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Application of Restoration Indices for the Automatic Generation Control in a Restructured Power System

R. Thirunavukarasu, I. A. Chidambaram

Abstract: ***The nature of power system restoration problem involves status assessment, optimization of generation capability and load pickup. Quick system restoration is of prime importance not only based on the time of restoration and also stability limits also play a very vital role in power system restoration problems due to unexpected load variations in power systems. To achieve a faster restoration process, installing new black start generators, network reconfigurations and load recovery can be beneficial in accelerating system restoration. This paper proposes evaluation of Power System Restoration Indices (PSRI) based on the Automatic Generation Control (AGC) assessment of interconnected power system in a restructured environment. The PSRI are useful for system planners to prepare the power system restoration plans to improve the efficiency of the physical operation of the power system and to increase the transmission capacity in the network. A specific restoration strategy can be synthesized by a combination of the milestones and actions based on the actual system conditions. In this study, AGC with two-area two-unit interconnected two types of test systems such as all-thermal units and thermal-hydro mixed units under deregulated environment have been investigated. The control parameters of Proportional-Integral (PI) gains of AGC loop are optimized through Bacterial Foraging Optimization (BFO) algorithm in order to achieve the optimal transient response of the system under different Poolco and bilateral transaction in restructured electricity market. From the simulated results it is observed that all-thermal unit test system indicates that more sophisticated control for a better restoration of the power system output responses and to ensure improved PSRI in order to provide reduce the restoration time, thereby improving the system reliability. In hydro test system, the non-minimum phase characteristic of hydro turbine shows an opposite initial power surge results in heavy frequency oscillations and the system is unable to regain its stable state than thermal generating unit.***

Keywords: Automatic Generation Control, Bacterial Foraging Optimization Algorithm, Proportional-Integral controller, Power System Restoration Indices, Restructured Power System.

I. INTRODUCTION

The power systems are normally composed of control areas or regions representing coherent groups of generators. In a practically interconnected power system, the generation normally comprises of a mix of thermal, hydro, nuclear and gas power generation. However, owing to their high efficiency, nuclear plants are usually kept at base load close to their maximum output with no participation in the system Automatic Generation Control (AGC). Gas power generation is ideal for meeting the varying load demand. Gas plants are used to meet peak demands only. Thus the natural choice for AGC falls on either thermal or hydro units. For large scale electric power systems with interconnected areas, Automatic Generation Control (AGC) is important to keep the system frequency and the inter-area tie power as near to the scheduled values as possible. The input mechanical power to the generators is used to control the frequency of output electrical power and to maintain the power exchange between the areas as scheduled. A small load fluctuation in any area causes the deviation of frequencies of all the areas and also of the tie-line power flow. These deviations have to be corrected through supplementary control. This supplementary control is basically known as Load-Frequency Control (LFC). Maintaining frequency and power interchanges with interconnected control areas at the scheduled values are the major objectives of a LFC [1, 2]. The frequency and the interchanged power are kept at their desired values using feedback for the integral of the Area Control Error (ACE), containing the frequency deviation and the error of the tie-line power, and controlling the prime movers of the generators. The controllers so designed regulate the ACE to zero. For each area, a bias constant determines the relative importance attached to the frequency error feedback with respect to the tie-line power error feedback; the bias is very often equal to the natural area frequency response characteristic. The conventional control strategy for the LFC problem is to take the integral of the ACE as the control signal. An integral controller provides zero steady state deviation, but it exhibits poor dynamic performance. Among the various types of load-frequency controllers, the most widely employed is the conventional Proportional -Integral (PI) controllers are still popular in power industry for frequency regulation as in case of any change in system operating conditions new gain values can be computed easily even for multi-area power systems. Thus PI controller is very simple for implementation and gives a better dynamic response, but their performances deteriorate when the complexity in the system increases due to disturbances [3-6]. In the deregulated power systems, the vertically integrated utility no longer exists. The deregulated power system consists of Gencos, Transcos and Discos with an open access policy. In the new structure, Gencos may or may not particulate in their same area or other areas. Thus, various combinations of possible contracted scenarios between Discos and Gencos are possible. All the transactions have to be cleared by the independent system operator or other risible organizations.

