A Firefly Algorithm-Based Load-Frequency Control Design Concerning the Integration of Renewable Energy Sources

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***Abstract*—Environmental concerns have made more utilities to be using Renewable Energy Sources (RESs) as new power generating units. Due to much variability posed by such sources, their impacts on frequency control performance have become a great concern. As a result, Load-Frequency Control (LFC) has undergone significant changes. In this paper, in order to regulate frequency in a modern power system, a Proportional Integral Derivative (PID) controller is employed and its parameters are tuned using firefly algorithm. A three-area interconnected power system in the presence of renewable energy sources is modeled and simulation results reveal that tuning PID gains using this optimization technique gives a desirable performance in damping frequency deviations. Furthermore, different scenarios have been performed to verify its robustness against diverse perturbations.**

***Index Terms*—Firefly algorithm, Load-frequency control, Power system control, Renewable energy sources.**

I. Introduction

In an interconnect power system, generation and load must be balanced in order to ensure the reliability of a power system. Following a disturbance, frequency and tie-line power deviate from the specified bound. As a result, the power system would be undergone a change. Thus, frequency and tie-line power flow deviations of all control areas should be kept within a specific limit. This goal is achieved by a proper Load Frequency Control (LFC) design [1]. Many researches have been done as of yet to propose a control scheme for LFC in the conventional power systems. Currently, most of the countries are moving toward utilizing more Renewable Energy Sources (RES), utilities are also encouraged to apply them due to environmental concerns. This, however, has made a significant effect on power system's reliability and stability. In other words, variable nature of RESs viz. wind or solar output power adds more uncertainties to the power systems which in turn results in more frequency deviations [2]. This is where LFC problem requires to be solved with proper control methodologies owing to reliability concerns which are being much bolder in a modern environment filled with a great deal of fluctuations.

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Proportional-Integral-Derivative (PID) controllers have been widely used due to their improving performances in reducing overshoot and shortening settling time [1]. However, their parameters need to be optimized in order to obtain a good response. Although there have been various methodologies for tuning PID gains, some of which are rarely used for either much complexities they have or a long time their implementation takes. Interests in using intelligent algorithms for LFC problem have been being increased over time for their effective capability in tuning PID controllers; among which Particle Swarm Optimization (PSO) [3-5], Artificial Bee Colony (ABC) [6-8], Genetic Algorithm (GA) [9,10], Bacterial Foraging Optimization (BFO) [11-13], Differential Algorithm (DE) [14] have been used extensively. An imperialist Competitive Algorithm (ICA) has been used in [15] to have a PID controller gains optimized. PI controller parameters were tuned using a hybrid BFO-PSO algorithm in [16]; results were compared with BFO, GA, PSO and Craziness-based PSO (CRAZYPSO) and showed a better performance than them. As a matter of fact, employing each of aforementioned techniques results in different outcomes. Not only the chosen algorithm impacts on the results, but also the used objective function and controller structure affect power system performance significantly [17]. Hence, adopting a less complex optimization technique provided to meet control objectives is a main goal of this paper. A new meta-heuristic algorithm capable of representing a favorable performance and developed by Xin-She Yang is Firefly Algorithm (FA) [18-21]. It was inspired by the flashing behavior of fireflies. FA has been playing an efficient role in solving optimization problems and has become a useful tool in this case. Authors in [22] showed that FA works efficiently and outperforms other meta-heuristic algorithms such as hybrid BFO-PSO, PSO, and DE. In [23], FA was successfully employed for clustering benchmark problems; furthermore, its robustness, efficiency, and reliability were proved. FA has been used in [24] for optimizing controller gains, also convergence characteristics of FA, GA, PSO, BFO and ABC were compared and configurations showed that FA converges faster than the rest of nature-inspired techniques. In [25], a binary real-coded FA was applied to solve unit commitment problem. Authors in [18,20] used FA to solve the non-linear and non-convex optimization problem, results showed FA's robustness,

