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Intelligent Load Frequency Controllers for Power Systems with Thermal and Photovoltaic (PV) Generations

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Abstract. This paper presents a comprehensive investigations of load frequency control (LFC) of a two-area interconnected power system consisting of plants with thermal and photovoltaic (PV) power generations. The two power systems areas are interconnected via AC transmission lines. The LFC regulators for the power system are designed using optimal control concept based on full state feedback control technique. Also, intelligent PID structured LFC regulators using Firefly Algorithm (FA), Genetic Algorithm (GA) and Fuzzy Logic Control (FLC) are designed. These regulators are implemented in the system considering step load disturbance in one of the power system areas. The dynamic system response plots are achieved with designed LFC regulators to investigate their effectiveness in mitigating the frequency and tie-line power deviations resulting out from the step load disturbance in the system. The dynamic response plots so obtained with various LFC regulator designs are compared under similar operating conditions. From the investigations carried out, it is inferred that the gains of optimal LFC regulator based on optimal control concept using full state vector feedback control technique are considerably larger as compared to those of gains achieved using FLC,FA and GA. The FA,GA & FLC based LFC regulators are capable to mitigate the frequency and tie-line power deviation in both areas caused due to load disturbance. Finally, FLC based LFC regulators have demonstrated to be the better choice for implementation for the power system model under investigation as compared to other designs of LFC regulators carried out in the study.

Keyword*: *Photovoltaic generation, Dynamic model, Optimal control, Fuzzy logic control, Firefly algorithm, Genetic algorithm.

1. Introduction

There has been a continuous and exponential growth in energy demand over the years all around the globe. Therefore, it has become one of the compelling reasons for power engineers to use natural fossil fuel resources extensively for power generation to match these demands. These resources are not only putting challenges to maintain clean environment standards but have been depleting at a very faster rate. Also, power industry has been transforming through many structural and technological changes which has made the system operational and control problems more difficult. The addition of electrical power from renewable energy-based plants comprising wind turbines, photovoltaic systems, fuel cells etc. continuously has attracted power engineers and researchers to pay their attention towards the renewable sources-based generations also.

The emergence of advanced technologies for manufacturing the photovoltaic (PV) module and wind turbines (WT), at reduced cost, have accelerated the pace of development of renewable source based electrical energy generating plants. Further, higher efficiency of PV systems has been achieved due to the best efforts of researchers. The fast depletion of fossil fuels and strict environmental regulations have motivated the power engineers to go for alternative feasible and viable renewable sources of energy. Photovoltaic power generation constitutes a major power share among all renewable generation due to enormous economic, technical and environmental advantages.

The Kingdom of Saudi Arabia has world's biggest feasible environment for the photovoltaic generation, and of course, the government has a very ambitious plan of setting up a very large scale photovoltaic (VLS-PV) power generation. The plan aims to produce power to the tune of 16GW by the year 2032[1,2]. The solar power and other renewable energy sources are playing Pivotal roles from rescinding our beautiful environment further and to produce clean energy to plug the power imbalance in the system network. The conceptualization of modern power system is to have mix power generation and to interconnect them through tie-lines and surely this way we shall be able to alleviate the shortage of power worldwide and optimistically our environment shall be preserved from further deterioration. Therefore, now the issues of integration of renewable sources shall be addressed meritoriously as it makes the operation and control of power system more challenging. The structure of interconnected power system also becomes more intricate with the integration of non-conventional energy sources. Use of sophisticated control tools will lead to more effective control and operation of whole system. So, it's a perplexing task for power engineer and researchers for the proper, effective and efficient design of scheme to handle operational and control of complex power systems. The present-day power systems have been operating in interconnected fashion and in future they may have a substantial amount of power from renewables on the grid.

For good quality power supply, keeping system frequency as near as nominal system frequency value under continuously varying operating conditions is an essential requirement which can be achieved by AGC/ LFC schemes. AGC schemes are designed for monitoring and controlling power generation to maintain frequency regulation and scheduled tie-line power [3]. The early designs of AGC regulators were based on classical and then on conventional control concept and gains were tuned merely based on operating experience or conventional tuning techniques. The performance of these AGC regulators may not be effective in the new environment of diverse sources power generation. As the structure of future power system model (i.e. Hybrid PV-Thermal interconnected power system model) may be large and complex in nature. The control of such systems using existing AGC schemes do not provide the desired dynamic performance and will not be adequate to deal control problems of these power systems. Therefore, the new emergent area of intelligent techniques may be utilized to alleviate the shortcomings of conventional and modern control concept based AGC controller designs.

The control methods and optimization techniques are decisive factors for design of AGC controller of power system dynamic performance aspects. The modern control theory gave a Pioneer breakthrough in the design of AGC regulators and replaced the classical controllers due its numerous features. The application of intelligent techniques in power system solved many stability problems and provides a more reliable and good quality power supply at optimum cost. Therefore, literature review is carried out for good number of papers considering each aspect separately.

The application of conventional techniques for design of AGC/ LFC regulator considering an isolated area is highlighted in [4-6]. Due the increasing load demand, the power system becomes large and interconnected with multi-areas to meet out the power demand. The control problem becomes more complicated if the control area has non-conventional source of power generation as it affects mainly the dynamic behaviour of the power system and negligible contribution in frequency regulation. The intelligent techniques-based controllers are proposed by many researchers [7,8]. The authors proposed the hybrid Fuzzy GA based optimal controller [9,10]. AGC controller design of the multisource power system with the renewable energy is becoming the state of the art for balancing the power in system [11,12]. The contribution of renewable energy for frequency regulation and the dynamic stability of the power system are evident from the research [13-16]. Elgerd and Fosha [17] proposed optimal LFC regulator incorporating state feedback control. Modern control theory gives the concept of suboptimal and eased the analysis and controller design of the complex power system

due to its big size and mix generation pattern [18-20].

In recent years, intelligent techniques have been extensively applied in power system and for automatic generation controller [21-23]. The authors designed intelligent controllers for AGC using fuzzy logic [24-26] and genetic algorithm [27,28]. The authors [29] presented a significant work of genetic algorithm tuned AGC regulator for an autonomous hybrid generation system consisting of renewable, conventional, fuel cells (FCs), battery energy storage system (BESS), flywheel (FW), ultra-capacitors (UCs) and aqua-electrolyser (AE). A potential work on AGC regulator design based on evolutionary techniques is reported in literature. The authors presented the work on AGC using Particle swarm optimization (PSO) algorithm [30-32] and hybrid of bacteria foraging and PSO technique [33]. Bat

Algorithm is a new metaheuristic method and is based on the echolocation behaviour of bats and now are widely used for solving the complex engineering optimization problems and its application in power system [34]. A new self-adaptive modified Bat Algorithm (SAMBA) and the Fuzzy Logic (FL) used for optimizing the gain of controller and the input and output membership functions of fuzzy logic in [35,36]. The authors [37-39] implemented Firefly Algorithm for optimal gain setting of frequency controller. This algorithm is an important part of computational intelligence and soft computing based optimization technique and is very efficient in solving multimodal optimization problems in various domain of engineering [37].The authors applied Bacterial Foraging Optimization Algorithm (BFOA) in the field of power system [40,41] for optimization of AGC controller for multi-area connected power system and the performance is compared with GA and conventional methods.