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R. Thirunavukarasu, Assoc. Prof., Department of Electrical Engineering, Annamalai University, Annamalainagar, Tamilnadu, India.

I. A. Chidambaram, Professor, Department of Electrical Engineering, Annamalai University, Annamalainagar, Tamilnadu, India.

These studies try to modify the conventional LFC system to take into account the effect of bilateral contracts on the dynamics and improve the dynamical transient response of the system under various operating conditions [7-12]. In recent years, although modern power system has improved greatly in the maintaining the reliability, security, stability in an economical manner, large-scale blackout in the world still occur frequently [13]. Large-scale power system after the accident had put forward more severe challenges for the quick recovery of the power system to ensure quality and reliability [14]. Therefore, to make the system restore after the blackout or to avoid blackout becomes one of the important problems which each power grid have to face. Under this situation a conventional frequency control i.e., a governor may no longer be able to compensate for sudden load changes due to the slow response [15]. Therefore, in an inter area mode, damping out the critical electromechanical oscillations is to be carried out effectively in an interconnected system. Moreover, system frequency deviations should be monitored and remedial actions to be provided to overcome the frequency excursions and are more likely to protect the system before it enters an emergency mode of operation [16]. 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. Inability to control the frequency may lead to unsuccessful restoration. The repeated collapse of the system islands due to tripping of generators causes delay in getting normalcy. Some aspects of computer application in restoration and Islanding satisfying some requirements of particular area has been presented [16]. In this study, the design of the Proportional plus Integral (PI) controller gains for the restructured power system are carried out using Bacterial Foraging Optimization (BFO) algorithm. BFO algorithm is a computational intelligence based optimization technique which exhibits the foraging behavior of e.coli bacteria. The BFO has been demonstrated in [19-21] which mimics the bacteria forage over a landscape of nutrients to perform parallel non gradient optimization. The BFO algorithm is not large affected by the size and nonlinearity of the problem and can converge the solution to an optimal solution where most of the analytical methods fail to converge. In this study to develop more effective and fast restoration procedures required for the interconnected power system are suggested with the computation of various Power System Restoration Indices (PSRI) for the two types of test systems such as Two - Area Hydro Thermal Reheat Interconnected Power System (TAHTRIPS) with hydro electric governor and Two - Area Thermal Reheat Interconnected Power System (TATRIPS) in a restructured environment. With the various Power System Restoration Indices (Feasible Restoration Indices, Comprehensive Restoration Indices) the remedial measures to be taken can be adjudged (like integration of additional spinning reserve, incorporation of FACTS devices in the tie-line, load shedding, etc).

II. AGC IN DEREGULATED ENVIRONMENT

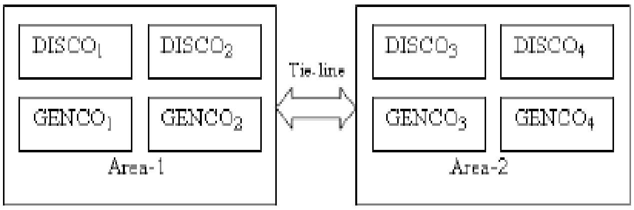

Fig. 1: Schematic diagram of two-area system in restructured environment

The electrical power system is quite complex and dynamic in nature. In the restructured or deregulated environment the power systems consists of generation companies (Genco), distribution companies (Disco), transmission companies (Transco) and Independent System Operator (ISO). An agreement between Disco and Genco should be established to supply regulation. The LFC in a deregulated electricity market should be designed to consider different types of possible transactions, such as Poolco-based transactions, bilateral transactions and a combination of these two [7]. In the open market based in bilateral contracts, Discos have the freedom to contract with any of the Genco in the own area or other area and these contracts are made under supervision of ISO. ISO is also responsible for managing the ancillary services like AGC etc. Same as Discos, ISO will also have freedom to get power from the same or other area to provide ancillary services to the system. Therefore, in system with an open access policy, there is a need for an AGC model which can be used for analysis as well as development of efficient control strategies. To make the visualization of contracts easier, the concept of a "DISCO Participation Matrix" (DPM) will be used [12] which essentially provides the information about the participation of a Disco in contract with a Genco. In DPM, the number of rows has to be equal to the number of Gencos and the number of columns has to be equal to the number of Discos in the system. Any entry of this matrix is a fraction of total load power contracted by a Disco toward a Genco. As a results total of entries of column belong to Disco$_i$ of DPM is $\sum_i cpf_{ij} = 1$. 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

