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A Framework for Economic Load Frequency Control Design Using Modified Multi-objective Genetic Algorithm

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CONTENTS

Abstract—This article deals with the coordination of security-constrained economic dispatch and load frequency control in an interconnected power system. The realistic and performance optimization inherent of the load frequency control (LFC) and security-constrained economic dispatch are fully considered without simplifying assumptions. For this purpose, modeling security-constrained economic dispatch as a discontinuous control action in the continuous frequency response model of a power system is well addressed. Considering conflict behavior of LFC and security-constrained economic dispatch beside the powerfulness of the multi-objective genetic algorithm (GA) to solve high-dimensional problems with conflicted objective functions makes it attractive for the automatic generation control coordination problem. The employed security-constrained economic dispatch utilizes the advantages of dynamic economic dispatch to achieve more realistic results. The GA is used to compute the decentralized control parameters and centralized generation levels of the on-line units to achieve an acceptable operating point. A significant modification in convergence speed has been performed by using LFC model properties in corporation with the genetic algorithm, so the proposed method gives considerable promise for implementation in multi-area power systems. The efficiency of the proposed algorithm and modification is demonstrated on a three control area power system.

1. INTRODUCTION

Automatic generation control (AGC) is a significant control process in the power systems, operating constantly to balance the generation and load at a minimum cost. AGC performs a continuous real-time operation to adjust power system generation for economically tracking load changes. Frequency control, economic dispatch (ED), and interchange transaction scheduling are the main functions of an AGC system [1]. Frequency control and interchange transaction scheduling are continuous control actions, while ED is discontinuous.

A permanent off-normal frequency deviation directly affects power system operation, security, reliability, and efficiency by damaging equipment, degrading load performance, overloading transmission lines, and triggering protection

Keywords: economic dispatch, load frequency control, automatic generation control, genetic algorithm, multi-objective, security-constrained economic dispatch, emission constraint, unit operation constraint, vector evaluated genetic algorithm

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devices [1]. Therefore, frequency control in the form of load frequency control (LFC) is one of the important power system control problems for which there has been considerable research works [2–9]. The LFC adjusts the generator set-point automatically in such a way that compensates the mismatch between the electrical load and the supplied power by the connected generators.

ED is defined as a process of allocating generation levels to the on-line generating units in which total operation cost is minimized. Conventionally, ED is considered separately from LFC, and sometimes it is only used to operate the power system as economically as possible without considering existing constraints, such as line flow limitations and emission allowances [10, 11]. However, AGC in modern power systems distributes area generation among generating units, subject to appropriate security and environmental constraints, so that equilibrium between demand and generation is regained and total operating costs are minimized [12]. ED is a discontinuous control action that readjusts the generators set-points at specified time intervals.

Several investigations have been reported in the past pertaining to readjusting the generator set-point [2–10], in most cases, a simplified approach of an AGC system adopted by neglecting ED and security constraints (SCs). Several preliminary and simplified works have been reported, such as [8], that consider equipment limitations. The state-of-the-art research only tries to keep system integrity, *i.e.*, balance between generation and load demand, while generator limitations, economical issues, and SCs are neglected; in other words, only LFC and the interchange transaction scheduling task have been done without considering economic problems. In other research, ED in dynamic and static points of view was discussed [7, 10, 13]. Static ED assumes that the output of generating units is constant for a given interval of time and tries to minimize the operation cost subject to the static behavior of generating units. Static ED determines the output power of each on-line generating unit by considering the unit slope for the cure of incremental fuel cost against the load demand at the scheduled time point, which is an impractical assumption. Dynamic ED determines the output of generators based on the load change characteristics over a time period and generator response speed. However, dynamic ED does not contain an LFC loop, and hence, the constantly continuous operation of a generator set-point readjusting is of concern. Therefore, the system may fall into the unstable mode. The aspects and challenges of ED in a modern power system were well discussed in [14].

LFC and interchange transaction scheduling are used to return frequency and net tie-line power interchange to their nominal values. However, ED tries to only keep balance between generation and load demand while the net tie-line power interchange may deviate from its nominal value to reduce operation cost. This conflict proposes a new prospect in the field of designing modern AGC systems, namely ED and LFC coordination. A methodology to coordinate ED and LFC in an electric power system was presented by Kwatny and Athay [12]. Simplifying assumptions, such as neglecting emission constraints and SCs, could degrade the performance of the designed controller. Moreover, in [12], both LFC and ED have been considered in a discontinuous manner, which is in contrast with the inherence of the LFC and constant operation of the AGC system. ED and LFC should be coordinated to track the load power changes economically. However, the proposed method in [12] could not satisfy this aim, as it considers LFC and ED in a discontinuous manner with different triggering times, *i.e.*, non-subscriber time intervals. In another attempt, three dependent stages that operate on different time horizons were introduced by Mukai *et al.* [15] for a coordinated design of ED and LFC. The results of each stage are employed by a prior one to get accurate results. Neglecting generator limitations and SCs could affect the implementation of this controller. Moreover, in [15], ED was considered to be triggered in a smaller time than LFC to get an accurate result, which is not a true assumption. Conventionally, LFC is considered to be triggered constantly and in a smaller time than ED. The problems associated with [15] were not solved by Zhu *et al.* [16]. LFC and ED were modeled on the same timescale as the ED controller (EDC) in [16]. In general, the existing conflict behavior of LFC and security-constrained ED (SCED), generator limitations, and SCs are neglected simultaneously or in a part in the recent published papers on the AGC problem.

