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FPA BASED OPTIMIZED PI CONTROLLER FOR AGC IN A TWO-AREA THERMAL-DIESEL INTERCONNECTED RESTRUCTURED POWER SYSTEM

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Abstract - This paper presents an application of bio-inspired Flower Pollination Algorithm (FPA) based Proportional-Integral (PI) controllers in Automatic Generation Control (AGC) of two-area thermal-diesel power system. The PI controller gain of the AGC problem are tuned by using the FPA algorithm in order to achieve the optimal transient response of the system under for different types of possible transactions in restructured environment. The Integral Square Error (ISE) is considered the objective function for the FPA. The supremacy performance of proposed algorithm for optimized PI controller is proved by comparing the results with Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Bacterial Foraging Optimization (BFO) based PI controller under the same investigated power system. The simulation results reveal that the performance of the FPA-optimized controller is better than its GA, PSO and BFO-optimized counterpart in terms of settling time and overshoot in deviation of frequency. The convergence speed performance of the proposed algorithm is significantly better compared to those achieved by the existing algorithms. Moreover the Power System Restoration Indices (PSRI) is computed based on system dynamic performances of two-area thermal-diesel interconnected power system and the remedial measures to be taken can be adjudged.

Index terms - Automatic Generation Control, Flower Pollination Algorithm, Diesel power plant, PI controller, Power System Restoration Indices.

I. INTRODUCTION

The objective of the Automatic Generation Control (AGC) in an interconnected power system is to maintain the frequency of each area within limits and to keep tie-line power flows within some pre-specified tolerances by adjusting the MW outputs of the generators so as to accommodate fluctuating load demands [1]. An interconnected power system is made up of several areas and for the stable operation of power systems; both constant frequency and constant tie-line power exchange should be provided. In each area, an Automatic Generation Controller (AGC) monitors the system frequency and tie-line flows, computes the net change in the generation required (generally referred to as Area Control Error – ACE) and changes the set position of the generators within the area so as to keep the time average of the ACE at a low value. Therefore ACE, which is defined as a linear combination of power net-interchange and frequency deviations, is generally taken as the controlled output of AGC. As the ACE is driven to zero by the AGC, both frequency and tie-line power errors will be forced to zeros [2]. With the restructuring of power system had led to the vast development amongst the new companies for generation (Genco), transmission (Transco), distribution (Disco) of power with an open assess policy. In restructured environment, a Disco can contract individually with any Genco for power demand and this transaction is completed under the supervision of Independent system operators (ISO) [3, 4]. The primary objective of the System Operator is allowing the contracted power to flow from Genco to Disco. To transport the contracted power at acceptable level of quality and reliability certain ancillary services are required by the System Operator [5].

Several advanced controller structures and techniques have been proposed in literature for AGC [6-10]. But, these advanced approaches are complicated and need familiarity of users to these techniques thus reducing their applicability. Alternatively, a classical Proportional Integral (PI) controller and its variant remain an engineer's preferred choice due to its structural simplicity, reliability and the favourable ratio between performances and cost. In this paper different artificial intelligence techniques have been used for the automatic generation control of two area restructured power system for bilateral contracts. Bio-inspired computation techniques such as Genetic Algorithm (GA) [11], Particle Swarm Optimization (PSO) [12], Bacterial Foraging Optimization (BFO) [13] and Flower Pollination Algorithm (FPA) [14, 15] have been used to optimize the control parameters of a PI controller for a two area power system. An attempt has been made to compare the performances in terms of time taken to damp out oscillations in the two areas. Other parameters for comparison include the final steady state value of frequency, tie-line power interchange and power generated by different generating companies (Gencos) in the event of load change for different controllers in automatic generation control (AGC) system. The concept of distribution companies (Disco) participation matrix to simulate different possible transactions is used in this study. The proposed Flower Pollination Algorithm (FPA) is a newly developed heuristic optimization method based on Pollination of flowers. It has only one key parameter p (switch probability) which makes the algorithm easier to implement and faster to reach optimum solution. FPA has special capabilities such as extensive domain search with quality and consistency solution. Large-scale power system when faces severe disturbance requires quick recovery of the power system and can somewhat be able to avoid blackouts with the black start units which can be able to produce power for the auxiliaries of the thermal units without black start capabilities. Under this situation a conventional frequency control i.e., a governor may no longer be able to compensate for such load changes due to the slow response. Therefore, in an inter area mode, damping out the critical electromechanical oscillations is essential and has to be implemented properly in an interconnected system. Proper monitoring of the system frequency deviations and remedial actions to overcome frequency excursions are more likely to protect the system before it enters an emergency mode of operation. Special attention is therefore given to the behavior of network parameters, control equipments as they affect the voltage and frequency regulation during the restoration process. During restoration due to wide fluctuations in the frequency and voltage it becomes very difficult to maintain the integrity in the system [16, 17]. The purpose of this paper is to provide a conceptually computational methodology for ensuring the system restoration strategies in a faster manner. To achieve a faster restoration process, new black start generators can be installed allowing network reconfigurations and the load recovery can also be adopted in accelerating the system restoration. In this study to evaluate Power System Restoration Indices (PSRI) based on the Automatic Generation Control (AGC) assessment of two area thermal-diesel interconnected power system in a restructured environment. In this PSRI are useful for system planners to prepare the power system restoration plans and to improve the efficiency of the physical operation of the power system with the increased transmission capacity in the network. From the simulated results it is observed that the restoration process for the system with diesel units ensures improved PSRI which provides good margin of stability.