$$DPM = \left[\begin{array}{cccc} & D\ I\ S\ C\ O & & \\ cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\ cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \\ cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} \\ cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} \end{array}\right] \begin{array}{c} G \\ E \\ N \\ C \\ O \end{array} \qquad (1)$$

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.

Linearized model of a Two-Area Hydro-Thermal Reheat Interconnected Power System in deregulated environment is shown in Fig.2. The actual and scheduled steady state power flow through the tie-line are given

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

$$\Delta P_{tie1-2,\,actual} = \left(2\,\pi\,T_{12}\,/\,s\right)\left(\Delta F_1 - \Delta F_2\right) \qquad (3)$$

And at any given time, the tie-line power error $\Delta P_{tie1-2,\,error}$ is defined as

$$\Delta P_{tie1-2,\,error} = \Delta P_{tie1-2,\,actual} - \Delta P_{tie1-2,\,scheduled} \qquad (4)$$

The error signal is used to generate the respective ACE signals as in the traditional scenario [6]

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

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

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

$$\Delta Pg_i = \sum_{j=1}^{DISCO=4} cpf_{i\,j}\Delta PL_j \qquad (7)$$

Also note that $\Delta PL_{1,LOC} = \Delta PL_1 + \Delta PL_2$ and $\Delta PL_{2,LOC} = \Delta PL_3 + \Delta PL_4$. In the proposed LFC implementation, contracted load is fed forward through the DPM matrix to Genco set points. The actual loads affect system dynamics via the input $\Delta PL_{,LOC}$ to the power system blocks. 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$_{22}$