Furthermore, it should be noted that LFC-ED coordination in the published literature is naturally a hierarchical control problem. ED could be regarded as optimizing the set-point of each unit in discontinuous manner so it is meaningful when the system reaches the equilibrium. On the other hand, LFC means to bring back the frequency deviations to zero in a continuous manner so it is a dynamic control problem. Therefore, LFC significantly affects ED performance in the hierarchical structure as it is a continuous control action. In addition to the above challenges associated with each algorithm, the major drawback of recent researches in the state of the art is in the complexity of the proposed methodologies. In real-world power systems, the AGC problem is a performance optimization problem rather than a stabilization control problem. In other words, the previous published research in the field preferred to design complex control structures instead of a simple integral controller, which is popular in real-world LFC systems.

In response to the above crudity, it seems that satisfying LFC, interchange transaction scheduling, and ED objectives subject to various constraints could be successfully done by formulating the AGC-ED coordination design as optimization of an objective function. For this purpose, appropriate modeling of SCED in the AGC loop controller is mandatory. In the modeling procedure, it should be noted that SCED and AGC are two conflict objectives with the non-subscriber time horizon. AGC synthesis considering SCs and emission constraints is proposed in this article. For this purpose, a model is developed for SCED combined with AGC. The proposed methodology uses measurable signals to tune simple integral controller gains and to allocate the unit generation, giving considerable promise for implementation. The genetic algorithm (GA) in a multi-objective optimization manner is then employed to coordinate LFC and SCED. However, the conventional GA's low convergence speed limits its application for power system optimization problems. In response to the above problem, the AGC model properties in cooperation with a conventional GA are used to significantly modify the convergence speed. To the best knowledge of the authors, there are only a few studies in the field of LFC and ED coordination that suffer from several of the above-stated concerns. Therefore, this article introduces a coordination design framework that considers the realistic and performance optimization inherent in LFC and SCED without any simplifying assumptions.

The rest of this article is organized as follows. Section 2 discusses AGC problem formulation, and Section 3 develops a model for the AGC system. Section 4 presents the GA and multi-objective GA concepts. In Section 5, simulation details and simulation results are explained, Section 6 discusses the proposed method features and advantages, and finally, Section 7 concludes the article.

2. AGC PROBLEM FORMULATION

As previously stated, the main objective of SCED is to determine the on-line unit generation levels as economically as possible subject to the operation constraints. The SCED formulation problem could be explained by the minimization of operation cost and amount of pollutants subject to the power balance constraint, unit operation constraint, line flow constraint, and emission constraint [11].

A summation of unit generation cost and emission control cost defines the operation cost. The unit generation cost includes the fuel cost and operation maintenance cost, which could be approximated by a quadratic and a linear function of output power, respectively. The mathematically representation of generation cost is as follows [11]:

$$C_{gi} = C_{fi} + C_{mi} = a_0 + a_1 P_i + a_2 P_i^2 + b_0 + b_1 P_i, \quad (1)$$

where P_i, a_i, and b_i are the output power and cost coefficients of unit i, respectively.

Modern power utilities have recently been equipped with emission reduction equipment to reduce their pollutant levels below the annual emission allowances assigned by official governments for steam units. This equipment imposed an extra cost approximated by a quadratic function of output power to the operation cost, called the emission control cost. Emission control cost can be explained as follows [7]:

$$C_{ei} = c_0 + c_1 P_i + c_2 P_i^2. \quad (2)$$

The SCED objective is to minimize the total operation cost of the system, which could be explained as follows:

$$\text{Min} C_t = \sum_{i=1}^{N_g} C_{gi}(P_i) + C_{ei}(P_i). \quad (3)$$

On the other hand, SCED tries to provide the required power in a system subject to some equalities and inequalities constraints. The equality constraints are the nodal power balance equations, while the inequality constraints are the limits of all control or state variables. The power balance constraint as equality states that the total generation of on-line units must be met by the load demand plus associated system losses. This constraint could be mathematically explained by

$$\sum_{i=1}^{N_g} P_i = P_d + P_l. \quad (4)$$

The inequality constraints include unit operation constraints, line flow constraints, control constraints, and emission constraints. The unit operation constraint could be mathematically explained by

$$P_{il} \le P_i \le P_{iu}, \quad (5)$$

where P_{il} and P_{iu} are the effective lower and upper limits, defined by

$$\begin{aligned} P_{il} &= \max\{P_{i,\min}, P_{i0} - T_d R_i\}, \\ P_{iu} &= \min\{P_{i,\max}, P_{i0} + T_d R_i\}, \end{aligned} \quad (6)$$

where $P_{i,\min}$, $P_{i,\max}$, and R_i are the physical lower and upper limits and the maximum ramping rate related to generator i, respectively. T_d is the dispatch time interval in minutes. As the employed SCED in this article takes into account generator response speed and load characteristic in the calculations, it employs dynamic ED properties to achieve realistic results.