II. AGC IN RESTRUCTURED POWER SYSTEM ENVIRONMENT

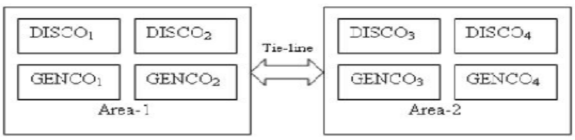

Figure 1: Schematic diagram of two-area system in restructured environment

The deregulated power system structure changed in such a way that would allow the evolving of more specialized industries for generation (Genco), transmission (Transco) and distribution (Disco). In the restructured power system, Discos in each area can contract with Gencos in its own or other areas. As there are several Gencos and Discos in the restructured power system, a Disco has the freedom to have a contract with any Genco for transaction of power. Such transactions are called bilateral transactions [7]. All the transactions have to be cleared through an impartial entity called an Independent System Operator (ISO). The ISO has to control a number of so-called ancillary services, one of which is load frequency control. There is some difference between the AGC operation in conventional and deregulation environment. After deregulation, optimization and operation are changed but their basic idea for AGC is kept same. In the new environment, Discos may contract power from any Gencos and independent system operator has to supervise these contracts. Disco Participation Matrix (DPM) concept is taken to understand the several contracts that are implemented by the Gencos and Discos [7]. A DPM is a matrix with the number of rows equal to the number of Gencos and the number of columns equal to the number of Discos in the system [8]. Each entry in this matrix can be thought of as fraction of a total load contracted by a Disco towards a Genco. The sum of all the entries in a column DPM is unity. In this study two-area interconnected power system in which each area has two Gencos and two Discos. Let $Genco_1$, $Genco_2$, $Disco_1$, $Disco_2$ be in area 1 and $Genco_3$, $Genco_4$, $Disco_3$, $Disco_4$ be in area 2 as shown in Fig 1. The corresponding DPM is given as follows

$$DPM = \begin{bmatrix} cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\ cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \\ cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} \\ cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} \end{bmatrix} \quad (1)$$

where cpf represents “Contract Participation Factor” and is like signals that carry information as to which the Genco has to follow the load demanded the Disco. The actual and scheduled steady state power flow through the tie-line are given

$$\Delta P_{tie1-2,\,scheduled} = \sum_{i=1}^{2}\sum_{j=3}^{4} cpf_{ij}\,\Delta P_{Lj} - \sum_{i=3}^{4}\sum_{j=1}^{2} cpf_{ij}\,\Delta P_{Lj} \quad (2)$$

$$\Delta P_{tie\,1-2,\,actual} = \left(2\pi T_{12}/s\right)\left(\Delta F_1 - \Delta F_2\right) \quad (3)$$

And at any given time, the tie-line power error is defined as

$$\Delta P_{tie\,12,\,error} = \Delta P_{tie\,12,\,actual} - \Delta P_{tie\,12,\,scheduled} \quad (4)$$

The error signal is used to generate the respective ACE signals as in the traditional scenario

$$ACE_1 = \beta_1 \Delta F_1 + \Delta P_{tie\,1-2,\,error} \quad (5)$$

$$ACE_2 = \beta_2 \Delta F_2 + \Delta P_{tie\,2-1,\,error} \quad (6)$$

For two area system as shown in Fig.1, the contracted power supplied by i[th] Genco is

$$\Delta Pg_i = \sum_{j=1}^{DISCO=4} cpf_{ij} \Delta P_{Lj} \quad (7)$$

In the proposed LFC implementation, the contracted load is fed forward through the DPM matrix to Genco set points. Any mismatch between actual and contracted demands will result in frequency deviations that will drive LFC to re-dispatch the Gencos according to ACE participation factors, i.e., apf_{11}, apf_{12}, apf_{21} and apf_{22}. The proposed PI controllers are design using FPA and implemented in two-area thermal-diesel power system and are compared with the output responses of the system considered with the PI controllers designed using GA, PSO and BFO algorithms. The detailed small perturbation transfer function block diagram model of the two-area thermal- diesel interconnected restructured power system is shown in Fig.2.