There are many other contributions also which have been appeared relating the controller designs and their implementations considering various aspects of power system structures, types of conventional energy sources, controller structures, types of auxiliary energy storing elements and types of area interconnections. Very few studies are done considering the hybrid sources of energy generations. Therefore, a due attention is required to design LFC schemes considering hybrid sources of power generations. As modern and intelligent techniques are found to deal complex and large system's control problems effectively, therefore design of LFC schemes based on these concepts are the need of hour. The present study addresses these concerns and incorporates the design and implantation of effective and efficient optimal and intelligent LFC regulators for the power system model consisting of hybrid power generating plants.

2. Power System Model Selected for Investigation

A Two Area Interconnected Power System (TAIPS) with Thermal-Photovoltaic (Th-PV) generations is considered for the study. The power system area-1 has the PV generation plants while area-2 is consisting of thermal plants with reheat turbines. The two are areas are interconnected via AC transmission link. The incremental tie-line power deviation is modelled based on the difference of frequency deviations of both power system areas. The power system model considered for the study is well described in [42]. The block diagram of TAIPS model is shown in Fig.1. Moreover, its linearized transfer function model is described by Fig.2.

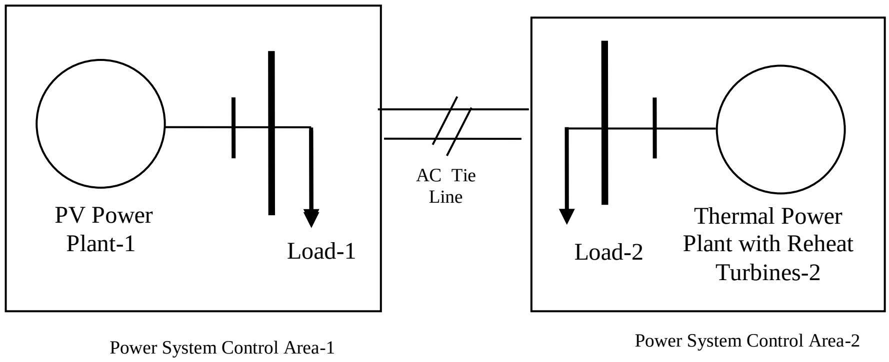

Fig. (1). Block diagram of TAIPS with Th-PV generations

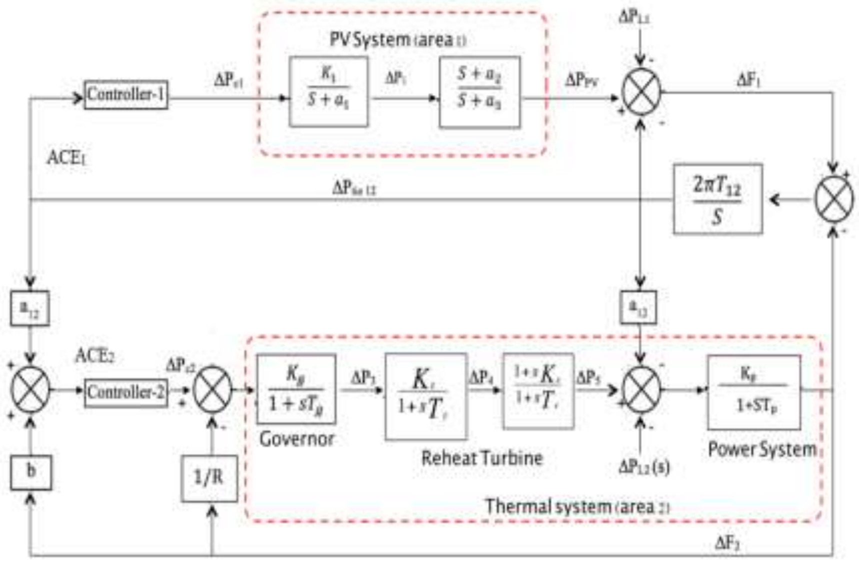

Fig. (2). Transfer function model of TAIPS with Th-PV generations

The researchers are very familiar with the development of dynamic model of reheat thermal plant of area-2 as it is described in many text/reference books of power systems [3]. However, the dynamic model of PV generation system for load frequency control studies as described in [42, 44] is considered for the study. There are some important aspects which should be given a considerable attention while developing the mathematical model of PV module for investigating its performance.

One of the most important aspects is the effect of solar radiation counts and temperature on PV cell voltage, current and power. Figs. 3-.6 show the effect of radiation and temperature on the characteristics of PV cell [42].

Fig. (3). Effect of radiation on voltage and current

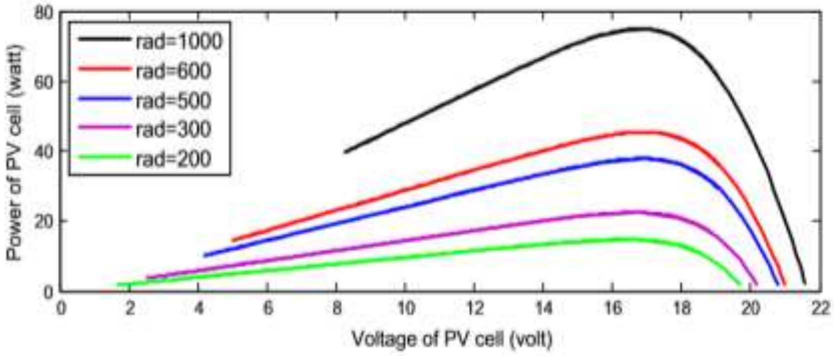

Fig. (4). Effect of radiation on voltage and power

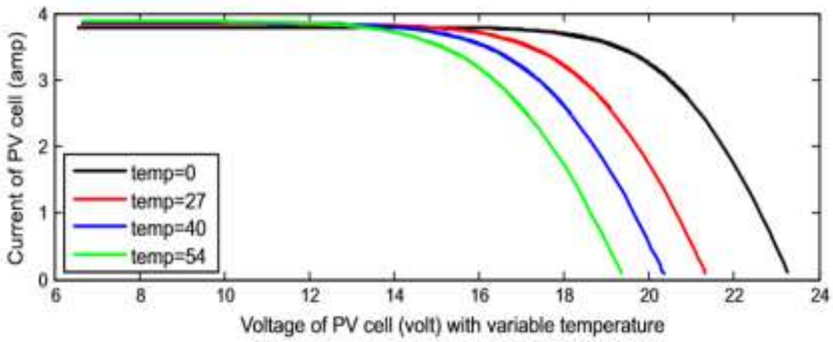

Fig. (5). Effect of temperature on voltage and current

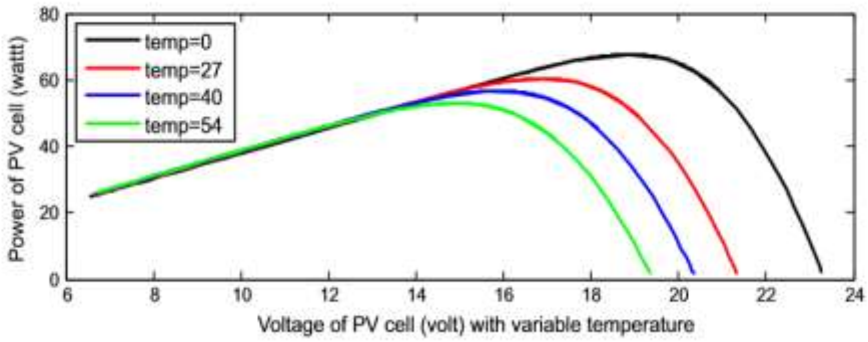

Fig. (6). Effect of temperature on voltage with power

The next significant aspect is the type of mounting configurations for PV module which have a significant effect on both the static performance and dynamic performance. The PV module may perform well under static loading conditions, but it has significantly higher displacements and stresses under dynamic loading in case of loading frequencies are near to some of natural frequencies. These effects are large enough to cause cracks or fractures in the solar cell layer, or even damage the whole PV module [43].