The line flow constraints are explained by inequality equation as follows:

$$L_{fk} \leq L_{fk,\max}, \tag{7}$$

where L_{fk} and $L_{fk,\max}$ are the MW line flow and the line capacity of line k, respectively.

Emission constraints are indirectly reflected by emission control cost, but the dominant value of operation cost in large-scale systems may affect the injected amount of a pollutant, such as CO_X, NO_2, or SO_X. Presently, minimizing the amount of a pollutant is a major goal of power utilities to reduce costs and detrimental impacts on the environment. The amount of injected pollutant could be estimated by [11]

$$E_{mi}(P_i) = E_{mi}(P_{i0}) + \frac{dE_{mi}}{dP_i}(P_i - P_{i0}) \leq E_{mi,\max}, \tag{8}$$

where $\frac{dE_{mi}}{dP_i}$ is a constant value imposed to the power plants by an official government. It is noteworthy that Eq. (8) restricts the emission of each power plant to be bounded by a maximum allowable value. The amount of a pollutant may be represented in a linear or quadratic function of the generating unit MW output [11]. The sensitivity factor of $\frac{dE_{mi}}{dP_i}$ is assumed to be constant and calculated at $P_i = P_{i0}$ for a linear inequality equation and assumed as a linear function of P_i for a quadratic function.

In addition to the physical lower and upper limitations on the output power of an on-line unit, the provided dispatchable power is also constrained by the associated ramp rate. The impact of ramp rate, *i.e.*, generation rate constraint (GRC) on the LFC dynamic was well discussed in [5]. Considering the ramp rate, *i.e.*, the GRC, in the LFC loop as well as SCED calculation leads to more realistic results.

As stated, the LFC and interchange transaction scheduling try to conduct frequency and net power tie-line interchange deviations to zero at steady state. The summation of tie-line power deviation and weighted frequency deviation from nominal values provides an area control error (ACE) signal, which is, in turn, utilized in AGC systems. The AGC systems usually employ a simple integral controller in each area to drive the ACE signal to zero [2]. A coordination strategy should be designed in such a way that minimizes the ACE in each control area. The proposed control strategy in the present article is a decentralized one. In the decentralized control strategies for a multi-area AGC, each area controller uses only the local states for feedback, and thus, the controller structure becomes simpler.

Taking into account the above formulation, the AGC problem could be explained by the following multi-objective optimization:

$$\min_{P_i} \left\{ \begin{array}{c} C_t = \sum_{i=1}^{N_g} C_{gi}(P_i) + C_{ei}(P_i) \\ \\ E_{mi}(P_i) = E_{mi}(P_{i0}) + \frac{dE_{mi}}{dP_i}(P_i - P_{i0}) \end{array} \right\}, \tag{9}$$

$$\min_{K_i} \int_0^T (ACE_i)^2$$

subject to

$$P_{il} \leq P_i \leq P_{iu},$$
$$\sum_{i=1}^{N_g} P_i = P_d + P_l,$$
$$L_{fk} \leq L_{fk,\max},$$
$$E_{mi}(P_i) \leq E_{mi,\max},$$

where ACE_i is the ACE signal, and K_i is the integral controller related to area i in the interconnected power system.

The conflict behavior of LFC and SCED beside the ability of the multi-objective GA to exploit historical information structures in an attempt to increase performance of future solutions makes the GA attractive for such engineering problems as coordination of LFC and SCED design.

3. MULTI-OBJECTIVE OPTIMIZATION

The GA is a numerical optimization algorithm, capable of being applied to a wide range of optimization problems that guarantee survival of the fittest [5]. Application of conventional GA optimization for the LFC in an interconnected power system was discussed in several papers [2, 3, 5]. The philosophy of multi-objective optimization is to minimize some goal functions that have conflict behavior; in other words, optimization of one prevents optimization of the others [17]. An optimal solution in respect to a single objective give rises to a highly unacceptable solution in respect to another one; therefore, instead of a perfect multi-objective solution that simultaneously optimizes each objective, a set of solutions that satisfies each objective at an acceptable level is calculated. There are two approaches in multi-objective optimization. The first optimizes a single composite objective, which is a combination of weighed objectives [17]. Determination of the weights is a key feature in all optimization weight, upon which calculation of the optimal solution depends. The second relies on the determination of the Pareto optimal solution set [18]. The vector-evaluated GA (VEGA) is used in this study to approximate the Pareto optimal set. In the VEGA, the fitness value for the population in relation with each objective is calculated. Population is then divided into equal sub-populations on the basis of fitness values. To process the optimization, the main operators of the