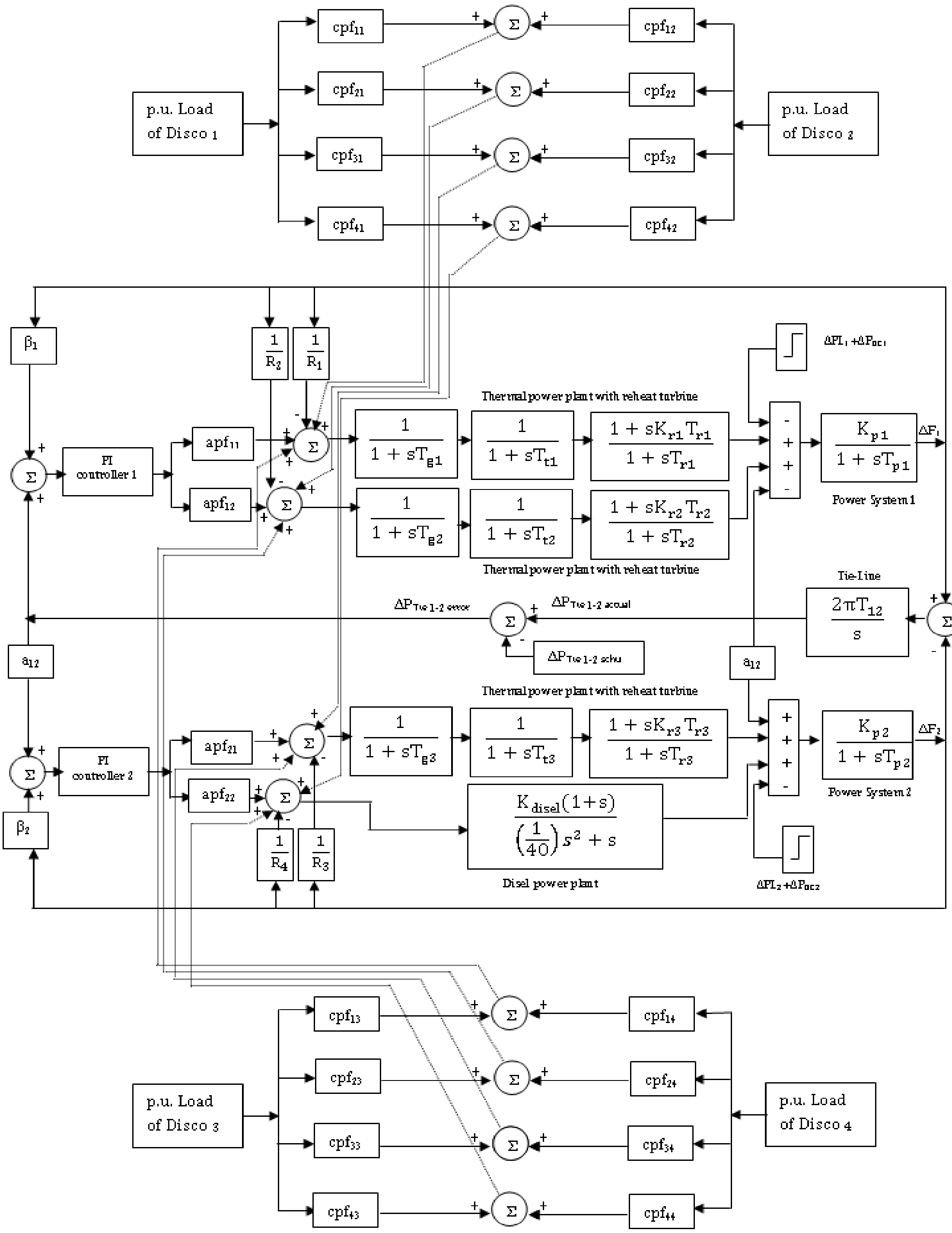

Figure 2: Linearized model of a two-area thermal diesel interconnected power system in a restructured environment

III. DESIGN OF PI CONTROLLERS USING FPA TECHNIQUE

Proportional and integral refers to reset action which involves integration of error signal over a period of time. The rate of change of correcting signals is proportional to the error signals. The combination of (i) proportional and integral terms is important to

increase the speed of the response and also to eliminate the steady state error. In this paper, PI controllers are used to improve the dynamic performance of AGC for a two area thermal-diesel power system. The PI control action depends on the proportional gain (K_{Pi}) and Integral controller gain (ii) (K_{Ii}) which vary for different applications. The tuning of these variables depends on the desired responses of the system. The main function of AGC is to control load frequency and tie line power during load disturbance. So the error signals of frequency and tie line power are used as design criteria to tune the PI controller. The error inputs to the controllers are the respective area control errors (ACE) given by Eqs. (5) and (6). The control inputs of the power system u1 and u2 with PI structure are given by Eqs. (8) and (9).