The exposure of PV systems to random wind loads, whose amplitude and frequencies vary with time, the dynamic performances of PV systems, requires a considerable attention on to ensure their lifetime safety and stability [43].

The inertial effect on PV performance is equally important as the others. The PV systems are interfaced through inverters to convert direct current to alternative current. Although Fig.20. shows the advantageous from the point-of-view of harvesting renewable energy sources, the inverter-based generation does not provide any mechanical inertial response, and hence compromises frequency stability [49]. Fig.7 displays the two types of power systems with high inertia and low inertia generating systems.

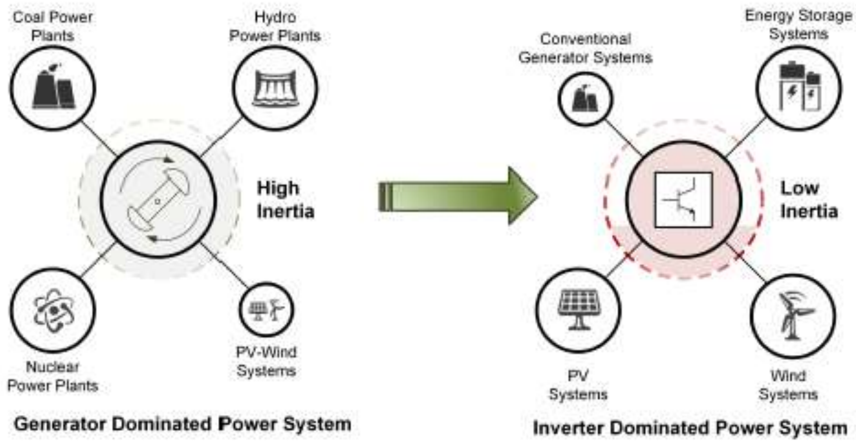

Fig. (7). Evolution towards an inverter dominated power system.

3. Load Frequency Control (LFC) Regulator Designs

The power systems are continuously subjected to load changes throughout the operation while generations are changed according to their economic schedule. This results in a mismatch of generation and load leading to frequency fluctuations in power systems affecting the performance of its equipment. Therefore, an effective LFC regulators are required to regulate the system frequency with these load changes automatically. In the present study, the LFC regulators are designed based on the following concepts;

A. Optimal LFC regulators based on modern control concept.

B. Intelligent LFC regulators based on;

(a) Firefly Algorithm (FA)

(b) Genetic Algorithm (GA).

(c) Fuzzy Logic (FL) concept.

4. Optimal LFC Regulators based on Optimal Control Theory

A linearized state-space model of the system is required for using modern control theory to design optimal controllers. The optimal LFC regulators are designed based on full state vector feedback control technique using performance index minimization.

4.1. Dynamic Model Development

The power system model under investigation is considered as a linear continuous-time dynamic system which can be represented by the following standard state space equations;

$$\frac{dx(t)}{dt} = \dot{\boldsymbol{A}}\boldsymbol{x}(t) + \mathbf{B}\boldsymbol{u}(t) + \boldsymbol{\tau}\boldsymbol{Pd}(t) \quad (1)$$

$$\boldsymbol{y}(t) = \boldsymbol{C}\boldsymbol{x}\,(t) \quad (2)$$

Where, x(t), u(t), Pd(t) and Y are state, control, disturbance and output vector respectively. A, B, $\boldsymbol{\tau}$ and C are system, control, disturbance and output matrices of compatible dimensions. The components of these matrices depend on the system parameters and the operating point. The various vectors and matrices for power system models are derived from the transfer function model of the power system as shown by Fig. 2. The state, control and disturbance vector for power system model are given as.

4.2 State-Space Model

Define the state vector x(t), the control vector u(t), the disturbance vector $\boldsymbol{Pd}(t)$and system output vector y(t) as:

$$\frac{\boldsymbol{dx}(t)}{dt} = \left[\Delta P_1\,(t)\;\Delta P_{pv}\,(t)\Delta P_{tie}\,(t)\Delta f_2\,(t)\Delta P_3\,(t)\Delta P_4\,(t)\Delta P_5\,(t)\int ACE_1(t)\,dt \int ACE_2(t)dt\,\right]^T \quad (3)$$

or $\boldsymbol{x}(t) = [\,x_1\;x_2\;x_3\;x_4\;x_5\;x_6\;x_7\;x_8\;x_9\,]^T$

where:

$x_1 = \Delta P_1\,(t),\; x_2 = \Delta P_{pv}(t),\; x_3 = \Delta P_{tie}(t),\; x_4 = \Delta f_2\,(t),\; x_5 = \Delta P_3\,(t),\; x_6 = \Delta P_4\,(t),$

$x_7 = \Delta P_5\,(t),\, x_8 = \int ACE_1(t)\,dt,\; x_9 = \int ACE_2(t)dt$

$$\boldsymbol{u}\,(t) = [\Delta P_{c1}\,(t)\Delta P_{c2}\,]^T \quad (4)$$

$$\boldsymbol{Pd}(t) = [\Delta P_{L1}\,(t)\;\Delta P_{L2}\,(t)]^T \quad (5)$$

$$\boldsymbol{y}\,(t) = [ACE_1(t)\;ACE_2(t)]^T \quad (6)$$

The state space model of the TAIPS with Th-PV generations as described by the equations (1) & (2) can be obtained by deriving the following differential equations from transfer function model of Fig.2.

$$\Delta\dot{P}_1\,(t) = -a_1\Delta P_1\,(t) + K_1\Delta P_{c1}\,(t) \quad (7)$$

$$\Delta\dot{P}_{pv}\,(t) = (a_1 - a_2)\Delta P_1\,(t) - a_3\Delta P_{pv}\,(t) + K_1\Delta P_{c1}\,(t) \quad (8)$$

$$\Delta \dot{P_{tie}}(t) = 2\pi T_{12}(\Delta P_{pv}(t) - \Delta P_{tie}(t) - \Delta f_2(t) - \Delta P_{L1}(t)) \quad (9)$$

$$\Delta \dot{f_2}(t) = \frac{K_P}{T_P}\Delta P_{tie}(t) - \frac{1}{T_P}\Delta f_2(t) + \frac{K_P}{T_P}\Delta P_5(t) - \frac{K_P}{T_P}\Delta P_{L2}(t) \quad (10)$$

$$\Delta \dot{P_3}(t) = -\frac{1}{RT_g}\Delta f_2(t) - \frac{1}{T_g}\Delta P_3(t) + \frac{1}{T_g}\Delta P_{c2}(t) \quad (11)$$

$$\Delta \dot{P_4}(t) = \frac{1}{T_t}\Delta P_3(t) - \frac{1}{T_t}\Delta P_4(t) \quad (12)$$

$$\Delta \dot{P_5}(t) = \frac{K_r T_r}{T_t T_r}\Delta P_3(t) + \left(\frac{1}{T_r} - \frac{K_r T_r}{T_t T_r}\right)\Delta P_4(t) + \frac{1}{T_r}\Delta P_5(t) \quad (13)$$