GA, such as selection, crossover, and mutation, are applied to the combination of sub-populations. In general, the applied GA can be described in the following steps [17, 19]:

Step 1: The initial random population is made.
Step 2: If termination conditions are satisfied, return the population P.
Step 3: Fitness values are evaluated for each member of the population as it relates to each of the Nobjectives.
Step 4: The population divided into N equal sub-populations.
Step 5: Select N_s solutions between the $(1 + (k - 1)\, N_s)$th and (kN_s)th solutions to create the next sub-generation P_k, where $N_s = \frac{P}{N}$, and N and K denote the number of objectives and index of objectives, respectively.
Step 6: Combine all sub-populations P_k and apply selection, crossover, and mutation to create the next generation.
Step 7: Go to Step 2.

Complete details about GA concepts and operators for both multi-objective and single can be found in [2, 17, 18, 19].

4. A DETAILED AGC MODEL

This section develops a model for AGC considering SCED and the basic understanding of AGC and its concepts. A realistic model for LFC in an interconnected power system considering important physical constraints is given in [2]. The presented model in this article is a developed version of that model, which appropriately includes the SCED concept. As previously stated, ED tries to adjust the generator set-point as economically as possible and, hence, should directly affect the governor valve position, as shown in Figure 1. Note that as the interchange transaction scheduling is not an ED objective, the integral controller should be located before the apply point of ED unit.

Per unit values of the calculated generation level by SCED P_{Di} and input power P_i of each area in its related base are employed to calculate the ED error signal. It is noteworthy that