$$u_1 = K_{P1}\, ACE_1 + K_{I1} \int ACE_1\, dt \qquad (8)$$

$$u_2 = K_{P2}\, ACE_2 + K_{I2} \int ACE_2\, dt \qquad (9)$$

In this study, FPA is used to tune the PI controller for a two area thermal-diesel interconnected power system. Proportional gain constant (K_{Pi}) and Integral gain constant (K_{Ii}), are considered as variables describing a population defined in an FPA. FPA requires an objective function which uses the design criteria to calculate the flower constancy of the defined population. An objective function is created which uses the variables of the population from FPA, passes through a model containing two area power system and obtains the error signals frequency and tie line power. The performance of these responses is measured using performance functions such as Integral of Squared Error (ISE) given by Eqs (10).

$$J = \int_0^{t_{sim}} (\Delta F_1^2 + \Delta F_2^2 + \Delta P_{tie}^2)\, dt$$

(10)

The relative simplicity of this controller is a successful approach towards the zero steady state error in the frequency of the system. With these optimized gain values the performance of the system is analyzed and various PSRI are computed. The proposed Flower Pollination Algorithm based PI controller for solving AGC application

Step 1: Initialize the objective function as given in the equation (10)

Step 2: Initialize a population of x = (x_1, x_2 ...x_{NF}) flowers/pollen gametes with the population size of NF x N. Where NF is the number of flowers as 30 and N is the dimension size depends on the number of controller gain values for each area in the two area system. In this study N is equal to four because PI controller is used to in each area (K_{P1}, K_{I1} K_{P2}, K_{I2}) and calculate the Fitness for each solutions.

Step 3: Find the best solution to the initial population and define a switch probability p ∈ [0, 1] and define a stopping criterion (a fixed number of generations/iterations)

Step 4: while (t <Maximum Generation) for i = 1: n (all n flowers in the population) if rand < p, Draw a (d-dimensional) step vector L which obeys a Levy distribution Global pollination has been done using equation (11). Else draw ε from a uniform distribution in [0, 1]. Randomly choose j^{th} and k^{th} flower among all the solutions and do local pollination through equation (13), end if

Step 5: Evaluate new solutions using the objective function. If new solutions are better, update them in the population, end for

Step 6: Find the current best solution g based on the objective fitness value, end while.

IV. EVALUATION OF POWER SYSTEM RESTORATION INDICES

Power system restoration is well recognized as an important task to reduce the duration of a disturbance that occurs in power systems. The high level strategy of the System Restoration Plan is to restore the integrity of the interconnection as quickly as possible. The system restoration strategies are found closely related to the systems' characteristics. After analyzing the system conditions and characteristics of outages, system restoration planners or dispatchers will select the Power System Restoration Indices (PSRI) which were obtained based on system dynamic performances and the remedial measures to be taken can be adjudged. In this study two-area thermal-diesel interconnected power system in a restructured environment are considered when the system is operating in a normal condition with Gencos units in operation and is one or more Gencos unit outage in any area. From these Restoration Indices the restorative measures like the magnitude of control input, rate of change of control input required can be adjudged. The various power system restoration ($PSRI_1$, $PSRI_2$, $PSRI_3$ and $PSRI_4$) indices are calculated as follows

Step 1: The Power System Restoration Index 1 is obtained from the ratio between the settling time of the control input deviation $\Delta P_{c1}(\tau_{s1})$ response of area 1 and power system time constant (T_{p1}) of area 1

$$PSRI_1 = \frac{\Delta P_{c1}(\tau_{s1})}{T_{p1}} \qquad (11)$$

Step 2: The Power System Restoration Index 2 is obtained from the ratio between the settling time of the control input deviation $\Delta P_{c2}(\tau_{s2})$ response of area 2 and power system time constant (T_{p2}) of area 2

$$PSRI_2 = \frac{\Delta P_{c2}(\tau_{s2})}{T_{p2}} \qquad (12)$$

Step 3: The Power System Restoration Index 3, is obtained from the peak value of the control input deviation $\Delta P_{c1}(\tau_p)$ response of area 1 with respect to the final value $\Delta P_{c1}(\tau_s)$

$$PSRI_3 = \Delta P_{c1}(\tau_p) - \Delta P_{c1}(\tau_s) \quad (13)$$

Step 4: The Power System Restoration Index 4 is obtained from the peak value of the control input deviation $\Delta P_{c2}(\tau_p)$ response of area 1 with respect to the final value $\Delta P_{c1}(\tau_s)$