$$\dot{ACE_1}(t) = \Delta P_{tie\ 12}(t) \quad (14)$$

$$\dot{ACE_2}(t) = -\Delta P_{tie\ 21}(t) + b\Delta f_2(t) \quad (15)$$

4.2.1 System Matrices

By arranging Eqns. (1), (2) and (7)-(15), the structure of matrices **A**, **B**, $\boldsymbol{\tau}$ and **C** can be obtained as;. $\boldsymbol{A} =$

$$\begin{bmatrix} -a_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ a_2 - a_1 & -a_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & T_{12} & -2\pi T_{12} & -2\pi T_{12} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{K_P}{T_P} & -\frac{1}{T_P} & 0 & 0 & \frac{K_P}{T_P} & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{RT_g} & -\frac{1}{T_g} & 0 & 00 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{T_t} & -\frac{1}{T_t} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{K_r T_r}{T_t T_r} & \frac{1}{T_r} - \frac{K_r T_r}{T_t T_r} & -\frac{1}{T_r} & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & b2 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\boldsymbol{B} = \begin{bmatrix} K_1 & 0 \\ K_1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{1}{T_g} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad \boldsymbol{\tau} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -2\pi T_{12} & 0 \\ 0 & -\frac{K_P}{T_P} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad \boldsymbol{c} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & B & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The data of the system is having been taken and they are shown in Table 1

4.2.2 System data and numerical system matrices

The numerical values of various system parameters are taken from reference [42]. These system parameter data are given in Appendix-A in Table-1.

Using these data, the numerical system matrices are calculating as;

$$\boldsymbol{A} = \begin{bmatrix} -99.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -149.5 & -0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.545 & -3.4243 & -3.4243 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 6 & -0.05 & 0 & 0 & 6 & 0 & 0 \\ 0 & 0 & 0 & -29 & -12.5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3.333 & -3.333 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 11 & -10.9 & -0.1 & 0 & 0 \\ 0.425 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0.125 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\boldsymbol{B} = \begin{bmatrix} -18 & 0 \\ -18 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 12.5 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad \boldsymbol{\tau} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -3.4243 & 0 \\ 0 & -6 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad \boldsymbol{c} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0.8 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

4. 3. Design of Optimal LFC Regulators

The continuous time dynamic model in the state variable form is given as;

$$\frac{dx(t)}{dt} = \dot{\boldsymbol{A}}\boldsymbol{x}(t) + \mathbf{B}\boldsymbol{u}(t) + \boldsymbol{\tau P d}(t) \quad (1)$$

$$\boldsymbol{y}(t) = \boldsymbol{Cx}\,(t) \quad (2)$$

In the application of optimal control theory, the term $\boldsymbol{Pd}(t)$ in equation (1) is eliminated by redefining the states and controls in terms of their steady-state values occurring after the disturbance. It can be rewritten as;

$$\frac{dx(t)}{dt} = \dot{\boldsymbol{A}}\boldsymbol{x}(t) + \mathbf{B}\boldsymbol{u}(t), \ \underline{x}(0) = x_0 \quad (16)$$

Moreover eq. (2) will remain the same. The control signal u is such that to minimize the performance index (J):

$$J = \int_0^{\infty} \frac{1}{2}[\underline{x}^T Q \underline{x} + \underline{u}^T R \underline{u}]dt \quad (17)$$

Where, Q and R are weighting matrices for the state variables and the input variables. This optimal control problem is referred to as the linear quadratic regulator design problem. To solve this LQ optimal control problem, let us first construct a Hamiltonian function.

$$J = -\frac{1}{2}[\underline{x}^T Q \underline{x} + \underline{u}^T R \underline{u}]dt + \underline{\lambda}^T [A\underline{x} + B\underline{u}] \quad (18)$$

When there is no constraint on the input signal, the optimal (in this case, the minimum) value can be solved by taking the derivative of H with respect to u and then solving the following equation;

$$\frac{\partial H}{\partial \underline{u}} = -R\underline{u} + B^T \underline{\lambda} = 0 \quad (19)$$

Denote by u* the optimal control signal u. Then, u* can be explicitly written in the following form:

$$\underline{u}^* = R^{-1} B^T \underline{\lambda} \quad (20)$$

On the other hand Lagrangian Multiplier (λ) can be written as;

$$\underline{\lambda} = S\underline{x} \quad (21)$$

Where, S is the symmetrical solution of the well-known DRE.

$$\frac{dS}{dt} = -SA - A^T S + SBR^{-1} B^T S - Q \quad (22)$$

The solution matrix S will tend to a constant matrix i.e. $\frac{dS}{dt} = 0$. In this case DRE reduced to so called algebraic Riccatti Equation:

$$SA + A^T S - SBR^{-1} B^T S + Q = 0 \quad (23)$$

Now optimal control matrix can be written as;

$$\underline{u}^* = R^{-1} B^T S \underline{x} \quad (24)$$

With a full state vector feedback control problem, a control law is stated as;

$$\underline{u}^* = -\Psi^* \underline{x}$$

(25)

Using (24) & (25), the desired optimal feedback gain matrix (Ψ*) is given by;

$$\Psi^* = R^{-1}B^T S \tag{26}$$

4.3.1 Design matrices

The design matrices Q and R can be developed using the coefficients involved in eqn. (18). However, for power system model under investigation, the matrices R and Q are taken as identity matrices of compatible dimensions i.e. matrix R is identity matrix of 2x2 order while matrix Q is of 9x9 order identity matrix respectively.

The value of [Ψ*] is usually obtained from the solution of matrix Riccati equation given by Eqn. (23).

4.4. Design of Intelligent LFC Regulators for TAIPS with Th-PV Generations

The design of intelligent LFC regulators for the power system model under consideration is using the Proportional and Integral (PID) structured controllers whose gains are optimized using Firefly Algorithm (FA) and Genetic Algorithm (GA). The PID structured controllers are in use in a lot of industries for their automated functioning [30-34]. The study also includes the design of LFC regulators using Fuzzy Logic (FL) concept. A general block diagram of PIDD controller is shown in Fig.8.

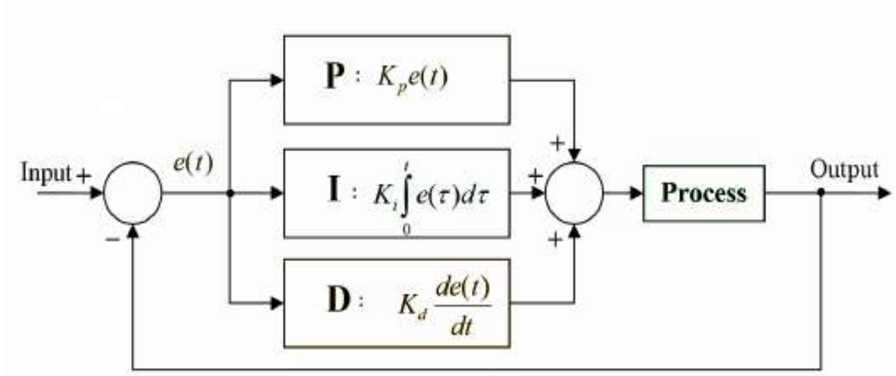

Fig. (8).The block diagram of PIDD controller

Where:

$$G(s) = Kp + K_I \left(\frac{1}{s}\right) + s\, K_D$$

K_p : proportional gain
K_I : integral gain
K_D : derivative gain

In this study two types of algorithms, Firefly Algorithm (FA) and Genetic Algorithm (GA) are used to optimize the gains of PID structured LFC regulators The

PID structured controllers are in use in about more than 90% industries for their automated functioning [30-34]. Also, LFC regulators are designed based on fuzzy logic (FL) control concept for the TAIPS model considered for the study. For FL based LFC regulator design, Mamdani fuzzy model is used to get optimized gains. The fuzzy logic concept uses if then rules and rule base, fuzzy system, fuzzification, inference, and defuzzification [45].

