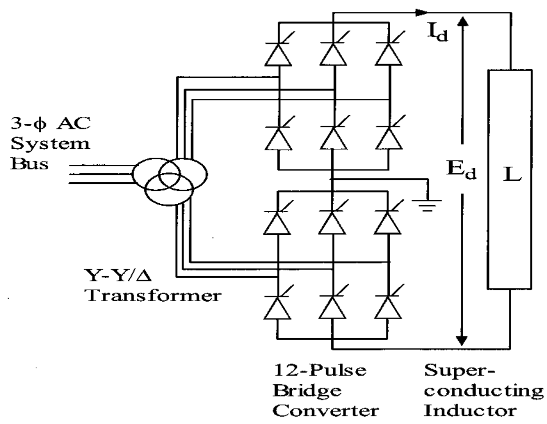


Fig. 1. The schematic diagram of SMES unit

conducting inductor is continuously controlled depending on the sensed area control error (ACE) signal. In this study, inductor voltage deviation of SMES unit of each area is based on ACE of the same area in power system. Moreover, the inductor current deviation is used as a negative feedback signal in the SMES control loop. So, the current variable of SMES unit is intended to be settling to its steady state value. Fig. 2 shows the block diagram of SMES unit [7].

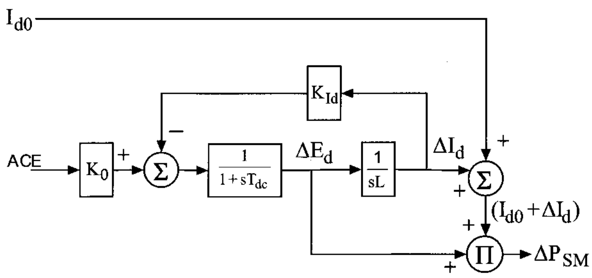


Fig. 2. Block diagram of SMES unit

4. Statement of the Problem

The block diagram representation of a two area interconnected thermal power system with SMES units is shown in Fig.3. 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. The limiting value of dead band is specified as 0.06%. The speed-governor dead band has a significant effect on the performance of the governors and it has a destabilizing effect on the transient performance of the system. Steam turbine dead band measured have been found to be due principally to backlash in the linkage connecting the servo piston to the camshaft. Much of this appears to occur in the rack and pinion used to rotate the camshaft that operates the control valves. A describing function approach is used to incorporate the GDB nonlinearity[3]. For an element with a backlash characteristic of