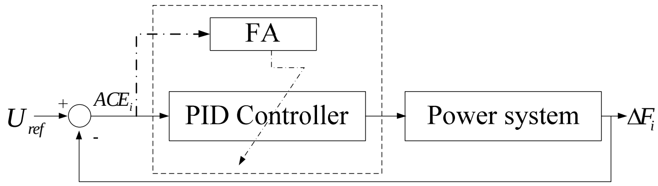

Fig. 2. Proposed control scheme.

flexibility and reliability, its superiority over PSO and BFO was illustrated. A recent research over FA advantages in [26] confirmed that it can provide a good balance of exploitation and exploration. Also, it was shown that FA needs far fewer function evaluations. As seen, Interests toward using FA in solving optimization problems are being increased. However, there have been few studies addressing LFC problem using FA. In this paper, firefly algorithm has been applied to solve LFC problem concerning renewable energy integration in a modern three-area power system comprised of various renewable energy sources. Simulations are carried out using MATLAB software and the effectiveness of the proposed strategy is verified via obtained results. Moreover, its robustness is confirmed via different scenarios.

II. Firefly Algorithm

Firefly Algorithm (FA) is a meta-heuristic population-based optimization algorithm developed by Xin-She Yang in late 2007 and 2008 [18-21]. It was biologically inspired by the behavior of fireflies and their flashing patterns produced by biochemical process bioluminescence which plays a significant role on mating. Basically, flashing characteristics of fireflies are classified as three following assumptions [21].

a) All fireflies are unisex; as a result, they are attracted to other fireflies regardless of their sex.
b) The degree of attractiveness is proportional to fireflies' attractiveness; their attractiveness is proportional to their light intensity. Thus, for any two flashing fireflies, the less bright one will be moving towards the one which is brighter. Brightness is also tied with distance; this is, by increasing distance between two fireflies, their brightness and in turn their attractiveness will decrease. Two fireflies having the same brightness will troll randomly.
c) The light intensity or brightness is determined by the objective function to be optimized.

Two important issues in FA notion are the variation of light intensity (I) and the formulation of attractiveness (β) [24]. A firefly's light intensity or brightness which is defined as below determines its attractiveness and is relevant to objective function.

$$I(r) = I_0 e^{-\gamma r} \tag{1}$$

where I_0 is the original light intensity, γ is the absorption coefficient, and r is the distance between two fireflies. As could be seen, while light intensity decreases with the distance monotonically and exponentially, light is being absorbed in the environment, and the attractiveness is changing with the degree of absorption.

The attractiveness is proportional to light intensity being observed by the other fireflies, so it is relative and varies from a firefly to another, and defined as

$$\beta = \beta_0 e^{-\gamma r^2} \tag{2}$$

where β_0 is the attractiveness at $r = 0$. In some studies r^2 is replaced by r^m with $m \geq 1$.

The distance between two fireflies i and j at x_i and x_j positions is expressed as below in the form of Euclidean equation,

$$r_{ij} = \left\| x_i - x_j \right\| = \sqrt{\sum_{k=1}^{n} \left(x_{i,k} - x_{j,k} \right)^2} \tag{3}$$

where r_{ij} denotes distance between two fireflies, $x_{i,k}$ is the kth of x_i, and n is the problem dimensions.

Movement of firefly i towards jth firefly is stated as

$$x_i = x_i + \beta_0 e^{-\gamma r_{ij}^2} (x_j - x_i) + \alpha \varepsilon_i \tag{4}$$

where x_i is the current position of ith firefly, the second term is attraction to another more attractive firefly, α is a randomization parameter from interval [0,1], and ε is a random number from interval [0,1]. As a matter of fact, the third term of the equation above is referred to as random walk [24].