4.4.1. Firefly Algorithm

FA can deal with non-linear optimization problem in an efficient and effective manner. Also, since it doesn't use velocity, hence, there is no problems that are associated with velocity function on the optimization of gains. Moreover, it has the flexibility of integration with other optimization techniques [42, 44, 46]. The FA and its application to LFC regulator designs are described in [42]. The Simulink model on MATLAB platform is developed for TAIPS model with Th-PV generations and is shown in Fig.9. The Simulink model has PID structured LFC regulator and the gains of the regulator are optimized using FA algorithm. The various error functions are used to minimize the performance index of regulators.

The dynamic system response for frequency deviation(s) in both the power system areas are achieved with FLC regulator design using FA in the wake of step load disturbance in area-1. The response plots are shown in Fig.10.

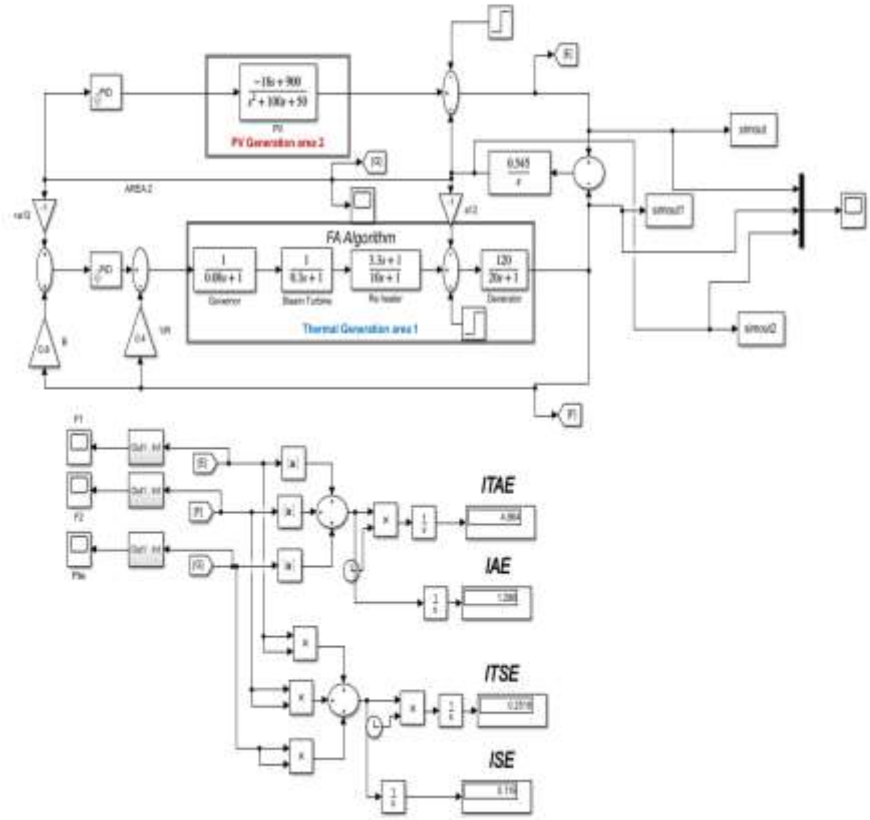

Fig. (9). Simulation diagram for PID structured LFC regulator based on FA

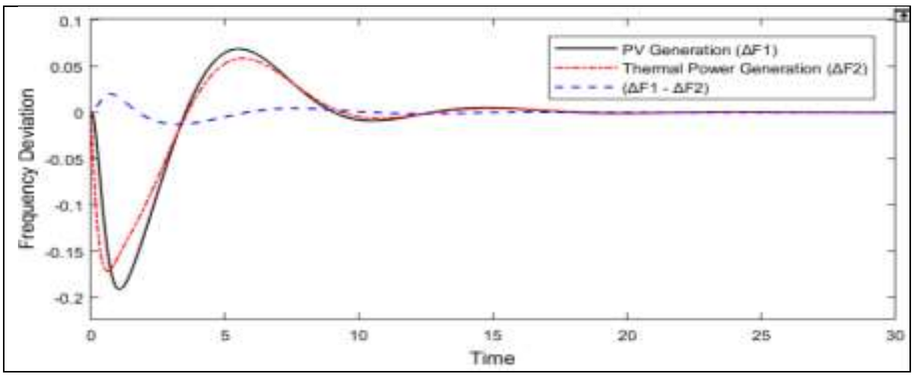

Fig. (10). Dynamic response of power system with FA based LFC regulators

4.4.2. Genetic Algorithm (GA):

GA is an adaptive heuristic search algorithm which uses natural evaluation technique. It is reflecting the process of natural selection where the fittest individual is identified and chosen for reproduction to produce offspring for the next generation. The GA is briefly described by Fig.11. [47].

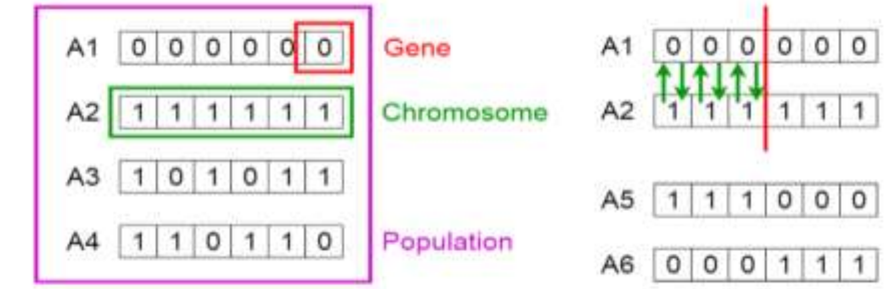

Fig. (11). Genetic algorithm

The Simulink model of on MATLAB platform for power system model selected for the study is shown in Fig.12. It has PID structured LFC regulator whose gains are optimized using GA algorithm. Again various error functions are used to minimize the performance index of the designed LFC regulator. A step load disturbance is considered in area-1 i.e. power system area which PV power generation and the designed LFC regulators are implemented in the system. The dynamic response plots for frequency deviation in both the areas (ΔF1 & ΔF2) and the net difference of frequency deviation (ΔF1 - ΔF2) responsible to change tie-line power to be exchanged between the two areas in the wake of step load disturbance in area-1 are obtained. These response plots are shown by Fig.13.