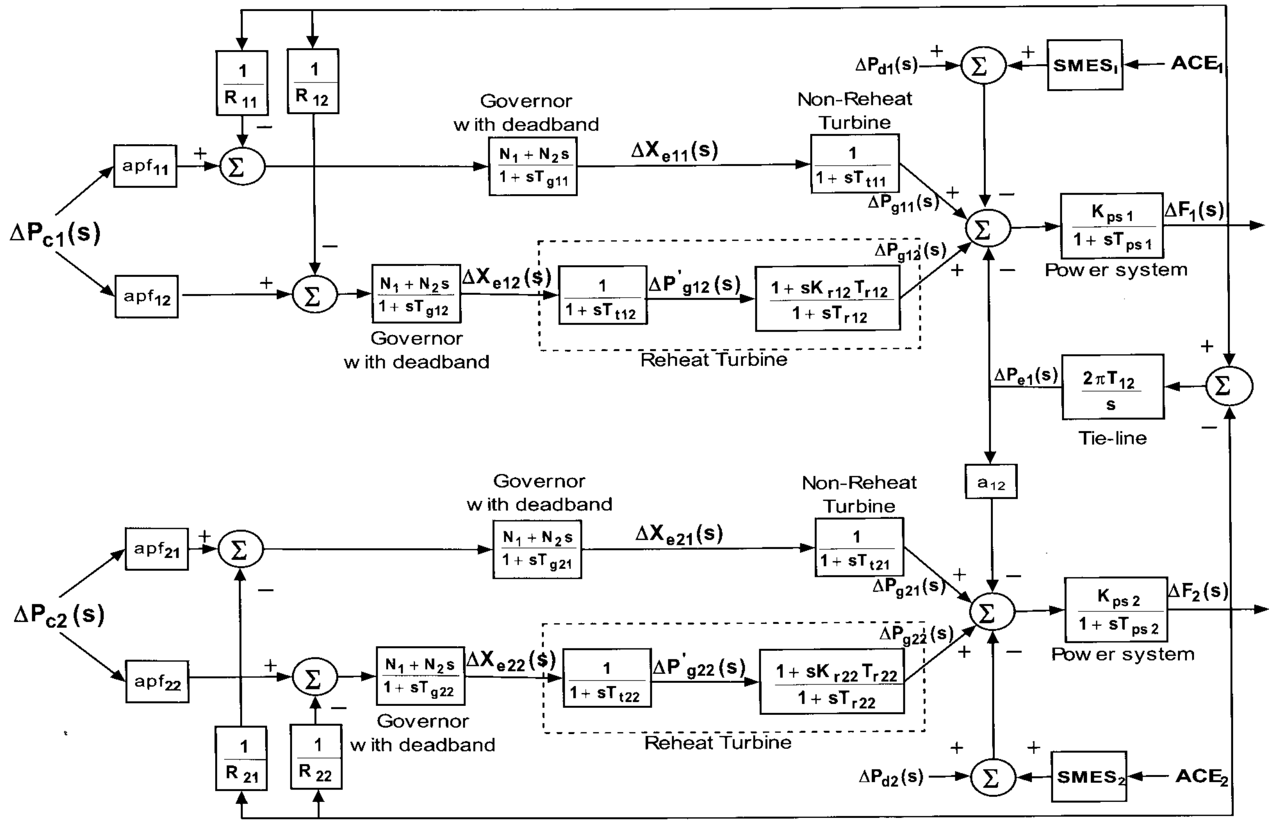


Fig. 3. Block diagram representation of a two area interconnected thermal power system with SMES units and GDB nonlinearity

hysteresis type in nature, the describing function giving the output-to-input relationship for the component of the fundamental frequency shows that the output lags the input by an angle which is independent of frequency but is a function of the ratio of the amplitude of the input oscillation to the width of the backlash loop. An adequate description of GDB nonlinearity is expressed as

$$y = F(x, \dot{x}) \tag{1}$$

If the variable 'x' in the nonlinear function $F(x, \dot{x})$ has the sinusoidal form, then the variable $F(x, \dot{x})$ is generally complex, but is also a periodic function of time. As such, it can be developed in a Fourier series as follows:

$$F(x, \dot{x}) = F^{o} + N_1 x + \frac{N_2}{\omega_o}\dot{x} + ... \tag{2}$$

A reasonable approximation of this solution is to consider the first three terms only. Therefore,

$$F(x, \dot{x}) = F^{o} + N_1 x + \frac{N_2}{\omega_o}\dot{x} \tag{3}$$

As the backlash nonlinearity is symmetrical about the origin, $F^{o} = 0$. Further, it has been found that the backlash nonlinearity tends to produce a continuous sinusoidal oscillation with a natural period of about 2 seconds. Then

$$\omega_o = 2\pi f_o = \pi \text{ with } f_o = 0.5\text{Hz}.$$

The governor transfer function with linearized dead band is given as

$$G(s) = \frac{N_1 + N_2 s}{1 + T_{gi} s} \tag{4}$$

where N_1 and N_2 are Fourier coefficients whose values are obtained as $N_1 = 0.8$ and $N_2 = -0.2/\pi$.

This will modify the system state matrix in the state space model.