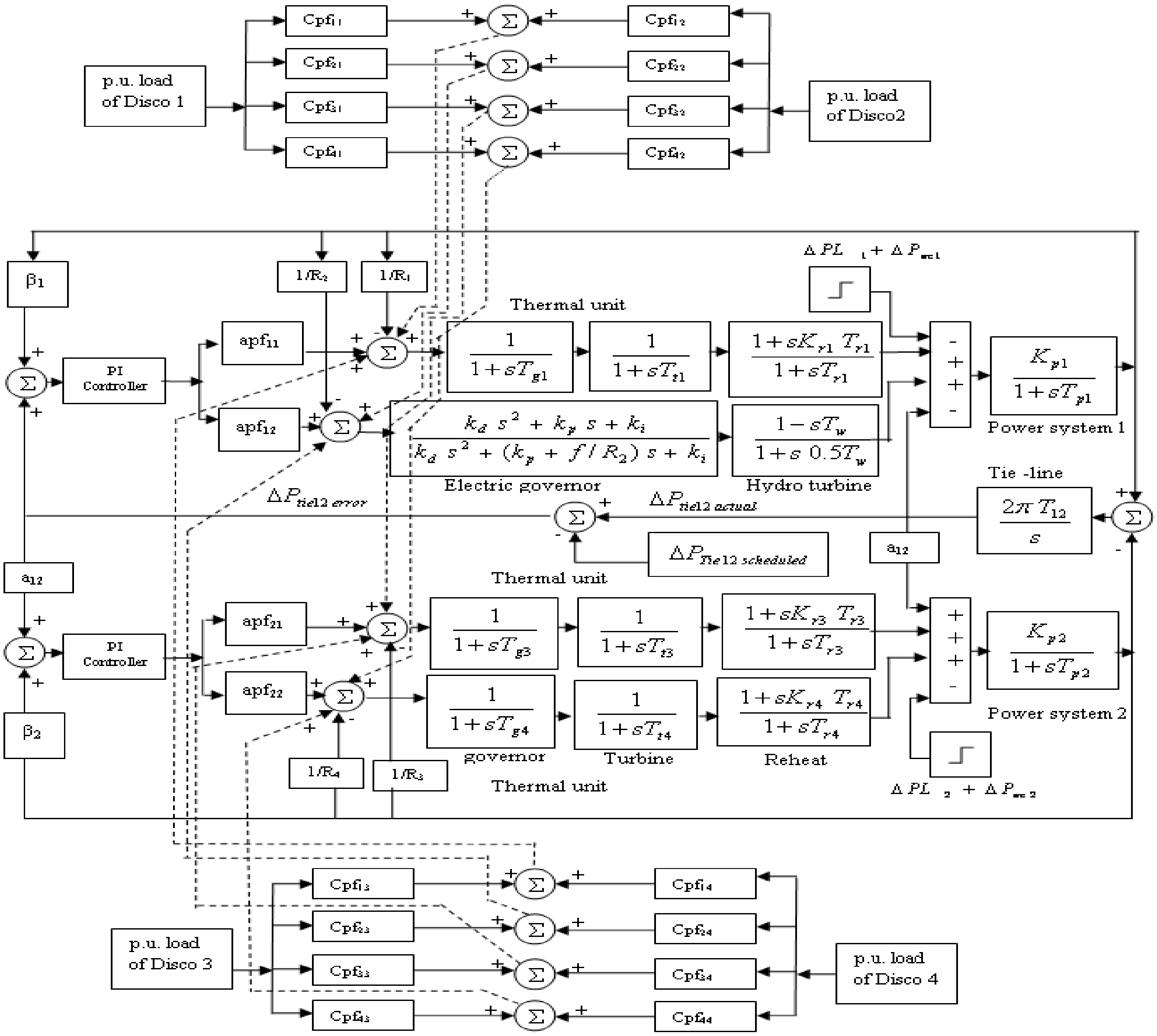

Fig. 2: Linearized model of a two-area Hydro-Thermal reheat interconnected power system in a restructured environment

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III. DESIGN OF DECENTRALIZED PROPORTIONAL PLUS INTEGRAL (PI) CONTROLLERS

Many investigations in the area of Load-Frequency Control (LFC) problem of interconnected power systems have reported over the past six decades. A number of control strategies have been employed in the design of load frequency controllers in order to achieve better dynamic performance. In feedback control systems a controller may be adopted to modify the error signal and to achieve better control action. The efficient incorporation of controllers will modify the transient response and steady state error of the system. Among the various types of load frequency controllers, the most widely employed is the conventional Proportional plus Integral controller (PI). In this work optimum gain values are tuned based on Area Control Error of the output response of the system (especially the frequency deviation and tie-line power deviation) and with these gain values the performance of the system is analyzed. And here in this case study it is used as a feedback controller which drives the plant to be controlled within a weighted sum of error and integral of that value i.e. it produces an output signal consisting of two terms one proportional to error signal and the other proportional to integral of error signal. In order to satisfy the above requirements, Proportional plus Integral gains (K_{Pi}, K_{Ii}) in the LFC loop are to be optimized using BFO algorithm. In the present work an Integral Square Error (ISE) criterion [18] is used to minimize the objective function which is defined as follows. The objective function is minimized with help of Bacterial Foraging Optimization Technique.

Where,

$$U_1 = -K_p \ ACE_1 - K_I \int ACE_1 \quad dt \tag{8}$$

$$U_2 = -K_p \ ACE_2 - K_I \int ACE_2 \quad dt \tag{9}$$

Where, K_p = Proportional gain, K_I = Integral gain, ACE = Area Control Error, U_1, U_2 = Control outputs of the respective areas. The relative simplicity of this controller is a successful approach towards the zero steady state error in the frequency of the system.