$$PSRI_4 = \Delta P_{c2}(\tau_p) - \Delta P_{c2}(\tau_s) \quad (14)$$

V. SIMULATION RESULTS AND OBSERVATIONS

In this study a test system such as two-area interconnected thermal-diesel power system. Both system have two generating unit in each area with different capacities is considered. In thermal-diesel test system consists of area-1 comprises of two thermal reheat power generation units and area -2 comprises of one diesel unit and other unit have thermal reheat power generation unit as shown in Fig 2. The model of the system under study has been developed in MATLAB/SIMULINK environment and FPA program has been written (in.m file). The nominal parameters are given in Appendix. In this work, Flower Pollination Algorithm (FPA) is used to tune the PI controller for a two- area interconnected power system. Proportional gain constant (K_P), Integral gain constant (K_I), are considered as variables describing a population defined in an FPA. The optimal solution of control inputs is taken an optimization problem and the cost function in Eq(10) is derived using the frequency deviations of control areas and tie-line power changes which uses the design criteria to calculate the flower constancy of the defined population. The parameter p defines the amount of local search and global search for FPA. To choose this parameter, the proposed method is simulated for various values and that simulated for p varies from 0.1 to 1 with step change of p with step size 0:01 in the range of 0.1 to 1. The optimum PI controller gain values for two area thermal-diesel system are tuned for various case studies are listed in the Table1. These PI controllers are implemented in a proposed power system for different types of transactions and compared with GA, PSO and BFO techniques. Based on the transaction made between them, it can be classified into two types of transactions. If a Disco has the contract with the Genco of the same area is called as poolco based transaction and if a Disco has a contract with a Genco of another area is called as bilateral based transactions. Two different transactions were considered as follows.

Scenario 1: Poolco based transaction

In this scenario, Gencos participate only in the load following control of their areas. It is assumed that a large step load change occurs in area1 alone, i.e. (0.2 p.u MW) load change in $Disco_1$ and Disco2. $Disco_3$ and $Disco_4$ do not demand power from any other Gencos, and then corresponding "cpf" is zero. Assume that a case of Pool-co based contracts between Discos and available Gencos is simulated based on the following Disco Participation Matrix (DPM) referring to Eq (1) is considered as

$$DPM = \begin{bmatrix} 0.5 & 0.5 & 0.0 & 0.0 \\ 0.5 & 0.5 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \end{bmatrix} \quad (15)$$

$Disco_1$ and $Disco_2$ demand identically from their local Gencos, viz., $Genco_1$ and $Genco_2$. Therefore, $cpf_{11} = cpf_{12} = 0.5$ and $cpf_{21} = cpf_{22} = 0.5$. It may happen that a Disco violates a contract by demanding more power than that specified in the contract and this excess power is not contracted to any of the Gencos. This uncontracted power must be supplied by the Gencos in the same area to the Disco. It is represented as a local load of the area but not as the contract demand. Consider scenario-1 again with a modification that Disco demands as given in Table 1 (case 1- 4). The optimum PI controller gain values for a two-area thermal-diesel power system are tuned using FPA for various case studies (case 1- 4) and are tabulated in the Table1. Then proposed controllers are also tuned with GA, PSO and BFO technique and are implemented in a two-area restructured power system for different types of case studies. In Fig 3 shows comparative transient performances of thermal-diesel power system for given load perturbation and results are tabulated in Table2. From the Fig 3, it can observed that the oscillations in the area frequencies and tie-line power deviations have decreased to a considerable extent with FPA tuned PI controller when compared the output responses obtained using GA, PSO and BFO technique based PI controller. It can be inferred that FPA tuned PI controller gives better results in terms of settling time, overshoot and undershoot. Simulation results reveals the accuracy of finding the best solution and convergence speed performance of the proposed algorithm is significantly better compared to those achieved by the existing algorithms. The settling time (τ_s) and peak over /under shoot (Mp) of the control input deviations (ΔP_c) in both the area were obtained from Fig 3(d, e). From the Fig the corresponding various power system restoration indices are calculated and tabulated in Table3 and 4 (case 1-4) for different diesel power plant participation factors (apf_{22} = 0.5, 0.4, 0.3, 0.2).