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

$$\dot{\boldsymbol{x}} = \boldsymbol{A x} + \boldsymbol{B u} + \boldsymbol{\Gamma d} \tag{5}$$

Where

$$x = \lfloor \Delta F_1\ \Delta P_{g11}\ \Delta X_{e11}'\ \Delta P_{g12}\ \Delta P_{g12}'\ \Delta X_{e12}'\ \Delta P_{e1}\ \Delta F_2\ \Delta P_{g21}\ \Delta X_{e21}'\ \Delta P_{g22}\ \Delta P_{g22}'\ \Delta X_{e22}'\ \Delta E_{d1}\ \Delta I_{d1}\ \Delta E_{d2}\ \Delta I_{d2} \rfloor^T$$

$$u = [\Delta P_{c1}\ \ \Delta P_{c2}]^T$$
$$d = [\Delta P_{d1}\ \ \Delta P_{d2}]^T$$

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. 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 (5) is augmented with new state variables defined as the integral of $\mathrm{ACE}_i \left(\int v_i dt\right), i = 1,2$.

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

$$\dot{\bar{x}} = \bar{A}\bar{x} + \bar{B}u + \bar{\Gamma}d \tag{6}$$

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

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

The decentralized feedback control law may be written in terms of v_i as [8]:

$$u_i = -k_{i1} \int v_i dt - k_{i2} v_i,\ i = 1,2 \tag{7}$$

where $k_i^T = [k_{i1}\ \ k_{i2}]$ is a 2-dimensional integral and proportional feedback gain vector [8].

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.

5. 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,

$$J_i = \int_0^t \left(x_{ei}^T W_i x_{ei}\right) dt, i = 1.2..., N \tag{8}$$

Where

$$W_i = diag\{w_{i1}, w_{i2}\} \text{ and } x_{ei}^T = [\Delta f_i, \Delta p_{ei}]$$

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 [9] and the values obtained are k_P = 2.39 and k_I = 0.42.

6. 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 [10]. Therefore, the design of proportional plus integral controller with improved stability using MSM criterion by Lyapunov method [3] is discussed in this section.

The stability index to be minimized is

$$\eta = \bar{x}^T P \bar{x} \tag{9}$$

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

$$\hat{A}P + P\hat{A} = -Q \tag{10}$$

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

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

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 [3]. 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= 0.8 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= 2.1 is obtained.

7. 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 [5].

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

7.1 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 [11]:

Minimize/ Maximize

$$f_m(X), \qquad m = 1,2,\ldots M; \tag{11}$$

Subject to

J inequality constraints

$$g_j(X) \geq 0, \qquad j = 1,2,\ldots J;$$

and K equality constaints

$$h_k(X) = 0, \qquad k = 1,2,\ldots K;$$

$$x_i^{(L)} \leq x_i \leq x_i^{(U)}, \qquad i = 1,2,\ldots n.$$

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 $f(X) = (f_1(X), f_2(X), \ldots f_M(X))^T$ considered in the above formulation. A solution X is a vector of n decision variables.

$$X = (x_1, x_2, \ldots\ldots x_n)^T.$$

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 [12].

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. The algorithm for ε – MOEA [13] is given below:

Step1: Randomly generate initial pool.

Step2: Sort by domination, and set first front as archive.

Step3: Generate one new individual by choosing the parents from the population and archive.

- (a) Choose two individuals from population.
- (b) Choose dominating solution, if dominates; choose random one, otherwise.
- (c) Choose one individual from archive.
- (d) Perform crossover and mutation.

Step4: Update archive.

- (a) Replace ε – dominated individual(s) in the archive with new individual, if new individual ε – dominates archive member(s).
- (b) Leave dominating member, if there are more than one archive members in the same grid.
- (c) Add new individual, if archive members do not dominate new individual.

Step5: Update population.

- (a) Replace dominating individual(s) with new individual.
- (b) Replace randomly selected population member with new individual, if there is no population member which dominates the new individual.

Step6: Check termination criteria.