IV. BACTERIAL FORAGING OPTIMIZATION (BFO) ALGORITHM

The BFO method was introduced by Passino [19] motivated by the natural selection which tends to eliminate the animals with poor foraging strategies and favor those having successful foraging strategies. The foraging strategy is governed by four processes namely Chemotaxis, Swarming, Reproduction and Elimination and Dispersal. Chemotaxis process is the characteristics of movement of bacteria in search of food and consists of two processes namely swimming and tumbling. A bacterium is said to be swimming if it moves in a predefined direction, and tumbling if it starts moving in an altogether different direction. To represent a tumble, a unit length random direction $\phi(j)$ is generated. Let, "j" is the index of chemotactic step, "k" is reproduction step and "*l*" is the elimination dispersal event. $\theta_i(j,k,l)$, is the position of i^th^ bacteria at j^th^ chemotactic step k^th^ reproduction step and l^th^ elimination dispersal event. The position of the bacteria in the next chemotatic step after a tumble is given by

$$\theta^i(j+1, \quad k, \quad l) = \theta^i(j, \quad k, \quad l) + C(i)\ \phi(j) \tag{10}$$

If the health of the bacteria improves after the tumble, the bacteria will continue to swim to the same direction for the specified steps or until the health degrades. Bacteria exhibits swarm behavior i.e. healthy bacteria try to attract other bacterium so that together they reach the desired location (solution point) more rapidly. The effect of swarming [19] is to make the bacteria congregate into groups and moves as concentric patterns with high bacterial density. Mathematically swarming behavior can be modeled

$$\begin{aligned} J_{cc}\left(\theta, P(j,k,l)\right) &= \sum_{i=1}^{S} J^i cc\left(\theta, \theta^i(j.k.l)\right) \\ &= \sum_{i=1}^{S}\left[-d_{attract}\exp\left(-\omega_{attract}\right)\sum_{m=1}^{p}\left(\theta^m-\theta_m^i\right)^2\right] \\ &+ \sum_{i=1}^{S}\left[-h_{repelent}\exp\left(-w_{repelent}\right)\sum_{m=1}^{p}\left(\theta^m-\theta_m^i\right)^2\right] \end{aligned} \tag{11}$$

Where J_{CC} -Relative distance of each bacterium from the fittest bacterium, S -Number of bacteria, p - Number of parameters to be optimized, θ^m - Position of the fittest bacteria, $d_{attract}$, $\omega_{attract}$, $h_{repelent}$, $\omega_{repelent}$- different co-efficient representing the swarming behavior of the bacteria which are to be chosen properly. In Reproduction step, population members who have sufficient nutrients will reproduce and the least healthy bacteria will die. The healthier population replaces unhealthy bacteria which get eliminated owing to their poorer foraging abilities. This makes the population of bacteria constant in the *evolution* process. In this process a sudden unforeseen event may drastically alter the evolution and may cause the elimination and / or dispersion to a new environment. Elimination and dispersal helps in reducing the behavior of stagnation i.e., being trapped in a premature solution point or local optima. In case of BFO technique each bacterium is assigned with a set of variable to be optimized and are assigned with random values [Δ] within the universe of discourse defined through upper and lower limits between which the optimum value is likely to fall. In the proposed method of proportional plus integral gain (K_{Pi}, K_Ii) (i=1, 2) scheduling, each bacterium is allowed to take all possible values within the range and the cost objective function which is represented by Eq (8) and (9) is minimized and the BFO algorithm parameters are reported in [20, 21].

