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Design of MOEA based Decentralized Load-Frequency Controllers for Interconnected Power Systems with AC-DC Parallel Tie-lines

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Abstract— **A new design of Multi-objective Evolutionary Algorithm based decentralized load-frequency controllers for interconnected power systems with AC-DC parallel tie-lines, is proposed in this paper. HVDC link is connected in parallel with the existing AC link for stabilizing the frequency oscillations of AC system. 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 optimal Proportional plus Integral controller, obtained by the proposed design, ensures a compromise between Integral Squared Error criterion and Maximum Stability Margin criterion. The proposed design is implemented on a two area interconnected thermal power system with parallel AC-DC tie-lines. System responses show that the transient performance is improved significantly with increased stability margin.**

Index Terms— **Power Systems, Load-Frequency Control, Multi-Objective Evolutionary Algorithm, AC-DC tie-lines**

I. INTRODUCTION

Load-frequency control (LFC) has gained importance with the growth of interconnected power systems. The main objective of LFC is balancing the total system generation against the system load and losses so that the desired frequency and power interchange (tie-line power flow) are maintained as economical and reliable as possible.

Literature survey shows that most of the research works carried out concerning the study of dynamic performance of interconnected power systems by implementing Load-frequency control schemes has mainly concentrated on the interconnection between two areas through an AC transmission network [1].

HVDC transmission has emerged on power scenario due to its numerous economical and technical advantages. One of the major applications of HVDC transmission is operating a DC link in parallel with an AC link interconnecting two control areas to get an improved system dynamic performance with greater stability margins under small disturbances in the system [2]. Very few researchers have carried out their work on LFC of interconnected power systems connected via HVDC link in parallel with AC link.

Therefore, this paper considers LFC of an interconnected power system with a DC tie-line in parallel with an AC tie-line. Incremental DC power flow is considered as an additional state variable in the LFC strategy. Proportional plus integral controllers are traditionally used for LFC of interconnected power systems because of their inherent simplicity, easy realization, robust and decentralized nature of the control strategy. The Integral Squared Error (ISE) criterion is used for obtaining the controller gain settings [3]. However, the frequency deviations and tie-line power deviations persist for a long duration even though zero steady state errors are ensured. 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. 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 except for 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 in 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 paper, for the decentralized load-frequency control of interconnected power systems with AC-DC tie-lines, 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 conflicting objectives. The proposed controller has been applied to an interconnected two-area thermal power system with AC-DC parallel tie-lines.

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II. STATEMENT OF PROBLEM

The block diagram representation of a two area interconnected thermal power system with AC-DC parallel tie-lines is shown in Fig.1. Each of the area in the interconnected power system consists of two thermal generating units.

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

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} + \boldsymbol{\Gamma}\boldsymbol{d} \qquad (1)$$

where

$$\boldsymbol{x} = \big[\Delta F_1\ \Delta P_{g11}\ \Delta X_{e11}\ \Delta P_{g12}\ \Delta P_{g12}'\ \Delta X_{e12}\ \Delta P_{e1}$$
$$\Delta P_{dce1}\ \Delta F_2\ \Delta P_{g21}\ \Delta X_{e21}\ \Delta P_{g22}\ \Delta P_{g22}'\ \Delta X_{e22}\big]^T$$

$$\boldsymbol{u} = \left[\Delta P_{c1}\ \ \Delta P_{c2}\right]^{\mathrm{T}}$$

$$\boldsymbol{d} = \left[\Delta P_{d1}\ \ \Delta P_{d2}\right]^{\mathrm{T}}$$

are the state, control and disturbance vectors and $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{\Gamma}$ 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 (1) is augmented with new state variables defined as the integral of $\mathrm{ACE}_i\ \left(\int \mathrm{v}_i\, \mathrm{dt}\right), \mathrm{i} = 1{,}2$.

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

$$\dot{\bar{\boldsymbol{x}}} = \bar{\boldsymbol{A}}\,\bar{\boldsymbol{x}} + \bar{\boldsymbol{B}}\boldsymbol{u} + \bar{\boldsymbol{\Gamma}}\boldsymbol{d} \qquad (2)$$

$$\text{Where } \bar{\boldsymbol{x}} = \begin{bmatrix} \int \boldsymbol{v}dt \\ \boldsymbol{x} \end{bmatrix} \begin{matrix} \}N \\ \}n \end{matrix}$$

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

The decentralized feedback control law may be written in-terms of $\boldsymbol{v}_i$ as [6]:

$$\boldsymbol{u}_i = -\boldsymbol{k}_{i1} \int \boldsymbol{v}_i \boldsymbol{dt} - \boldsymbol{k}_{i2} \boldsymbol{v}_i \ , \ \ i = 1.2.....,N \qquad (3)$$

where $\boldsymbol{k}_i^T = \left[k_{i1} \quad k_{i2}\right]$ 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 $\left(k_{11} = k_{21} = k_I\right)$ and the decentralized proportional controller feedback gains $\left(k_{12} = k_{22} = k_P\right)$ of the 2 - identical areas are assumed to be equal.