7.2 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

$$f_1(\mathbf{X}) = f_1(x_1, x_2) = f_1(k_{Pm}, k_{Im}) = \boldsymbol{J_1}$$

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

Subject to

$$k_{Pm}^{(L)} \leq k_{Pm} \leq k_{Pm}^{(U)}$$

$$k_{Im}^{(L)} \leq k_{Im} \leq k_{Im}^{(U)} \qquad (12)$$

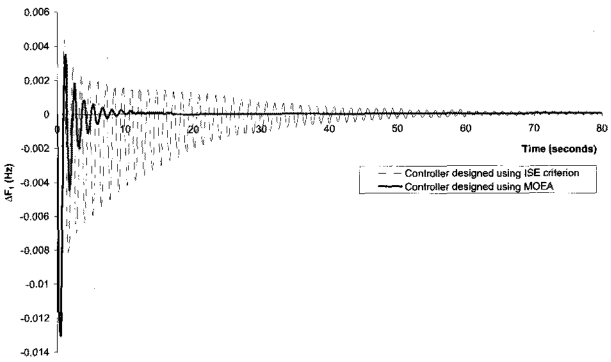
The proportional controller feedback gains obtained by ISE and MSM criteria, namely k_P=2.39 and k'_P=0.8, are treated as the upper and lower bounds for the decision variable k_{Pm} in the MOEA. Similarly, the integral controller feedback gains obtained by MSM criterion and ISE criterion, namely, k'_I=2.1 and k_I=0.42 are treated as the upper and lower bounds for the decision variable k_{Im}. The proposed controller feedback gains are obtained as k_{Pm}=1.12 and k_{Im}=1.87 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 ε_1=0.05 and ε_2=0.05 are found to be robust enough and are used in our study.

8. Simulation Results and Observations

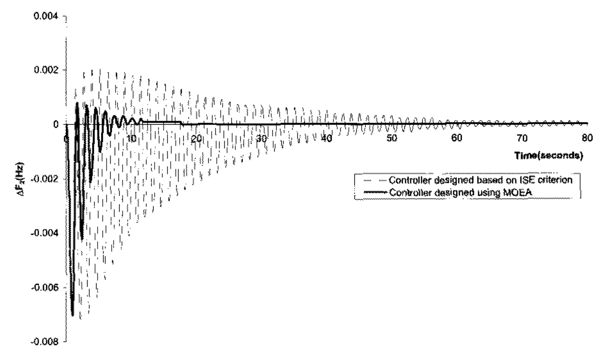
The decentralized controller with output feedback is designed using MOEA with multiple objectives, namely the ISE criterion and MSM criterion, and implemented in the interconnected two-area thermal power system with SMES units and GDB nonlinearity. The system is simulated with the proposed controller 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.4. It is observed that the proposed controller offers better dynamic performance and any further improvement in one of the design objectives will lead to degradation in the other objective.

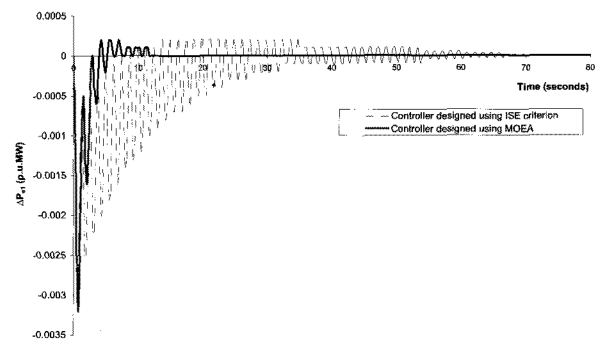
The cost function values of both the controllers are given in Table 1. It is observed from Fig.4 and Table 1 that the proposed controller using MOEA has improved stability as well as reduced cost function value when compared to the controller designed on the basis of ISE criterion.