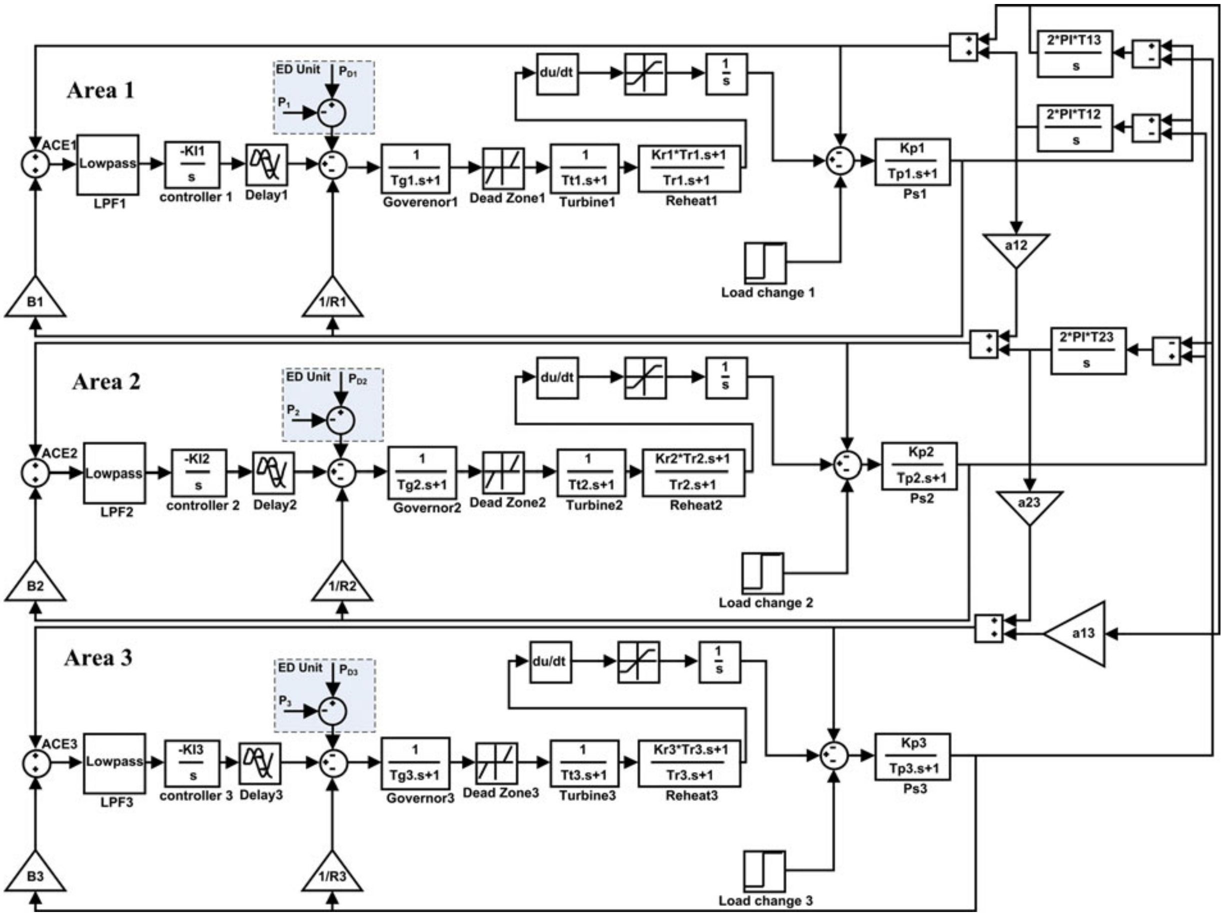

FIGURE 1. Thermal three control area power system considering GRC, time delay, and speed governor dead band.

the input power of each area at the specified time is calculated by adding the net tie-line power interchange to the associated area load.

Although LFC and ED affect the power system in a same way; however, they operate in a different time horizon. To account for this difference, SCED is assumed to have a discrete manner applied at $n \times 100$ sec, where n denotes natural digits.

5. SIMULATION AND RESULTS

A three control area power system (Figure 1) is considered as an application example of the proposed solution strategy. Each area is considered to be supplied by a single generating unit with the following input–output characteristics:

$$F_1 = 0.001562P_{G1}^2 + 7.92P_{G1} + 561\frac{\$}{h},$$
$$F_2 = 0.00194P_{G2}^2 - 7.85P_{G2} + 310\frac{\$}{h},$$
$$F_3 = 0.00482P_{G3}^2 - 7.92P_{G3} + 78\frac{\$}{h}.$$

Suppose that the system tries to deliver a total load of 841.5 MW subject to the emission constraints and SCs. The emission constraints related to the units could be also explained as follows:

$$E_1 = 0.0042P_{G1}^2 + 0.33P_{G1} + 13.86\frac{kg}{h},$$
$$E_2 = 0.00683P_{G2}^2 + 0.5455P_{G2} + 40.267\frac{kg}{h},$$
$$E_3 = 0.00460P_{G3}^2 - 0.5112P_{G3} + 42.9\frac{kg}{h}.$$

The inequality unit operation constraints are considered as

$$10 \le P_{g1} \le 450,$$
$$10 \le P_{g2} \le 300,$$
$$5 \le P_{g3} \le 150,$$

and finally, the line flow constraint for all tie-lines is assumed as

$$\Delta L_{fk} = 0.05 \text{ p.u.}$$

To demonstrate the efficiency of the GA in solving the system, a 0.02-p.u. step load perturbation (SLP) is applied to the first area (area 1) at the 5th second (system load becomes 850 MW). In this article, the initial population consists of 102 chromosomes, each of which contains 48 binary bits (genes). The fitness proportionate selection method (known as the roulette-wheel selection method) is used to select the elite strings for recombination. The normal crossover and normal mutation coefficients are considered as 0.8 and 0.2. Crossover between any two solutions in the entire population is employed to find intermediate solutions. In this way, a crossover between two good solutions, each corresponding to a different objective, give rises to offspring that are good compromised solutions between the two objectives. It should be noted that dual displacement mutation and mathematical crossover could be employed instead of normal ones.

Scenario	A	B
KI_1	0.2594	0.010
KI_2	0.2780	0.560
KI_3	0.0010	0.932

TABLE 1. Optimum value of integral gains

At the first step, the behavior of a power system only in the presence of LFC and without SCED is investigated. The optimum results of integral controllers are reported in Table 1 as scenario A. The frequency response and the net tie-line power change in each area are shown in Figure 2. It is obvious that the frequency and net power exchanged between the control areas deviations became zero in the steady state. In another simulation, SCED and LFC are simultaneously considered in the system, and the frequency response and net tie-line power change in each area are shown in Figure 3. The optimum results of integral controllers (scenario B) and generated power of generating units are reported in Tables 1 and 2, respectively. In scenario A, only LFC is considered, and hence, the conventional GA is employed to calculate the integral controller's gain in each area. However, conflict objectives of scenario B make the multi-objecctive optimization procedure mandatory. Schaffer's VEGA [18] is a non-Pareto-based technique that differs from the conventional GA only in the way in which the selection step is performed; the VEGA algorithm is easy to implement but suffers from the speciation problem. The specification problem causes the algorithm to fail to generate solutions that are not necessarily the optimum in one objective but are optimal in the Pareto sense. The optimum value reported in Table 1 is a Pareto optimal point that defines the vertices of the Pareto optimal set [20, 21]. Although Pareto optimal solution sets are often preferred to a single solution, the reported values in Tables 1 and 2 are also a single solution as they aim to compare results with scenario A. The Pareto optimal solution is preferred because they can be practical when considering real-life problems since the final solution of