III. System Modeling

A three-area interconnected power system including various energy sources viz. Wind Turbine power Generation (WTG), Photovoltaic power generation (PV), Fuel-cell power generation (FC), Aqua-electrolyzer (AE), Flywheel Energy Storage System (FESS), Battery Energy Storage System (BESS), and conventional generators has been considered as a test system in this study. Moreover, in nonlinear power systems Generation Rate Constraint (GRC) is of major constraints that should be considered. WTG generates power depending on wind speed. Since current facilities are not accurate enough to predict wind speed, somehow its output power comes with lots of variability. Likewise, PV's output power might have unpredictable fluctuations while producing energy via absorbing solar radiation through solar panels. FC is an important source converting hydrogen directly into electrical energy; what makes it special is due to its plenty of advantages such as low pollution, high efficiency and so on. Since FC consumes hydrogen to be able to produce energy, AE is used for producing required hydrogen for FC. Energy storage systems are used to storage energy while there is surplus generation, and can be used during load demand [27]. For modeling conventional generators, turbines, and power system, simple first-order transfer functions are used and the parameters are taken from [1]. Different RESs and batteries are integrated here to have a reliable power supply following a change in load conditions. However, some of which, especially WTG and PV, may represent a complimentary behavior that would result in energy capacity reduction. Therefore, FC is integrated here along with energy storage systems like BESS or FESS. They are also modeled as first-order transfer functions with their parameters taken from [27] along with the detailed characteristics about selected RESs. Since three aforementioned interconnected control areas are quite similar in size and components, block diagram of one control area is illustrated in Fig. 1.

$$G_{WTG}(s) = \left(\frac{K_{WTG}}{1 + sT_{WTG}} \right) \tag{5}$$

$$G_{PV}(s) = \left(\frac{K_{PV}}{1 + sT_{PV}} \right) \tag{6}$$

$$G_{AE}(s) = \left(\frac{K_{AE}}{1 + sT_{AE}} \right) \tag{7}$$

$$G_{FC}(s) = \left(\frac{K_{FC}}{1 + sT_{FC}} \right) \tag{8}$$

$$G_{DEG}(s) = \left(\frac{K_{DEG}}{1 + sT_{DEG}} \right) \tag{9}$$

IV. Proposed Control Scheme

Load-Frequency Control known as of the major problems that interconnected power systems have been dealing with. Pragmatically, Conventional controllers such as PID controller are widely used to improve LFC problems in [1]. These controllers, however, are incapable of presenting a good dynamical performance in the presence of non-linearity as well as various operating conditions [2]. Owing to environmental concerns, the need for utilizing more RESs is being increased [28]. Obviously, taking new uncertainties imposing by fluctuated output power of such sources into account, new control strategies must be adopted to ensure power system's reliability and avoid further devastation. This section describes a FA-based PID controller for addressing the LFC problem in the new environment. The parameters of PID controller are automatically tuned via firefly algorithm. For meeting this goal, in the first place, a proper objective function based on specific constraints should be defined. In most studies regarding meta-heuristic optimization techniques four criteria have been being used in control methodology: Integral of Squared Error (ISE), Integral of Time multiplied Squared Error (ITSE), Integral of Absolute Error (IAE), and Integral of Time multiplied Absolute Error (ITAE). Using each criterion within optimization process has its own advantages. ITSE objective functions result in large output following a sudden change in the controller input; thus, from the notion of LFC studies, ITSE would not seem to be a proper objective function [15]. In this case, applying ITAE into control scheme has proved to be a good option in terms of reducing overshoot and settling time [17]. It is defined as

$$J = ITAE = \int_0^{t_{sim}} (|error|) \cdot t \cdot dt \tag{10}$$

where J is the cost or objective function and t_{sim} is the simulation time range. In LFC studies, keeping generation and load in balance is considered as the main objective. Thus, driving the error to zero needs to be considered in the control scheme. Area Control Error (ACE) is stated as