Scenario 2: Bilateral based transaction

All Discos contracts with the Gencos for power as per the following DPM,

$$DPM = \begin{bmatrix} 0.4 & 0.35 & 0.2 & 0.2 \\ 0.2 & 0.25 & 0.2 & 0.3 \\ 0.25 & 0.3 & 0.4 & 0.3 \\ 0.15 & 0.1 & 0.2 & 0.2 \end{bmatrix} \quad (16)$$

In this case, the $Disco_1$, $Disco_2$, $Disco_3$ and $Disco_4$, demands 0.25 pu.MW, 0.15 pu.MW, 0.3 pu.MW and 0.1 pu.MW from Gencos as defined by cpf in the DPM matrix. Each Gencos for thermal-thermal system participates in AGC as defined by the following ACE participation factor $apf_{11} = apf_{12} = 0.5$ and $apf_{21} = apf_{22} = 0.5$. In thermal-diesel system, the diesel power plant participation factors have been considered with various participation factors like apf_{22} = 0.5, 0.4, 0.3, 0.2. The corresponding power system restoration indices are calculated from dynamic output responses of the proposed test system using FPA tuned PI controller is shown in Table 3 and 4 (case 5-8) for different gas power plant participation factors (apf_{22} = 0.5 ,0.4, 0.3, 0.2.). Apart from the normal operating condition of the test systems few other case studies like outage Genco-2 in area 1 and uncontracted power demand in any area and Disco Participation Matrix (19) is considered. The corresponding PSRI are evaluated using Eq (14-17) for the both test system and tabulated in Table 3 and 4 (case 9-12).

The main focus in this paper PSRI are useful for system planners for restoration planning in advance.

(i) If $1.0 \leq PSRI_1, PSRI_2 \leq 2.0$, then the system subject to a large steady error for step load changes. The integral control action is required based on the performance criteria. The integral controller gain of each control area has to be increased causing the speed changer valve to open up widely. Thus the speed- changer position attains a constant value only when the frequency error is reduced to zero.

(ii) If $PSRI_1, PSRI_2 \geq 2.0$, then the system required more amount of distributed generation requirement is needed and the FACTS devices are needed to improvement tie-line power oscillations.

(iii) If $0.2 \leq PSRI_3, PSRI_4 \leq 0.3$, then the system required the stabilization of frequency oscillations in an interconnected power system. In deregulated system, regulation and load following are the two frequency-related ancillary services required for balancing the varying load with matching generation. In cases where a dramatic decline in frequency occurs during the restoration process, it is necessary to reduce the amount of load that are connected, which can be accomplished by the application of under load shedding scheme.

(iv) If $PSRI_3, PSRI_4 \leq 0.3$, then the system is vulnerable and the system becomes unstable and may result to blackout. To restore the system as quickly as possible, especially for a bulk system, partitioning system into islands is necessary. Islands are resynchronizes after restoration of each island. Major actions involved in this restoration process are start up of black start units, cranking of non-black start units, restoration of islands, and synchronization of islands.

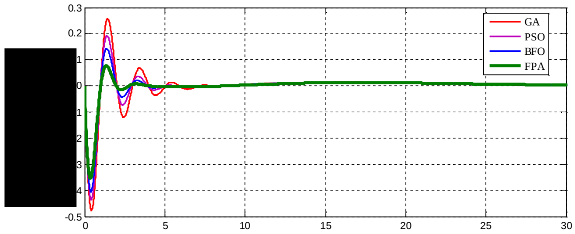

Figure 3(a): ΔF_1 (Hz) Vs Time(s)

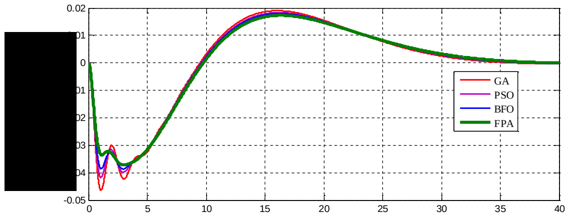

Figure 3(b): ΔF_2 (Hz) Vs Time (s)

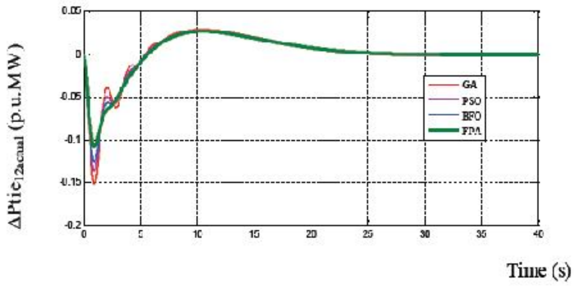

Figure 3(c): $\Delta Ptie_{12, actual}$ (p.u.MW) Vs Time (s)

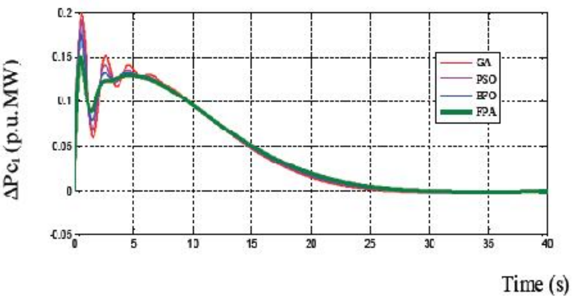

Figure 3(d): ΔPc_1 (p.u.MW) Vs Time (s)