V. POWER SYSTEM RESTORATION

Power system disturbances are most likely to occur as the result of loss of generating equipment, transmission facilities, or as the result of unexpected load changes. These disturbances may be affecting the reliable operation of the power system. The associated conditions under severe system disturbances generally result in critically loaded transmission facilities, critical frequency deviations, or high or low voltage conditions. Each Transmission / Generation owner has an obligation to protect their own system's equipment and reliability. However, steps taken to do so are coordinated, if at all possible, with the System Operator so as to solve the problem in the best manner, realizing that actions taken may have a far reaching effect [22-24]. Power system restoration is well recognized as an important task to reduce the duration of a disturbance that occurs in power systems. The complex tasks of emergency recovery require advanced decision support tools to enhance the resilience and, ultimately, self-healing capabilities for a smart grid. The high level strategy of the System Restoration Plan is to restore the integrity of the interconnection as quickly as possible. In general, the following steps are taken by ISO, Transmission Owners and Generation Operators: (i) Perform a system assessment to determine extent of outage, (ii) Start Black Start units to form islands, (iii) Build cranking paths to other generating units (iv) Restore critical load Synchronize and interconnect islands to form larger islands, (v) Connect to outside areas and Return to normal operations. 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 these study two types of test system is considered such as interconnected two-area multi-unit such as all thermal units and mixed with hydro thermal unit (unit-2 has hydro unit. with hydro electric governor and remaining unit has thermal unit) in a restructured environment More over Power System Restoration Indices namely Feasible Restoration Indices (FRI) when the system is operating in a normal condition with Gencos units in operation and Comprehensive Restoration Indices (CRI) are 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 Feasible Restoration Indices are calculated as follows. The Feasible Restoration Indices 1 (ε_1) is obtained as the ratio between the settling time of frequency deviation in area 1 (ς_{s1}) and power system time constant (T_{p1}) of area 1

$$\varepsilon_1 \;=\frac{\varsigma_{s1}}{T_{p1}} \tag{12}$$

The Feasible Restoration Indices 2 (ε_2) is obtained as the ratio between the settling time of frequency deviation in area 2 (ς_{s2}) and power system time constant (T_{p2}) of area 2

$$\varepsilon_2 \;=\frac{\varsigma_{s2}}{T_{p2}} \tag{13}$$

The Feasible Restoration Indices 3 (ε_3) is obtained as the ratio between the settling time of Tie –line power deviation (ς_{s3}) and synchronous power coefficient T_{12}

$$\varepsilon_3 \;=\frac{\varsigma_{s3}}{T_{12}} \tag{14}$$

The Feasible Restoration Indices 4(ε_4) is obtained as the peak value frequency deviation $\Delta F_1(\varsigma_p)$ response of area 1 exceeds the final value $\Delta F1(\varsigma_s)$

$$\varepsilon_4 = \Delta F_1(\varsigma_p) - \Delta F_1(\varsigma_s) \tag{15}$$

The Feasible Restoration Indices 5(ε_5) is obtained as the peak value frequency deviation $\Delta F_2\ (\varsigma_p)$ response of area 2 exceeds the final value $\Delta F2\,(\varsigma_s)$

$$\varepsilon_5 = \Delta F_2(\varsigma_p) - \Delta F_2(\varsigma_s) \tag{16}$$

The Feasible Restoration Indices 6 (ε_6) is obtained as the peak value tie-line power deviation $\Delta P_{tie}\ (\varsigma_p)$ response exceeds the final value $\Delta P_{tie}\ (\varsigma_s)$

$$\varepsilon_6 = \Delta P_{tie}(\varsigma_p) - \Delta P_{tie}(\varsigma_s) \tag{17}$$

The Feasible Restoration Indices 7 (ε_7) is obtained from the peak value of the control input deviation $\Delta P_{c1}(\varsigma_p)$ response of area 1 with respect to the final value $\Delta P_{c1}(\varsigma_s)$

$$\varepsilon_7 = \Delta P_{c1}(\varsigma_p) - \Delta P_{c1}\ (\varsigma_s) \tag{18}$$

The Feasible Restoration Indices 8(ε_8) is obtained from the peak value of the control input deviation $\Delta P_{c2}(\varsigma_p)$ response of area 2 with respect to the final value $\Delta P_{c2}(\varsigma_s)$

$$\varepsilon_8 = \Delta P_{c2}(\varsigma_p) - \Delta P_{c2}\ (\varsigma_s) \tag{19}$$

Apart from the normal operating condition of the test system few other case studies like one unit outage in any area, outage of one distributed generation in both areas are considered individually. The optimal controller gains and their performance of the system various case studies the corresponding the Comprehensive Restoration Indices (CRI) ($\varepsilon_9, \varepsilon_{10}, \varepsilon_{11}, \varepsilon_{12}, \varepsilon_{13}, \varepsilon_{14}, \varepsilon_{15}, \varepsilon_{16}$) is obtained from Eq (12- 19).