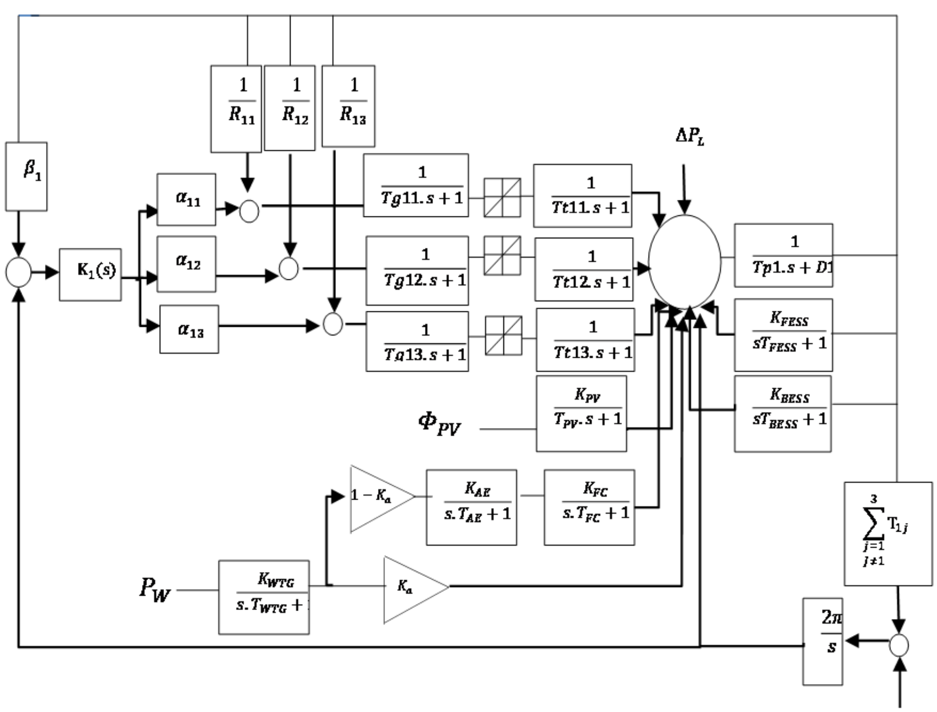

Fig. 1. Block diagram of one control area.

Table I
FA parameters used

FA parameters	Value/Expression
γ	0.5
β	0.2
α	0.5
Population	5
Iteration	100

Table II
Optimized gains of PID controller

Tuned gains	Area 1	Area 2	Area 3
K_p	-9e-5	-9e-4	-1.6e-4
K_i	-0.5	-0.3435	-0.50398
K_d	-0.2	-0.25	-0.45

$$ACE = \beta \Delta f + \Delta P_{tie-line} \quad (11)$$

where β is the frequency bias, Δf is he frequency deviation, $\Delta P_{tie-line}$ is the tie-line power error. So, the final form of cost function is expressed as

$$J = ITAE = \int_{0}^{t_{sim}} \left(\left| \Delta f_i \right| + \left| \Delta P_{tie-i} \right| \right) \cdot t \cdot dt \quad (12)$$

where Δf_i is the frequency deviation related to area i, $\Delta P_{tie-line} - i$ is the tie-line power error between area i and its adjacent area.

Taking all these into account, the optimization problem can be stated as

$$Min\left(J\right) \begin{cases} -2 \le K_p \le 2 \\ -2 \le K_i \le 2 \\ -2 \le K_d \le 2 \end{cases} \quad (13)$$

where K_p, K_i, and K_d are proportional, integral and derivative gains of PID controller, respectively. The related bound are chosen from [15].

The proposed control scheme is shown in Fig. 2. There are three parameters being introduced before that FA is controlled by: α, β, and γ, which are selected from interval [0,1]. Since, FA is a population-based algorithm, choosing the proper number of fireflies leads to have fewer calculations [17]. Flowchart of firefly algorithm is depicted in Fig. 3.