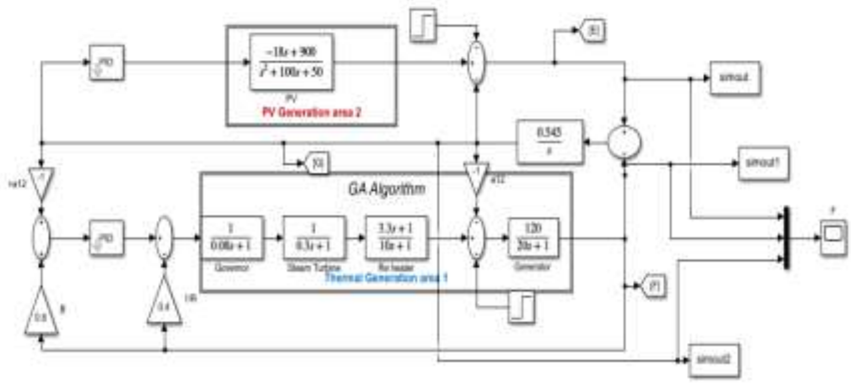

Fig. (12). Simulation diagram for PID structured LFC regulator based on GA

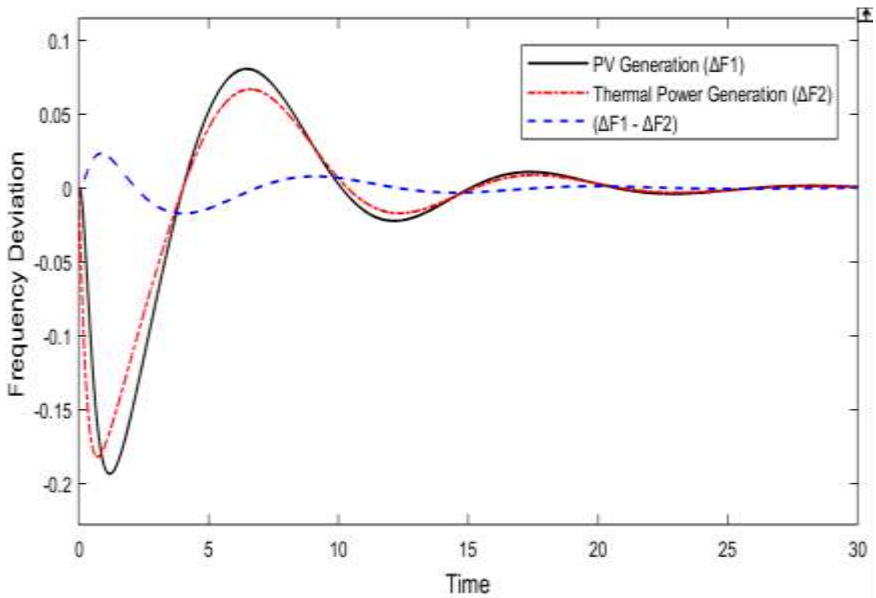

Fig. (13). Dynamic response of power system with GA based LFC regulators

4.4.3. Fuzzy Logic Control

The traditional LFC control strategies are incompetent to deal the stochastic load pattern in power systems. Therefore, researchers are trying to find novel control strategies in conjunction with suitable optimization techniques to sustain the system frequency and tie-line power flow at scheduled levels effectively under small load disturbances. Fuzzy logic based LFC schemes have been found to tackle these problems efficiently. For the fuzzy systems, we need to determine the input and output of the system. Here for LFC of power system problems, the two inputs are area control Error (ACE) and derivative of ACE. The PID gains are multiplied with fuzzy logic controller (FLC) output to get controller's output.

FLC has four modules besides the crisp input and output. The fuzzifier models the input numerical values (crisp) into fuzzy sets. The FIS performs all the logical functions. The rule base consists of membership functions (MFs) and control rules. The output of FIS is a fuzzy set to be transformed into numerical value using a defuzzification method. The components of a simple FLC are described in Fig. 14.

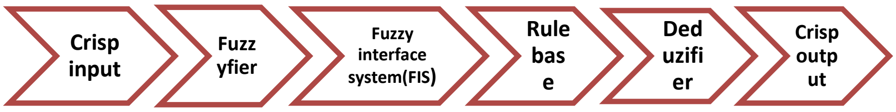

Fig. (14). Various components of fuzzy logic control system

The triangular, trapezoidal, Gaussian and bell shaped MFs are used due to their numerous merits over the other shapes. However, triangular MFs are preferred in FLC applications. For the present study, seven triangular MFs are selected with seven fuzzy linguistic variables. The membership functions for each input are; LN, MN, SN, Z, SP, MP, LP. The outputs have the same membership functions, therefore, there will be total of 49 rules as shown in Table-1. In the Table, abbreviations used for various membership functions have the meanings as;

LN: Large Negative, MN: Medium Negative, SN: Small Negative, Z: Zero, SP: Small Positive, MP: Medium Positive, LP: Large Positive

The centroid defuzzification method and Mamdani FIS are used to get the output values converted into numerical values.

Table (1). Rule base for ACE, derivative of ACEC and FLC output

ACE	**ACE derivative**						
	LN	**MN**	**SN**	**Z**	**SP**	**MP**	**LP**
LN	LP	LP	LP	MP	MP	SP	**Z**
MN	LP	MP	MP	MP	SP	**Z**	SN
SN	LP	MP	SP	SP	**Z**	SN	MN
Z	MP	MP	SP	**Z**	SN	MN	MN
SP	MP	SP	**Z**	SN	SN	MN	LN
MP	SP	**Z**	SN	MN	MN	MN	LN
LP	**Z**	SN	MN	MN	LN	LN	LN

The number of rules is not definite since it has no fixed criteria for its formation. It is as per the experience of the designer of the system and it can thus be different from one designer to another. The fuzzy logic is applied in a system by using three steps (shown in chart.1) [48].

Again, Simulink model of on MATLAB platform for power system model with PID structured LFC regulator is developed in Fig.15 and the PID gains are optimized using fuzzy logic concept. The dynamic response plots for ΔF1, ΔF2 and (ΔF1 - ΔF2) are obtained for step load disturbance in area-1 which are shown by Fig.16.