(a) Frequency deviation of area 1



(b) Frequency deviation of area 2



(c) Tie-line power deviation of area 1

Fig. 4. Frequency deviations and tie-line power deviation for 0.01 p.u.MW step load change in area 1 with MOEA based decentralized controller

In practice, load variations are stochastic in nature. Hence, for a realistic evaluation of the proposed system, it has to be tested under different load levels. The investigated power system is subjected to different small perturbations varying from 0.005 p.u.MW to 0.02 p.u.MW and the effectiveness of the proposed controller is verified. Fig.5 shows the frequency deviation of area1 with the proposed controller for different load levels. It is found from Fig.5 that the maximum frequency deviation due to ΔP_d occurs at exactly the same time for different values of ΔP_d. This indicates that the time of maximum frequency deviation is independent of the disturbance magnitude.

Table 1. Comparison of cost function values

Type of proportional plus integral controller	Feedback gains	cost function value
Controller designed using ISE criterion	$k_P = 2.39$ $k_I = 0.42$	0.8838
Controller designed using MOEA	$k_{Pm} = 1.12$ $k_{Im} = 1.87$	0.4456

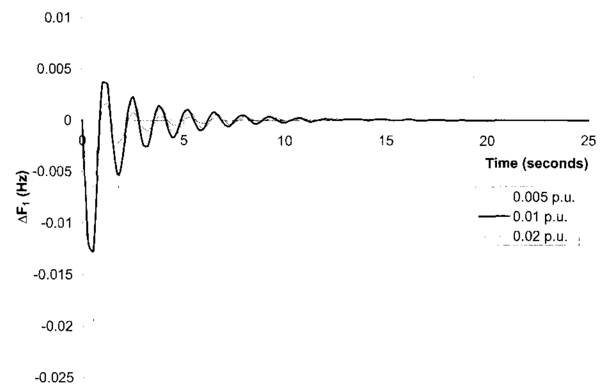


Fig. 5. Frequency deviation of area 1 with the proposed controller for different load levels

Further, Sensitivity is considered as an important factor for any control algorithm. Therefore the performance of the proposed controller has been analyzed under parameter variation of the speed regulation coefficient R by 20 % from its nominal value. The closed loop response of ΔF_1 has been shown in Fig.6 for the proposed controller.

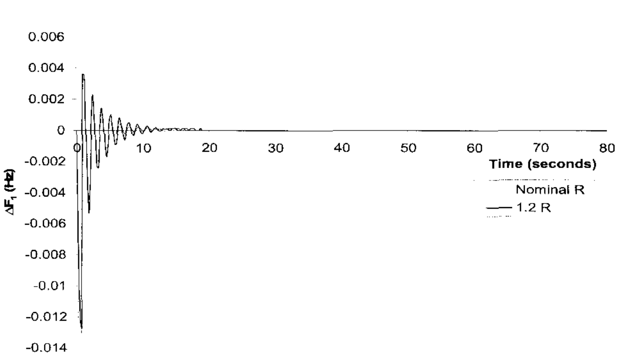


Fig. 6. Frequency deviation of area 1 for controller designed using MOEA with parameter variation of R

From Fig.6, it is observed that the system response is affected only marginally due to the parameter variation. Hence, it is inferred that the proposed controller is insensitive to the changes in the system parameters.

9. Conclusion

A new design of Multi-Objective Evolutionary Algorithm based decentralized load-frequency controllers for an interconnected power system with SMES units 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. The proposed controller ensures the quick attenuation of frequency and tie-line power deviations to zero and guarantees the stability of the overall system even in the presence of GDB nonlinearity. Further, the sensitivity analysis reveals that the proposed controller is practically insensitive to system parameter variations.