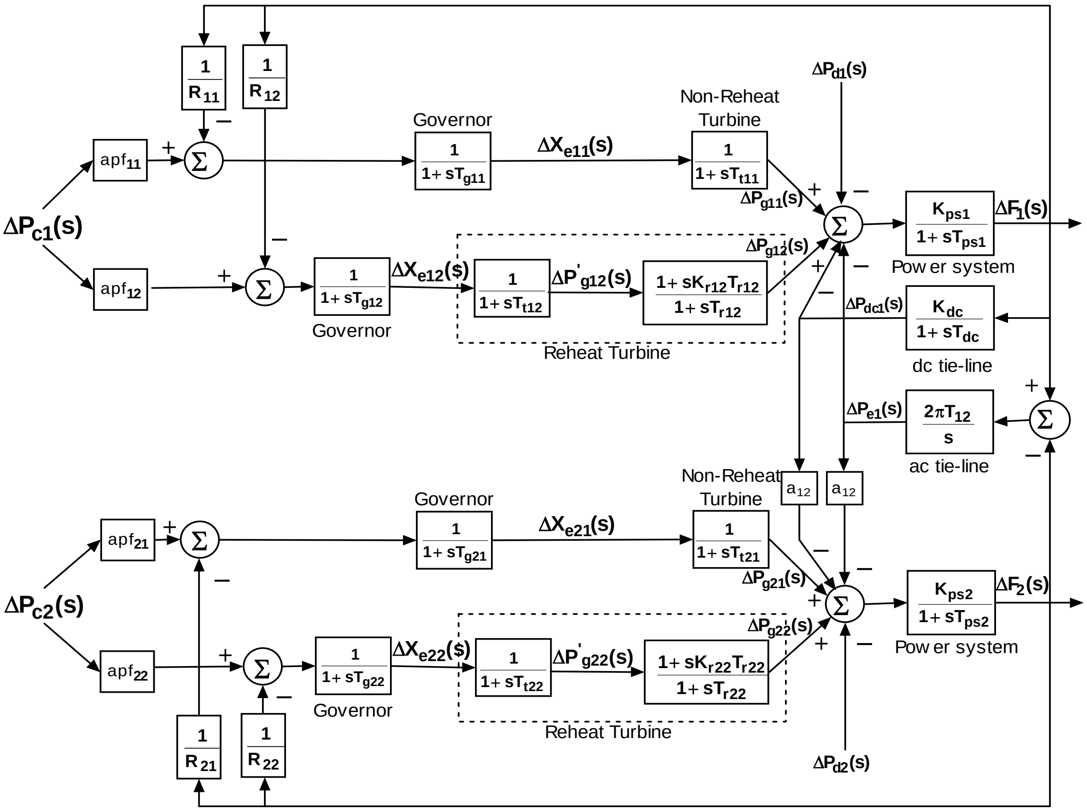


Figure 1. Block diagram representation of a two area interconnected thermal power system with AC-DC parallel tie-lines.

III. 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,

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

where

$$\boldsymbol{W_i} = diag\{w_{i1} \; w_{i2} \; w_{i3}\} \text{ and } \boldsymbol{x_{ei}}^T = \left[\Delta f_i \; \Delta p_{ei} \; \Delta p_{dce1}\right]$$

w_{i1}, w_{i2} and w_{i3} are weighting factors for the frequency deviation, AC tie–line power deviation and DC 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 =0.76 and k_I = 0.28.

IV. 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 [9] is discussed in this section.

The stability index to be minimized is

$$\dot{\overline{\boldsymbol{x}}} = \hat{\boldsymbol{A}}\overline{\boldsymbol{x}} + \overline{\boldsymbol{\Gamma}}\,\overline{\boldsymbol{d}} \tag{5}$$

The stability index **η** to be minimized can be written as

$$\boldsymbol{\eta} = \overline{\boldsymbol{x}}^{\boldsymbol{T}} \boldsymbol{P} \overline{\boldsymbol{x}} \tag{6}$$

Where $\boldsymbol{P}$ is a symmetric positive definite matrix obtained from the solution of

$$\hat{\boldsymbol{A}}\boldsymbol{P} + \boldsymbol{P}\hat{\boldsymbol{A}} = -\boldsymbol{Q} \tag{7}$$

where $\boldsymbol{Q}$ is a positive semi-definite matrix and $\hat{\mathrm{A}}$ is augmented system matrix. The weighting matrix $\boldsymbol{Q}$ is $\boldsymbol{Q} = diag\,\{0,0,1,0,0,\ 0\ ,0,0,1,1,\ 1,\ 0,0,0,0,0\}$.

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** [9]. 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 = -0.15 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 = 0.9 is obtained.

V. 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.

A. 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" [10]. 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.

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 [11]. 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 [12]. The algorithm for ε – MOEA is given in [13].