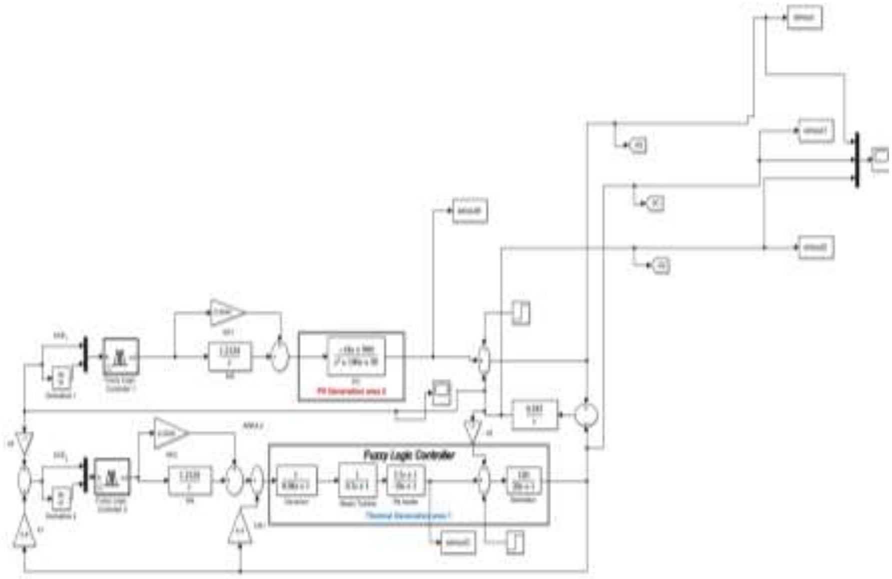

Fig. (15). Simulation diagram for PID structured LFC regulator based on FLC

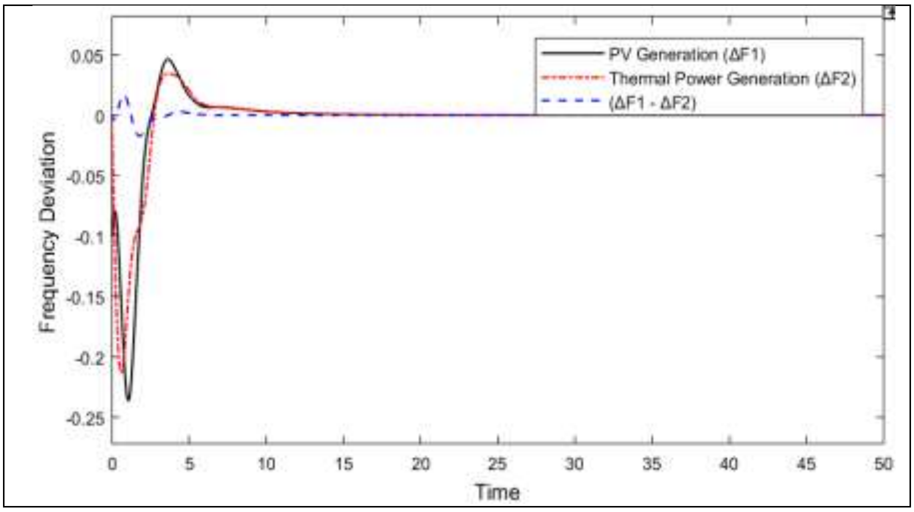

Fig. (16). Dynamic response of power system with FLC based LFC regulators

5. Simulation Results

The TAIPS model with Th-PV generations selected for the investigation is simulated on MATLAB platform using standard SIMULINK Tool Box. The numerical values for various system parameters and design parameters used to optimize the gains of LFC regulators are given in Appendix A. For the optimal LFC regulators, the feedback from all the system states is used to get optimized feedback gains. The optimized gains for all the system states so achieved are given in Table 2. However, for PID structured intelligent LFC regulator gains obtained by using FA, GA, and FLC are tabled in Table 3.

Table (2). Optimal feedback gains

[Ψ*]	$\begin{bmatrix} -1.5864 & 0.9576 & 0.3203 & 0.0644 & 0.0113 & 0.1078 & -0.0 \\ -0.0450 & 0.0372 & 0.7968 & -0.2487 & 1.1182 & -1.9396 & 2.00 \end{bmatrix}$

Table (3). Optimized gains of PID structured regulators

Fuzzy logic control(FLC)			Firefly algorithm(FA)			Genetic algorithm(GA)		
K_p	K_i	K_d	K_p	K_i	K_d	K_p	K_i	K_d
0.2545	1.2124	-0.0021	-0.8811	-0.5765	-0.5643	-0.5127	-0.7256	-0.4535

The system dynamic response plots are obtained for frequency deviation in area-1 (ΔF1) and frequency deviation in area-2 (ΔF2) and tie-line power deviation ($\Delta P_{tie\ line}$) with the implementation of designed optimal and various intelligent LFC regulators using FA, GA and FL in the wake of step load disturbance in area-1 are obtained. These response plots are shown in Figs. 10, 13, 16, 18, 19 and 20.

As shown in Simulink model of Fig.9, the performance indices can be evaluated using the following expressions which are the function of error signal.

- Integral Absolute Error (IAE)
- Integral Time Absolute Error (ITAE)
- Integral Square Error (ISE)
- Integral Time Square Error (ITSE)

6. Discussion of Results

From the investigations of optimal gains given in Tables 2 & 3, it is inferred that the gains of LFC regulator based on optimal control theory using full state vector feedback control technique are considerably larger as compared to those of gains achieved using FLC,FA and GA. The larger values of gains simply reflect the cost of physical realization of controller circuit synthesis. Moreover, among intelligent LFC regulators, fuzzy logic based design has appreciable larger integral gain in comparison to FA & GA.

As stated earlier, dynamic response plots of Fig. 10, 13 & 16 are obtained with the LFC regulators designed using FA, GA & FLC respectively. The close investigation of these reveals that the magnitude of response peaks is higher for frequency deviation of area-1 in comparison to that of area-2. It means there is large frequency disturbance in the area where load disturbance has occurred. However, frequency if area-2 is also disturbed even the disturbance is occurred in area-1. Therefore, in interconnected systems load disturbance in any area will transferred to other area also. Another point to be noted is that the implementation of FA,GA & FLC based LFC regulators ensure that the after a lapse of time the frequency deviation in both areas caused due to load disturbance are mitigated and settled to zero. However, they offer different settling times ie. It is about 10 sec. for FLC, 20 sec. for FA and 30 sec. for GA. Moreover, the responses offered by FLC based regulators are having minimum number of oscillations and settling very smoothly. It has a positive impact on the physical (mechanical) stress on rotating parts of the power system equipment and equipment connected as load on the power system.

The inspection of the response plots of Figs. 18, 19 & 20 clearly shows that all the LFC regulator designs are capable of settling the frequency deviations and tie-line power deviations within about 25 sec. time after their implementation when disturbance occurred in area-1. The system dynamic responses offered by FA & GA based LFC regulators are sluggish as they are associated with oscillatory modes for a long time. They are taking more time to settle down to new steady state value in comparison to those offered by optimal & FLC based LFC regulators. If we compare the responses achieved with FA & GA based LFC regulators, the FA based regulators are found superior than GA based regulators. As far as the magnitude of first peak of responses is concerned, it is larger for FLC based regulator as compared to that of FA & GA based LFC regulators. However, optimal LFC regulators offer the system response closer to that of FLC based LFC regulators. In nut shell, FLC based LFC regulators have demonstrated to be the better choice for implementation for the power system model under investigation as compared to other designs of LFC regulators carried out in the study.

7. Conclusions

The research article is aimed to propose the LFC regulator designs using various control strategies using optimal control concept, FA, GA and FLC for an interconnected power system model consisting of plants of thermal and PV generations. From the investigations carried out in the study, following conclusions are drawn;

- The gains of LFC regulator based on optimal control theory using full state vector feedback control technique are considerably larger as compared to those of gains achieved using FLC,FA and GA. The larger values of gains simply reflect the cost of physical realization of controller circuit synthesis.
- The magnitude of response peaks is higher for frequency deviation of area of disturbance in comparison to other interconnected area. It shows that in interconnected systems load disturbance in any area will transferred to other area also.
- The implementation of FA,GA & FLC based LFC regulators ensure that after a lapse of time the frequency deviation in both areas caused due to load disturbance are mitigated and settled to zero. However, they offer different settling times i.e. it is about 10 sec. for FLC, 20 sec. for FA and 30 sec. for GA.
- The system dynamic responses offered by FA & GA based LFC regulators are sluggish as they are associated with oscillatory modes for a long time. They are taking more time to settle down to new steady state value in comparison to those offered by optimal & FLC based LFC regulators.
- Finally, FLC based LFC regulators have demonstrated to be the better choice for implementation for the power system model under investigation as compared to other designs of LFC regulators carried out in the study.