V. Simulation Results

As mentioned before, due to lots of uncertainties being posed by fluctuated output power of sources like wind and solar power generators, because of their unpredictable nature viz. permanent variations in wind speed and sunlight flux, also regarding the fact that up to current facilities accurate prediction is not plausible yet; is it quite important to examine control strategies under different scenarios by taking RESs fluctuations' effects into account. Therefore, the performance of proposed methodology is evaluated via testing some scenarios to investigate its robustness and observe impacts of these fluctuations on the power system under study. FA parameters used in this paper is tabled in Table I. Optimized gains of PID controller using FA are also given in Table II.

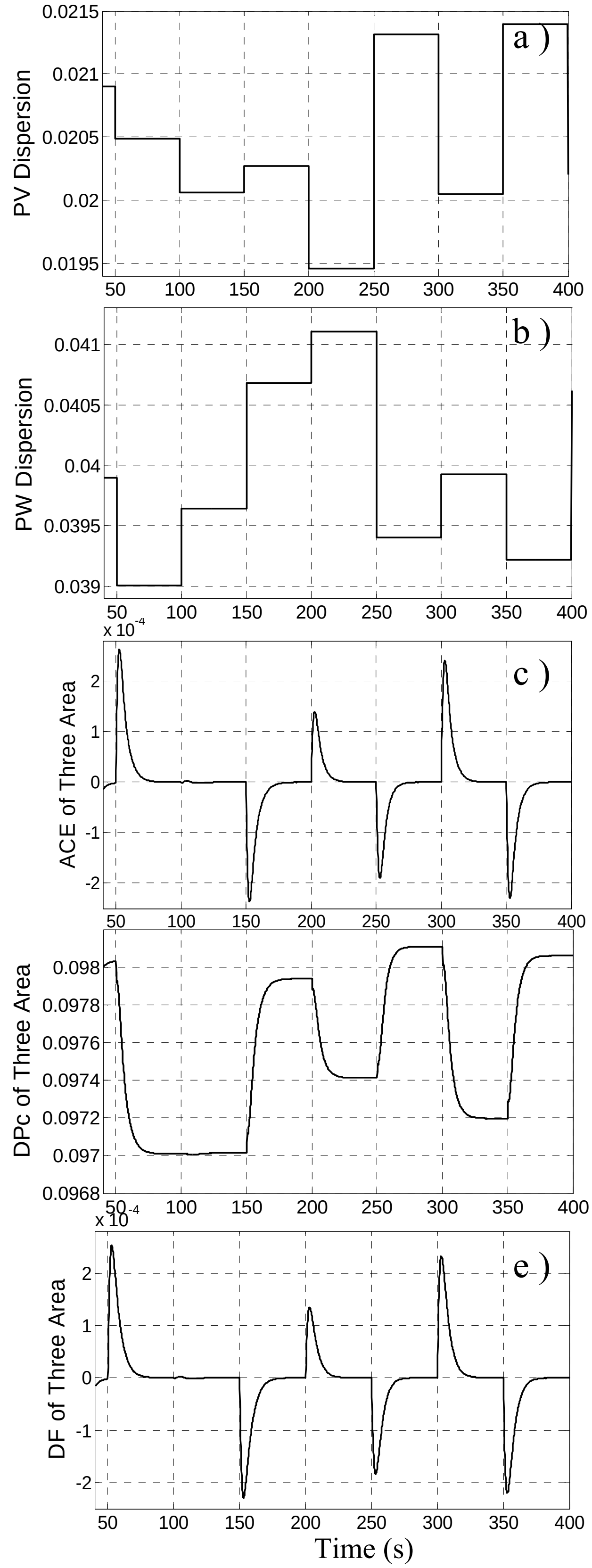

Fig. 4. (a) PV dispersion. (b) PW dispersion. (c) ACE of three area. (d) ΔPC of the third area. (e) Δf of the third area.

A. *Scenario 1*

For the scenario 1, different valued output power variations of WTG and PV are considered and simultaneously applied to the test system over time; simulation results are obtained and can be seen in Fig. 4. Considered power variations of PV and WTG are given in Fig. 4a and Fig. 4b, respectively. Results for ACE, ΔPC, and Δf of the third control area are shown in Fig. 4c, Fig. 4b, and Fig. 4d, respectively. Figures show the superior performance of the proposed strategy. Optimal frequency response proves its eligibility. It can be observed how swift and desirable the recommended controller acts against disturbances being posed from these very generating powers. Since three control areas are quite similar with a same size, Δf, ΔPC, and ACE of the third control area considering changes in PV and WTG are depicted.