Generators	G_1	G_2	G_3
Output power (MW)	424.13	295.86	130.01

TABLE 2. SCED results

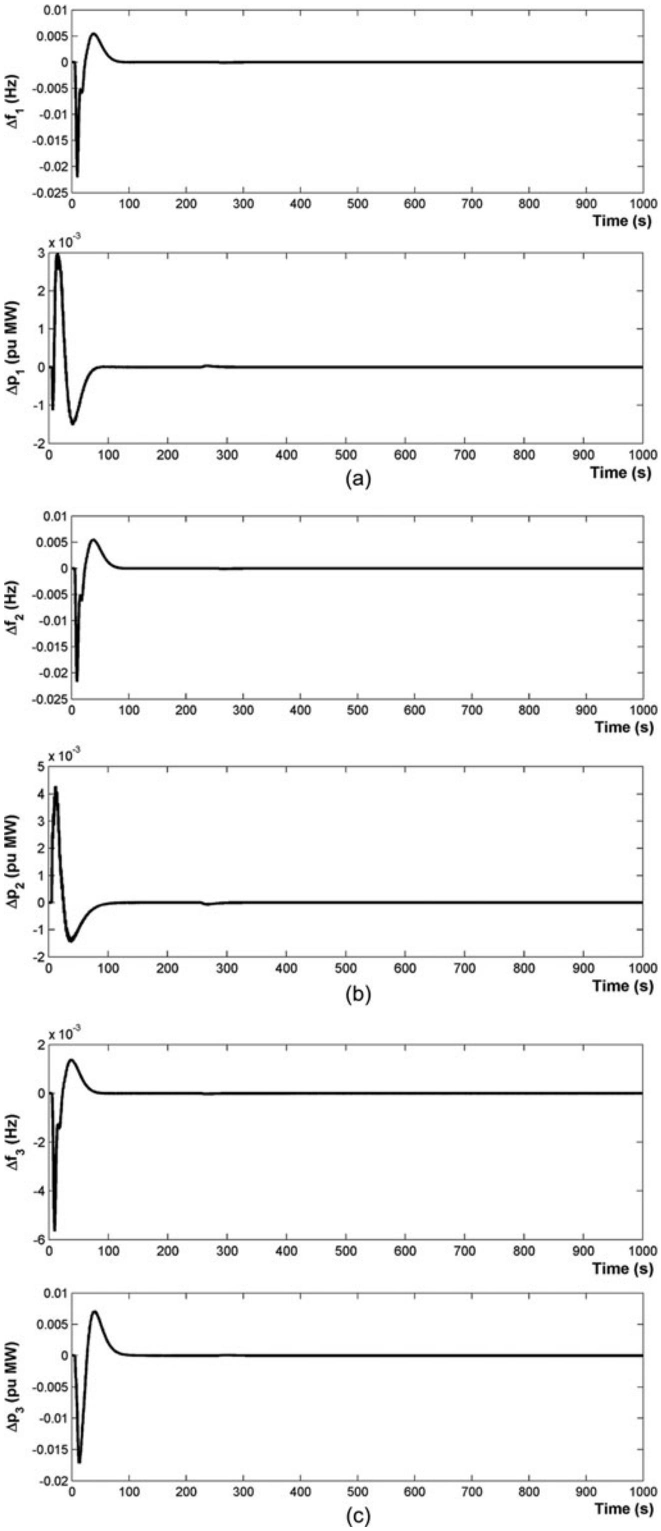

FIGURE 2. Frequency and tie-line power responses for scenario A: (a) area 1, (b) area 2, and (c) area 3.