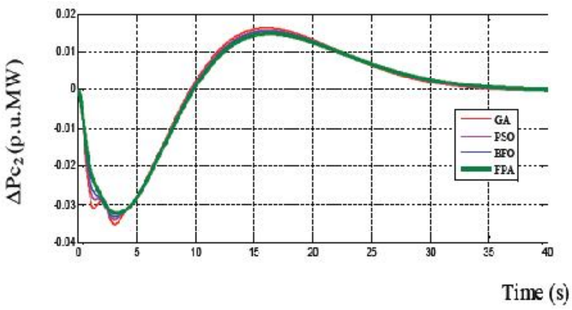

Figure 3(e): ΔPc_2 (p.u.MW) Vs Time (s)

Figure 3: Dynamic responses of the frequency deviations, tie-line power deviations, and Control input deviations for a two area thermal-diesel system using PI controllers (case-1)

Table 1 Optimal PI controller gain values using FPA for two-area reheat thermal- diesel power system with corresponding Load demand change

Two-area thermal-thermal system	PI controller gain of area 1		PI controller gain of area 2		Load demand in pu.MW				un contracted load demand pu.MW	
	K_P	K_I	K_P	K_I	$Disco_1$	$Disco_2$	$Disco_3$	$Disco_4$	area1	area 2
Case 1	0.241	0.353	0.101	0.236	0.2	0.2	0.0	0.0	0.0	0.0
Case 2	0.295	0.391	0.141	0.208	0.2	0.2	0.0	0.0	0.1	0.0
Case 3	0.326	0.456	0.164	0.224	0.2	0.2	0.0	0.0	0.0	0.1
Case 4	0.305	0.425	0.176	0.256	0.2	0.2	0.0	0.0	0.1	0.1
Case 5	0.271	0.161	0.234	0.291	0.25	0.15	0.3	0.1	0.0	0.0
Case 6	0.326	0.183	0.275	0.345	0.25	0.15	0.3	0.1	0.1	0.0
Case 7	0.334	0.203	0.288	0.349	0.25	0.15	0.3	0.1	0.0	0.1
Case 8	0.348	0.376	0.294	0.383	0.25	0.15	0.3	0.1	0.1	0.1
Case 9	0.261	0.247	0.304	0.741	0.32	0.08	0.26	0.14	0.0	0.0
Case 10	0.304	0.238	0.315	0.348	0.32	0.08	0.26	0.14	0.1	0.0
Case 11	0.317	0.253	0.323	0.367	0.32	0.08	0.26	0.14	0.0	0.1
Case 12	0.334	0.267	0.337	0.391	0.32	0.08	0.26	0.14	0.1	0.1

Table 2 Comparison of the system dynamic performance for two-area thermal-diesel power system (case-1)

PI controller design	Setting time (τ_s) in sec			Peak over / under shoot		
	ΔF_1	ΔF_2	ΔP_{tie}	ΔF_1 in Hz	ΔF_2 in Hz	ΔP_{tie} in p.u.MW
GA	20.64	35.25	22.47	0.473	0.045	0.145
PSO	19.57	33.64	20.78	0.431	0.041	0.132
BFO	17.45	32.39	19.34	0.395	0.037	0.121
FPA	16.34	30.14	17.78	0.344	0.031	0.104

Table 3 PSRI for two-area interconnected power system using FPA based PI controller considering diesel power plant participation factors (apf_{22}) = 0.5 and (apf_{22}) = 0.4

Load demand change	PSRI for thermal-diesel power system considering $apf_{11} = apf_{12} = apf_{21} = 0.5$ and diesel power plant participation factors (apf_{22}) = 0.5					PSRI for thermal-diesel power system considering $apf_{11} = apf_{12} = apf_{21} = 0.5$ and diesel power plant participation factors (apf_{22}) = 0.4				
	$PSRI_1$	$PSRI_2$	$PSRI_3$	$PSRI_4$	$\int P_{c2}$	$PSRI_1$	$PSRI_2$	$PSRI_3$	$PSRI_4$	$\int P_{c2}$
Case 1	1.235	1.319	0.166	0.023	0.138	1.237	1.321	0.167	0.024	0.141
Case 2	1.534	1.457	0.234	0.036	0.257	1.538	1.458	0.235	0.037	0.259
Case 3	1.463	1.732	0.163	0.128	3.922	1.464	1.735	0.164	0.129	3.924
Case 4	1.771	1.864	0.242	0.123	3.827	1.773	1.866	0.243	0.124	3.828
Case 5	1.242	1.257	0.211	0.173	1.736	1.243	1.258	0.212	0.175	1.737
Case 6	1.554	1.306	0.315	0.186	1.632	1.556	1.307	0.316	0.187	1.633
Case 7	1.218	1.568	0.216	0.263	4.603	1.219	1.569	0.218	0.264	4.604
Case 8	1.667	1.689	0.313	0.274	4.121	1.671	1.691	0.316	0.275	4.123
Case 9	2.086	2.191	0.608	0.166	1.627	2.087	2.193	0.609	0.167	1.628
Case 10	2.172	2.008	1.105	0.176	1.694	2.173	2.009	1.106	0.177	1.695
Case 11	2.161	2.102	1.097	0.217	4.462	2.169	2.105	1.098	0.218	4.464
Case 12	2.269	2.079	1.214	0.289	4.479	2.272	2.081	1.213	0.290	4.480