B. Scenario 2

For this scenario, to examine capabilities of the suggested controller, this time diverse variations in load, WTG and PV are exerted to the power system, simultaneously. Simulations were carried out. Fig. 5a, Fig. 5b, and Fig. 5c are the dispersion patterns for PV, WTG, and load, respectively. ACE, ΔPC, and Δf are depicted in Fig. 5d, Fig. 5e, and Fig. 5f as well. Obtained results verify the robustness of the designed controller; configurations imply that unlike the unstable condition, frequency has overcome the perturbations and returns to the optimal bound successfully. It shall be noted that load disturbance size is greater than that of PV and WTG, in other words, the difference between generation and load is higher than the previous scenario; as a result, frequency performance is more affected by changes in load.

C. Scenario 3

As the last scenario, it is tried to apply a sever disturbance to the interconnected power system as a serious condition. In this case, a white-noise ranging from -0.2 pu to +0.2 pu is considered as a larger disturbance here and can be seen in Fig. 6a. Following this disturbance, simulation results for ACE, ΔPC, and Δf are shown in Fig. 6b, Fig. 6c, and Fig. 6d indicating the desired performance of proposed LFC scheme in driving frequency deviations and ACE to zero and reducing overshoots and settling times even despite having larger perturbations.

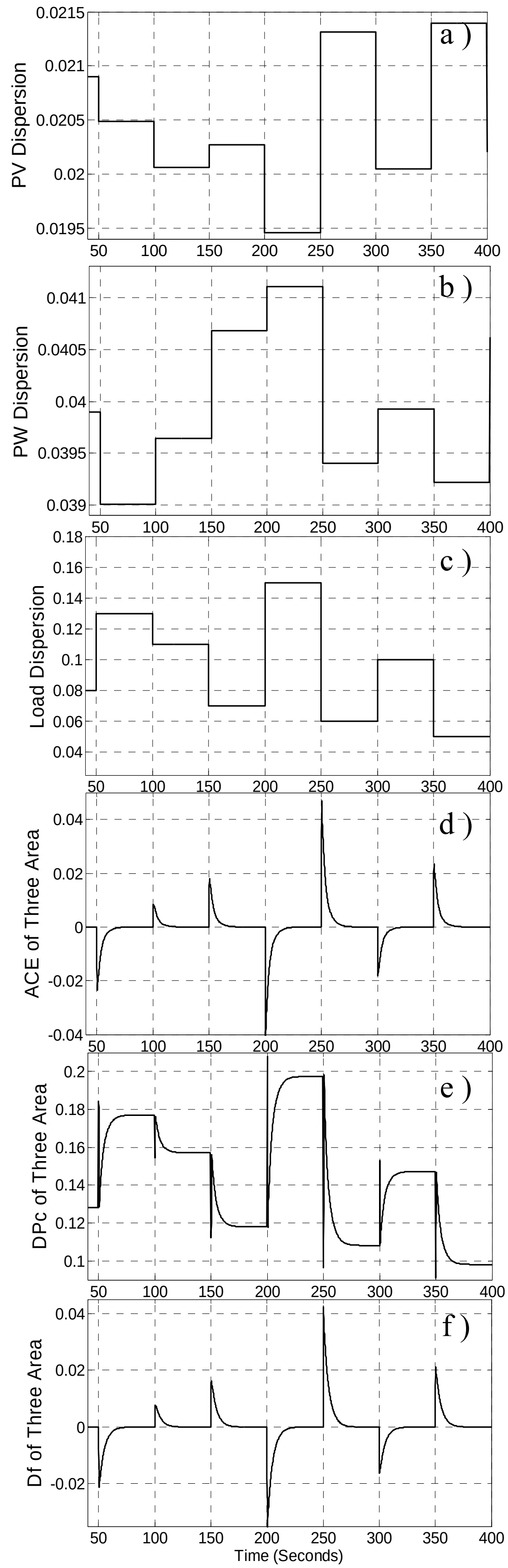

Fig. 5. (a) PV dispersion. (b) PWTG dispersion. (c) load dispersion. (d) ACE. (e) ΔPC. (f) Δf .