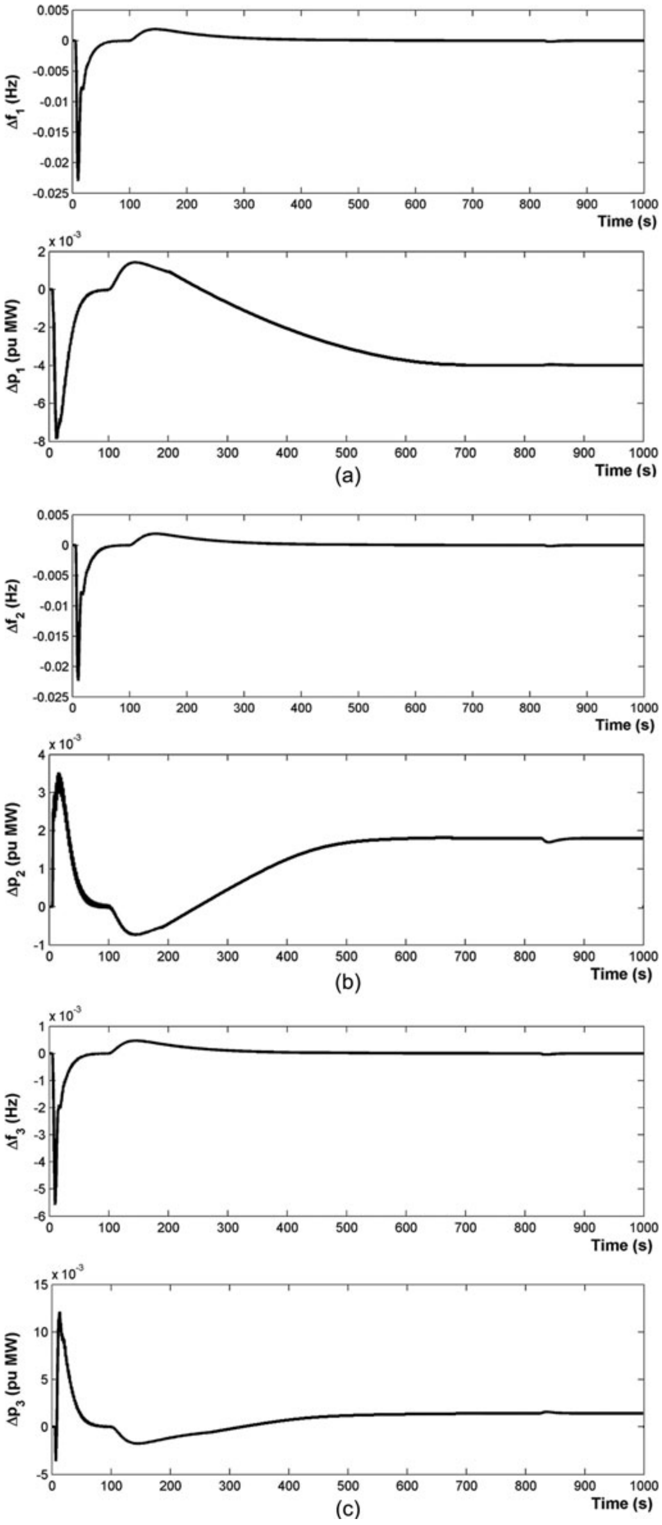

FIGURE 3. Frequency and tie-line power responses for scenario B: (a) area 1, (b) area 2, and (c) area 3.

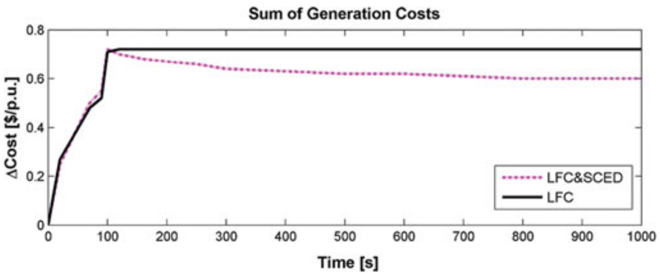

FIGURE 4. Generation cost for scenarios A and B.

the decision maker is always a trade-off. It could be seen that SCED prevents a net tie-line power change from being zero at steady state. In this situation, the added error signal supplied by the ED unit deviates the net tie-line power from zero to operate the system as economically as possible. At the first triggering of the SCED unit, *i.e.*, at 100 sec, sudden changes occur in the frequency and net tie-line power exchange, as depicted in Figure 3. From Figure 3 it is obvious that all tie-lines meet the inequality constraints related to the power flow. Figure 4 compares the generation costs of both control strategies, *i.e.*, scenarios A and B, in response to a load disturbance. As clearly seen in Figure 4, the GRC limits the cost increment rate as well as incremental rate of generation.

The quantities $a_{12} = -P_{r1}/P_{r2}, a_{13} = -P_{r1}/P_{r3},$ and $a_{23} = -P_{r2}/P_{r3}$ are employed in Figure 1 to take into account the inequality of loads in the interconnected power system [2, 5]. These quantities are used in cooperation with the GA to enhance the efficiency of the optimization procedure. For this propose, random selection of the initial population related to SCED is restricted by these quantities. In other words, the population related to the generation of unit i (in this article, area 1) is selected randomly, and the others are considered as $a_{ij}P_i$. The simulation results show that randomly selecting the entire population (conventional multi-objective GA) causes the algorithm be converged to the optimum values at the 86th iteration; however, the introduced modification in the applied GA improves the convergence speed by reducing the iterations number to 17. The convergence characteristics of the GA for the conventional and modified GA are depicted in Figure 5. In the optimization problem, the calculation of J (cost function) takes all the computational time, and hence, the number of the Jth evaluation could be assumed as the calculating time of integral controllers.

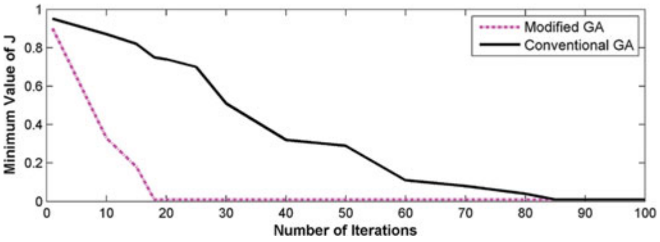

FIGURE 5. Convergence characteristics of GA for conventional and modified GA.