Table 4 PSRI for two-area interconnected power system using FPA based PI controller considering diesel power plant participation factors (apf_{22}) = 0.3 and (apf_{22}) = 0.2

Load demand change	PSRI for thermal-diesel power system considering $apf_{11} = apf_{12} = apf_{21} = 0.5$ and diesel power plant participation factors (apf_{22}) = 0.3					PSRI for thermal-diesel power system considering $apf_{11} = apf_{12} = apf_{21} = 0.5$ and diesel power plant participation factors (apf_{22}) = 0.2				
	$PSRI_1$	$PSRI_2$	$PSRI_3$	$PSRI_4$	$\int P_{c2}$	$PSRI_1$	$PSRI_2$	$PSRI_3$	$PSRI_4$	$\int P_{c2}$
Case 1	1.238	1.323	0.168	0.025	0.143	1.239	1.324	0.169	0.026	0.144
Case 2	1.539	1.459	0.236	0.038	0.261	1.540	1.461	0.235	0.039	0.263
Case 3	1.465	1.736	0.165	0.130	3.925	1.466	1.737	0.166	0.131	3.926
Case 4	1.774	1.867	0.244	0.125	3.829	1.775	1.868	0.245	0.126	3.830

Case 5	1.244	1.259	0.213	0.176	1.738	1.246	1.261	0.214	0.177	1.739
Case 6	1.557	1.308	0.317	0.188	1.632	1.558	1.309	0.318	0.189	1.634
Case 7	1.220	1.571	0.219	0.265	4.603	1.221	1.573	0.220	0.266	4.605
Case 8	1.673	1.692	0.318	0.276	4.124	1.675	1.693	0.319	0.277	4.125
Case 9	2.088	2.194	0.610	0.168	1.629	2.089	2.196	0.611	0.169	1.630
Case 10	2.175	2.010	1.108	0.178	1.696	2.176	2.011	1.109	0.179	1.697
Case 11	2.172	2.106	1.099	0.219	4.465	2.173	2.107	1.101	0.220	4.466
Case 12	2.274	2.083	1.215	0.291	4.481	2.275	2.084	1.216	0.292	4.482

CONCLUSION

This study presents the design and performance evaluation of Flower Pollination Algorithm (FPA) optimized PI controller for Automatic Generation Control of two-area thermal-diesel power system in restructured environment. The superiority of the proposed FPA approach has been shown by comparing the results with GA, PSO and BFO technique for the same interconnected power system. It is observed that the proposed FPA optimized PI controller outperforms the GA, PSO and BFO optimized PI controller and the best performance is obtained with FPA optimized PI controller. Moreover Power System Restoration Indices (PSRI) can be utilized to help the system operators even in real time by suggesting relevant actions taken to adhere for the automation of the power system restoration. The proposed thermal-diesel test system shows better performance to ensure improved PSRI in order to provide reduce the restoration time, thereby improving the system reliability.

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APPENDIX

Control Area Parameter [18]

Parameters	Area 1	Area 2
Kp (Hz/p.u.MW)	120	72
Tp (sec)	20	14.3
β (p.u.MW / Hz)	0.8675	0.785
Tij (p.u.MW / Hz)	T12 = 0.545	
F in Hz	60	
Kdisel	16.5	

Gencos Parameter (Thermal Generating Unit) [18]

MVA_{Base} (1000 MW) Parameters	Gencos (k in area i)			
	1-1	1-2	2-1	2-2
Rate (MW)	1000	1100	800	900
Tg (sec)	0.06	0.06	0.07	0.08
Tt (sec)	0.36	0.44	0.42	0.4
Tr (sec)	10	10	10	10
Kr	0.5	0.5	0.5	0.5
R (Hz / p.u.MW)	2.4	2.5	3.3	2.4
apf	0.5	0.5	0.5	0.5

★★★