VI. SIMULATION RESULTS AND OBSERVATIONS

The proposed PI controllers are designed and implemented in two types of test system for different type of transactions.

In test system-1 (TAHTRIPS) consists of two Gencos and two Discos in each area. $Genco_2$ in area 1 consists of hydro unit with electric governor and other Gencos have thermal reheat unit with different capacity is shown in Fig 2. In test system-2 (TAHTRIPS) consists of all the Gencos each area consists of thermal reheat unit with different capacity. The nominal parameters are given in Appendix. The optimal solution of control inputs is taken an optimization problem, and the cost function in Eq (8) and (9) is derived using the frequency deviations of control areas and tie- line power changes. The PI controller gain (K_p K_i) for each area tuned simultaneously with help of BFO algorithm for two type test system (TAHTRIPS and TATRIPS) examples using both traditional and bilateral based LFC schemes with a wide range of load changes are given to illustrate the proposed approach. The results are obtained by MATLAB 7.01 software and 50 iterations are chosen for the convergence of the solution in the BFO algorithm. The optimum PI controller gain values for two test system such as TAHTRIPS and TATRIPS are tuned for various case studies are tabulated in the Table 1 and Table 2 respectively. These PI controllers are implemented in a proposed power system for different type of transactions.

6.1 Feasible Restoration Indices

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 0.1 pu MW is demanded by each Disco in area 1. Assume that a case of Poolco based contracts between Dicos and available Gencos is simulated based on the following Disco Participation Matrix (DPM) referring to Eq (1) is considered as

$$DPM = \begin{bmatrix} 0.5 & 0.5 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{20}$$

$Disco_1$ 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 and Table-2. From the simulation results Power System Restoration Indices namely Feasible Restoration Indices are evaluated using Eq (12)-(19) from dynamic output responses of the proposed test system is shown in Table 3 and Table 4 (case 1- 4).

Scenario 2: Bilateral transaction

Here all the Discos have contract with the Gencos and the following Disco Participation Matrix (DPM) be considered.

$$DPM = \begin{bmatrix} 0.5 & 0.25 & 0.5 & 0.4 \\ 0.2 & 0.25 & 0.2 & 0.2 \\ 0.0 & 0.3 & 0.2 & 0.25 \\ 0.3 & 0.2 & 0.1 & 0.15 \end{bmatrix} \tag{21}$$

In this case, the $Disco_1$, $Disco_2$, $Disco_3$ and $Disco_4$, demands 0.15 pu.MW, 0.05 pu.MW, 0.15 pu.MW and 0.05 pu.MW from Gencos as defined by cpf in the DPM matrix and each Gencos participates in LFC as defined by the following ACE participation factor $apf_{11} = apf_{12} = 0.5$ and $apf_{21} = apf_{22} = 0.5$. The dynamic responses of frequency deviations (Δf) both area, tie- line power deviation ΔP_{tie} and control input deviations ΔP_c are obtained with respect to time as shown in Fig 3. The corresponding Feasible Restoration Indices are calculated from dynamic output responses of the proposed test system are shown in Table 3 and Table-4 (case 5- 8).

6.2 Comprehensive Restoration Indices

Apart from the normal operating condition of the test systems few other case studies like outage generating unit in any area and uncontracted power demand in any area during outage the corresponding Power System Restoration Indices is called Comprehensive Restoration Indices (CRI). In this study Genco-4 in area 2 is outage and uncontracted power demand in any area and Disco Participation Matrix (21) is considered. The optimum PI controller gain values for two test system such as TAHTRIPS and TATRIPS are tuned for various case studies are tabulated in the Table 1 and Table 2 respectively (case 9-12). These PI controllers are implemented in a proposed two types test system for different type of transactions. The dynamic output responses of the proposed test system are shown in Fig 4 and corresponding Comprehensive Restoration Indices (CRI) are calculated and tabulated in Table 5 and Table 6. From the simulated results it is observed that the restoration process with the reheat thermal generation unit ensures not only reliable operation but provides a good margin of stability compared with that of a Hydro Turbine with electric governor. When hydro power system is adopted to deliver power for compensating the frequency deviations of power system the power output has a non minimum phase characteristic, e.g. when opening the guide vanes to give more power, the power will temporarily decrease due to the acceleration of the water in the waterways.