6. DISCUSSION

AGC is an optimization system performance rather than a stability issue. Therefore, formulating the LFC-ED coordination design as an optimization problem is of interest and completely lacking in the literature. Simple integral or proportional-integral (PI) controllers are popular in real-world AGC systems. However, the recent research works in the state of the art try to introduce a complex control structure instead of simple PI controller, which might not be practically adapted to real power systems. Lack of an appropriate model for an ED-LFC coordination design causes the recent literature to formulate the problem as a hierarchical control design with a complex structure. In hierarchical strategies, LFC operates on the top of ED in the first level. The coordinator at the second level receives the local solutions (ED and LFC control signals) and then provides a new set of interaction parameters. The interactions are exchanged several times until convergence is achieved. As ED is a discontinuous control action and LFC is a continuous one, interaction convergence is too slow and somehow causes a far from optimal result. This is because of the undesirable effect of ED in triggering time on the LFC performance and causing a steady-state error on the net tie-line power. Before the next ED rescheduling, the LFC loop tries to conduct the tie-line power deviation to zero. At the next ED triggering time, ED tries to operate the power system as economically as possible, while the net-tie line power deviation from its scheduled value receives no attention. Therefore, hierarchical control strategy convergence is of great concern and somehow causes divergence. In on-line applications, this periodically actuates the governor valve to change its position and return the tie-line power and frequency deviations to zero.

Several generator set-point readjustments via governor reaction cause valve damage. This introduces a significant extra expense to the generating units' owner, which cannot be neglected. Therefore, hierarchical control strategies seem inappropriate for real applications. Moreover, by increasing the system dimensions, *i.e.*, system areas, the interactions and coordinator structures become complex and maybe impractical. AGC for multi-area power systems is discussed in this article with incorporation of both ED and LFC into one optimization framework. For this purpose, an attempt is made to consider the optimization inherent of AGC by developing two steps. The first step includes appropriate modeling of discontinuous

ED in the realistic power system dynamic model, while the second tries to drive the system as stably, securely, and economically as possible by a simple optimization algorithm. The employed power system dynamic model is a realistic and was recently validated in [2]. Therefore, the proposed economic model considers all real system non-linearities and physical constraints that were simultaneously or partially neglected in the recent research.

One of the most important concerns raised from optimization formulating is that the convergence speed is significantly decreased; *i.e.*, computational time is increased, especially for large-scale systems. The developed method in this article combined the proposed dynamic model features with the GA in a new heuristic way to eliminate the dependency between the system dimensions and computational time. Simple implementation of the VEGA makes it attractive for the coordination design problem in a real power system. However, the VEGA give rises to an optimal point in a Pareto set, which is the vertex of the Pareto optimal set instead of the entire set. This solution could be satisfactory for secure and economic operation of power systems, especially in on-line applications. As the calculated result is in the Pareto optimal set and gives rise to an acceptable system performance in regards to security and economically issues, sensitivity of the VEGA to the Pareto front could not be a limitation issue. However, in the new restructured power system, *e.g.*, the electricity market with a complex structure, independent system operator (ISO) and generation companies (GENCOS) require compromise solutions to trade-off and achieve maximum benefit, so the VEGA could not be acceptable. In such situations, a more complex methodology, such as multi-objective particle swarm optimization, could be appropriate.

In all investigations, the long-term time-domain simulation is considered as a criterion for performance assessment and results verification. Considering all model uncertainties, non-linearities, and saturations, in addition to simplicity and good response of the proposed coordination strategy, the proposed method is reliable for real large-scale power systems.

7. CONCLUSION

The need for power system performance optimization driven by the demand for economic and secure operation of systems is the main motivation of this article. AGC is one of the important power system performance optimization problems in interconnected power system design and operation, and it is becoming more significant due to the increasing size, environmental constraints, and complexity of power systems. On the other hand, power system operators are faced with the difficult task of providing economic and secure operation of power systems. This article tries to explain SCED and AGC coordination as an optimization problem to satisfy the performance optimization inherent in AGC and SCED. This formulation give rises to the tuning of simple integral (I) controller gain, which is popular in real-world LFC systems and overcomes the complexity of the recently published methodologies in the field.

In the proposed methodology, generation rescheduling is appropriately modeled in the frequency control loop, which affects AGC performance by deviating the net tie-line power exchange from a nominal value to drive the system economically and with acceptable environmental impacts. To validate the application of the proposed methodology for large-scale interconnected power systems, it is required to modify the optimization approach. For this purpose, despite system dimensions, the GA tries to optimize the power system performance in an area and the others take into account the quantities related to the inequality of loads in the power system model. Simulation results reveal that the proposed methodology could satisfy the AGC and SCED objective in the Pareto set solution.

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