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Appendix

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

Rating of each area = 2000MW, Base power = 2000MVA, f^o=60Hz,$R_{11}=R_{12}=R_{21}=R_{22}$=2.4Hz/p.u.Hz, $T_{g11}=T_{g12}=T_{g21}=T_{g22}$=0.08s,$T_{t11}=T_{t12}=Tt_{21}=Tt_{21}$=0.3s, $T_{r12}=T_{r22}$=10s, $K_{ps1}=K_{ps2}$=120 Hz/p.u.MW, N_1=0.8,N_2=-0.2/π,$K_{r12}=K_{r22}$=0.5,$T_{ps1}=T_{ps2}$=20s, $\beta_1=\beta_2$=0.425p.u.MW/Hz,$2\pi T_{12}$=0.545 p.u. MW/Hz, a_{12}=-1, ΔP_{d1}=0.01 p.u.MW, $apf_{11}=apf_{12}=apf_{21}=apf_{22}$=0.5

SMES data:

$K_{01}=K_{02}$=50kV/unitACE; $I_{d1,2min}$=4.05kA; $I_{d1,2max}$=6.21kA; I_{do}=5kA;L=2H; $K_{id1}=K_{id2}$=0.20 kV/kA

References

[1] H.Shayeghi, H.A.Shayanfar, and A. Jalili, "Load frequency control strategies: A state-of-the-art survey for the researcher", *Energy Conv. Management*, Vol. 50(2), pp.344-353, Feb.2009.

[2] S.C. Tripathy, R.Balasubramanian, and P.S. Chandra mohan Nair, "Effect of super conducting magnetic energy storage on automatic generation control considering governor dead band and boiler dynamics", *IEEE Trans. Power Systems*, Vol.7, No.3, pp. 1266-1272, 1992.

[3] S.C.Tripathy, G.S.Hope, and O.P.Malik, " Optimisation of load-frequency control parameters for power systems with reheat steam turbines and governor

dead band nonlinearity", *IEE Proc.*, Vol. 129, Pt. C, No. 1, pp. 10-11, Jan. 1982.

[4] O.E.Elgerd,. and C.E.Fosha, "Optimum megawatt-frequency control of multi area electric energy systems", *IEEE Trans. Power Apparatus Syst.*, PAS-89, No.2, pp.556-563, 1970.

[5] I.A.Chidambaram, and S.Velusami, "Design of decentralized controllers for load-frequency control of interconnected power systems", *Elect. Power Compon. Syst.*, Vol. 33, pp. 1313-1331, 2005.

[6] H.D. Mathur, and S.Ghosh,. "A comprehensive analysis of intelligent controllers for load frequency control", *Proc. IEEE Power India Conference*, New Delhi, pp. 853-857, 2006.

[7] A.Demiroren, and E. Yesil, "Automatic generation control with fuzzy logic controllers in the power system including SMES units", *Electric Power and Energy Systems*, Vol. 26, pp. 291-305, 2004.

[8] K.Ramar, and S.Velusami, "Design of decentralized load-frequency controllers using pole placement technique", *Elect. Mach. Power Syst.,* Vol. 16, pp. 193-207, 1989.

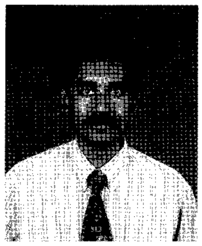
[9] J.Nanda, and B.L.Kaul, "Automatic generation control of an interconnected power system", *IEE Proc.*, Vol. 125, No. 5, pp. 385-390, May 1978.

[10] K.Ogatta, *Modern control engineering*, Prentice-Hall, New Jersey, pp.. 296-313, 1970.

[11] K.Deb, *Multi-objective optimization using evolutionary algorithms*, John Wiley, UK,2001.

[12] K.Deb, M.Mohan, and S.Mishra, "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., pp.1-18, 2003.

[13] S.-Y.Shin, I.-H. Lee, B.-T. Zhang, 'Micro array probe design using ε-multi-objective evolutionary algorithms with thermodynamic criteria", *EvoWorkshops 2006*, LNCS 3907, Budapest, pp.184-195, 2006.



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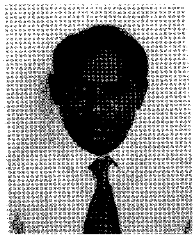

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