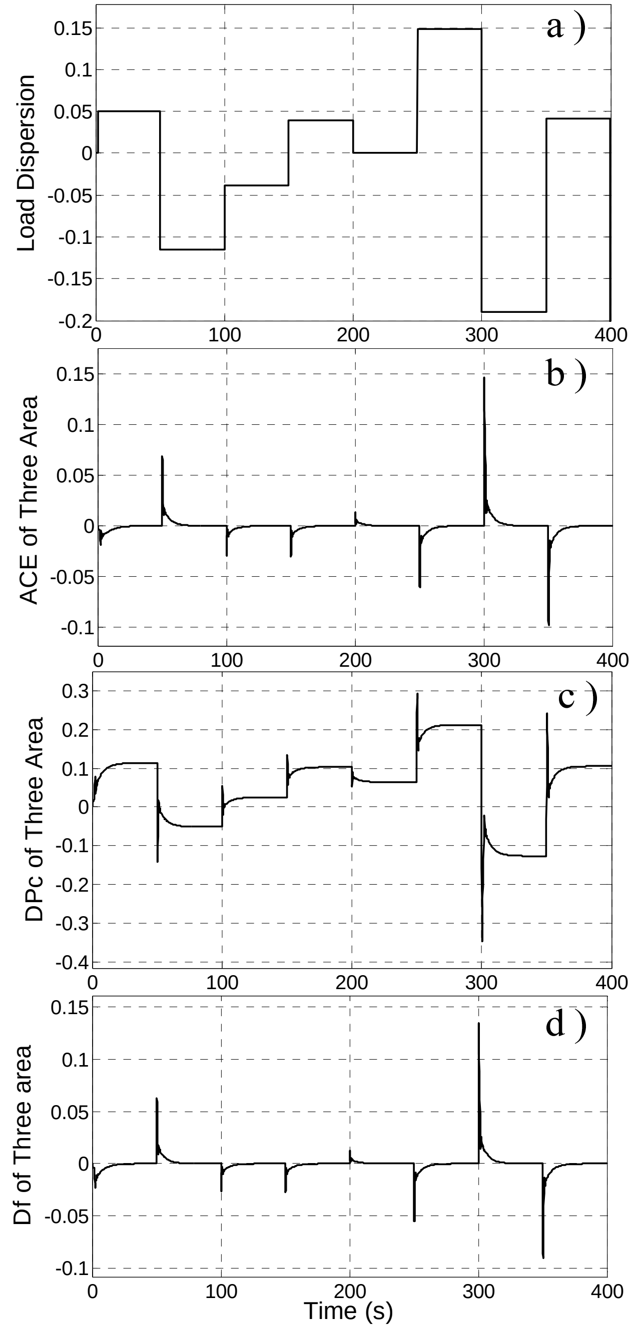

Fig. 6. (a) Load dispersion. (b) ACE. (c) ΔPC. (d) Δf.

VI. Conclusion

An FA-based PID controller has been designed to address LFC problem in a modern interconnected power system consisting of WTG, PV, AE, FC, and Energy Storage Systems. PID parameters have been successfully tuned, and its performance was favorable in terms of driving frequency deviations to zero. Several control scenarios were applied to the three-area power system under study concerning permanent fluctuations in load, solar radiation and wind turbine speed to examine the controller's flexibility and robustness. Obtained results proved that the proposed methodology provides a desirable performance against sudden load changes as well as WTG and PV fluctuations.

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