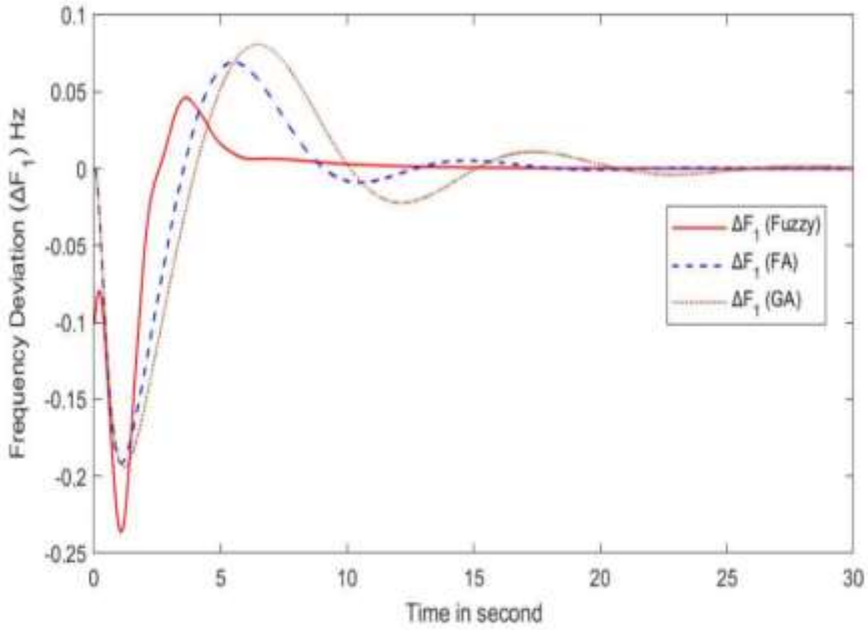

Fig. (18). Dynamic response of frequency deviation of area-1(ΔF_1)

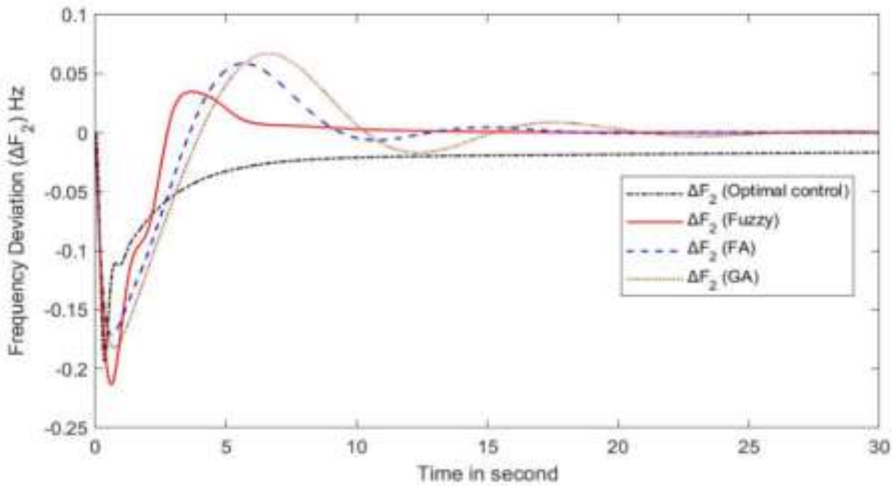

Fig. (19). Dynamic response of frequency deviation of area-2(ΔF_2)

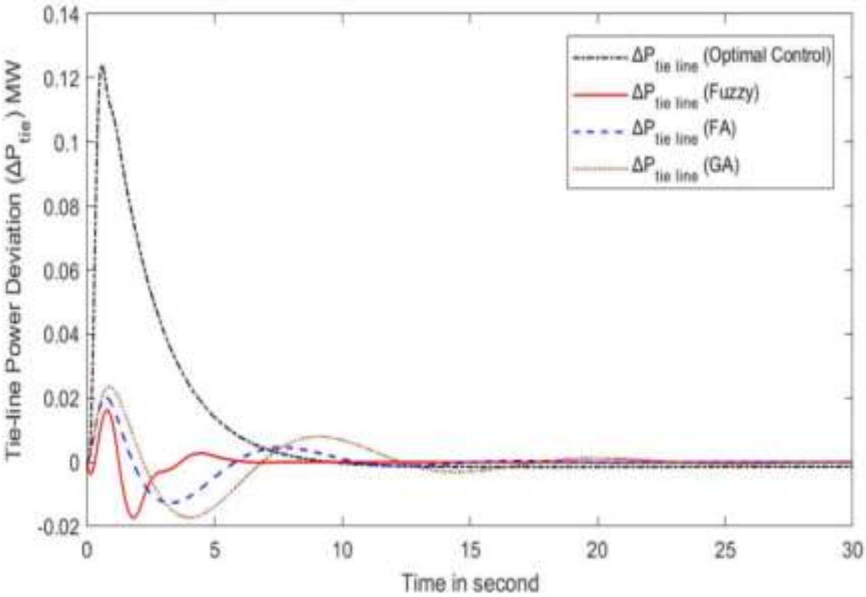

Fig. (20). Dynamic response of tie-line power deviation (ΔP_{tie})

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Appendix A

The system data used in the study are given as [42]:

The nominal system parameters of the thermal plant in area-2.:
T_P = 20 s; T_t = 0.3 s; Tr =10 s; T_{12} = 0.545 p.u; Tg = 0.08 s, K_P = 120 Hz/p.u MW, B = 0.8 p.u MW/Hz, a_{12} =-1, R = 0.4 Hz/p.uMW, K_r = 0.33p.uMW.
The parameters of FA:
The contrast of attractiveness = 1.0; The attractiveness = 0.1 at r ¼ 0; randomization parameter ða$_Þ$ = 0.1, maximum no. of generations = 100, number of fireflies = 50..
The parameters of GA:
The max generation = 100, population size = 50, crossover probabilities = 0.75, mutation probabilities = 0.1.

التحكم الذكي في تردد الأحمال لنظم القوى من خلال التوليد الحراري والخلايا الضوئية

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ملخص البحث. يقدم البحث دراسة للتحكم الذكي في تردد الأحمال لنظم القوى من خلال التوليد الحراري والخلايا الضوئية. تتصل منطقتا أنظمة الطاقة ببعضهما عبر خطوط نقل التيار المتردد. سيتم التحكم بالنظام بعدة طرق وهي: استخدام خوارزمية اليراع (FA) مع متحكم تناسبي تكاملي تفاضلي (PID)، والخوارزمية الجينية (GA) مع متحكم تناسبي تكاملي تفاضلي (PID)، وأخيراً التحكم القوي (FLC). ثم سيتم عمل مقارنة بين أنواع التحكم السابقة مع التحكم الديناميكي (التحكم الأمثل) على أساس أسلوب مراقبة ردود الفعل الكاملة للنظام. الهدف الرئيسي من هذه الورقة العلمية هو تطوير التحكم في نظم القوى التي تحتوي على التوليد الحراري والخلايا الضوئية. سيتم عمل محاكاة لأنواع التحكم المختلفة وتعريض النظام لتغيرات مختلفة (اضطراب في الأحمال) سيساعد على المقارنة بين أواع التحكم المختلفة للنظام. يمكن لأنظمة التحكم في تردد الأحمال باستخدام (FA) و (GA) و (FLC) التخفيف من انحراف الطاقة الكهربائية بسبب اضطراب الأحمال في كل من المنطقتين (التوليد الحراري والخلايا الضوئية). وأخيرًا ، أثبتت أنظمة التحكم في تردد الأحمال القائمة على FLC أنها أفضل خيار لتنفيذ نموذج نظام قوى موثوق يحتوي على توليد حراري وخلايا ضوئية مقارنة بالتصميمات الأخرى التي أجريت في الدراسة.