B. 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

$$f_1(\mathbf{X}) = f_1(\mathrm{x}_1, \mathrm{x}_2) = f_1(k_{Pm}, k_{Im}) = \boldsymbol{J_1}$$

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

Subject to

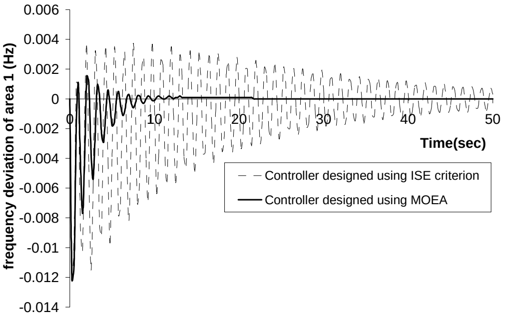
$$k_{Pm}^{(L)} \leq k_{Pm} \leq k_{Pm}^{(U)}$$

$$k_{Im}^{(L)} \leq k_{Im} \leq k_{Im}^{(U)} \qquad (8)$$

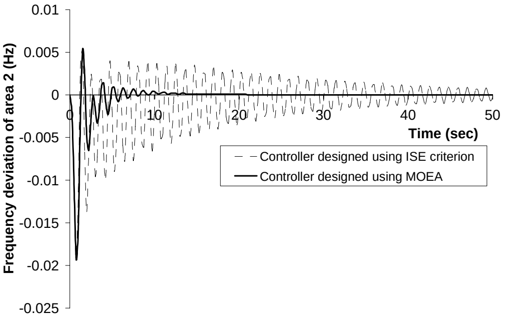
The proportional controller feedback gains obtained by ISE and MSM criteria, namely k_P =0.76 and k'_P =-0.15, are treated as the upper and lower bounds for the decision variable k_{Pm} in the MOEA. Similarly, the integral controller feedback gains obtained by MSM criterion and ISE criterion, namely, k'_I =0.9 and k_I =0.28, are treated as the upper and lower bounds for the decision variable k_{Im}. The proposed controller feedback gains are obtained as k_{Pm} =0.14 and k_{Im} =0.85 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.

VI. SIMULATION RESULTS AND OBSERVATIONS

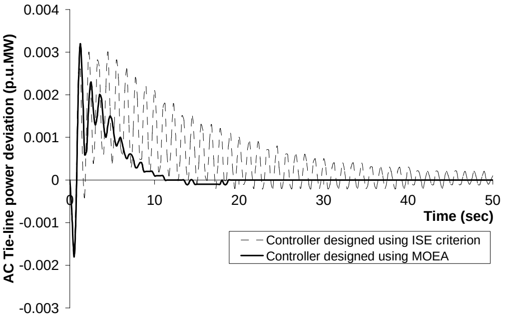
The decentralized controller with output feedback is designed using MOEA and implemented in the interconnected two-area thermal power system. The system is simulated with the proposed controller for 0.01 p.u.MW step load change in area 1 and the corresponding frequency deviations and tie-line power deviations are plotted with respect to time. For easy comparison, the responses of Δf and ΔP_e of the system are shown along with the responses obtained with the optimal decentralized proportional plus integral controller designed based on ISE criterion in Fig.2.



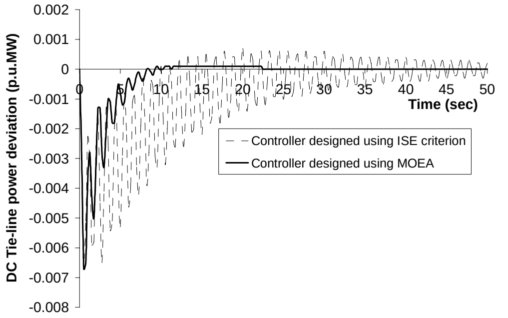
(a) Frequency deviation of area 1



(b) Frequency deviation of area 2



(c) AC Tie-line power deviation of area 1



(d) DC Tie-line power deviation of area 1

Figure 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.

It is observed that the transient performance is improved significantly with quick settling time.

The Gain values and cost function values of the various controllers are given in Table I.

TABLE I.
COMPARISON OF COST FUNCTION VALUES

Type of proportional plus integral controller	Feedback gains	cost function value
Controller designed using ISE criterion	$k_P = 0.76$ $k_I = 0.28$	0.22
Controller designed using MOEA	$k_{Pm} = 0.14$ $k_{I\,m} = 0.85$	0.06

It is observed from Table I that the cost function value of the proposed controller is drastically reduced when compared to that of the controller designed based on ISE criterion. Any further improvement in one of the design objectives will lead to degradation in the other objective.

VII. CONCLUSION

A new design of Multi-Objective Evolutionary Algorithm based decentralized load-frequency controllers for an interconnected power system with AC-DC parallel tie-lines is presented. This design has been successfully applied to an interconnected two-area thermal power system with AC-DC parallel tie-lines. Simulation results reveal that the proposed controller gives much better dynamic performance by bringing all the desired system variables to steady-state faster and quite smoothly than that with ISE criterion. Moreover, excellent closed loop stability is ensured. The suggested design can be extended to interconnected power systems including nonlinearities.

APPENDIX

Data for the interconnected two-area thermal power system:

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

Data for DC link:
$K_{dc}=1.0$, $T_{dc}=0.5s$.
All notations carry the usual meanings.

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