6.3 Power System Restoration Assessment

Power System Restoration Indices (PSRI) based on the Automatic Generation Control (AGC) assessment of interconnected power can be used in different ways: (i) Automatic power system restoration. (ii) Operator support, suggesting actions to the operator in real time. (iii) Off-line planning for restoration in advance of the blackout. This includes both comparing different restoration plans/strategies' and comparing restoration sequences after modifications in the net. The focus of this paper is to ensure restoration planning well in advance.

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(i) If $1.0 \le \varepsilon_1, \varepsilon_2, \varepsilon_9, \varepsilon_{10} \le 5$ and $40 \le \varepsilon_3, \varepsilon_{11} \le 50$, then the system subject to a large steady error for step load changes. Under a steady state condition, change in frequency of each area and change in tie-line power exchange will become more in some of case studies in Table 3-6. The integral control action is required based on the performance criteria such as ACE must be equal to zero at least one time in all 10-minute periods and average deviation of ACE from zero must be within specified limits based on a percentage of system generation for all 10-minutes periods. So that the above case studies, the integral controller gain (K_I) is made very large then only steady state frequency error reduces to zero. In other words, this means that speed regulation (R) should be made equal to zero, which is not desirable. Proportional control is not suitable for reducing the steady state error to zero. So that 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 $\varepsilon_1, \varepsilon_2, \varepsilon_9, \varepsilon_{10} \ge 5$ and $\varepsilon_3, \varepsilon_{11} \ge 50$ then the system required more amount of distributed generation requirement is needed and the FACTS devices are needed to improvement tie-line power oscillations. In this cases, the gain of the integrator is sufficiently high, over shoot will occur, increasing sharply as a function of the gain; this is highly undesirable. In the absence of integral control, one can sharply increase the gain of the closed- loop system and thereby improves the system response. However, the system will have a steady- state error. So that the Flexible Alternating Current Transmission (FACTS) devices coordinated with Energy Storage Systems (ESS) for LFC application has improve relatively stability of the power system and also to over come the draw back of the designing integral controller.

(iii) If $0.5 \le \varepsilon_4, \varepsilon_5, \varepsilon_{12}, \varepsilon_{13} \le 1$ and $0.15 \le \varepsilon_7, \varepsilon_8, \varepsilon_{15}, \varepsilon_{16} \le 0.2$ then the system required the stabilization of frequency oscillations in an interconnected power system. The conventional load-frequency controller may no longer be able to attenuate the large frequency oscillation due to the slow response of the governor for unpredictable load variations. Fast-acting energy storage systems having storage capacity in addition to the kinetic energy of the generator rotors is advisable to damp out the frequency oscillations. So that in deregulated system, regulation and load following are the two frequency-related ancillary services required for balancing the varying load with matching generation. Ancillary Services are defined as all those activities on the interconnected grid that are necessary to support the transmission of active power while maintaining reliable operation and ensuring the required degree of quality and security.

(iv) If $0.05 \le \varepsilon_6, \varepsilon_{14} \le 0.15$ then the FACTS devices are needed to improvement tie-line power oscillations. The recent advances in power electronics have led to the development of the Flexible Alternating Current Transmission Systems (FACTS). As these FACTS devices are capable of controlling the network condition in a very fast manner the usage of FACTS devices are more apt to improve the stability of power system. Several FACTS devices such as Thyristor Controlled Series Capacitor (TCSC), static synchronous compensator (STATCOM), Thyristor Controlled Phase Shifter (TCPS), Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC) have been developed in recent decades. These FACTS devices are capable of controlling the network conditions in a very fast and economical manner.

(v) If $\varepsilon_4, \varepsilon_5, \varepsilon_{12}, \varepsilon_{13} \ge 1$, $\varepsilon_6, \varepsilon_{14} \ge 0.15$ and $\varepsilon_7, \varepsilon_8, \varepsilon_{15}, \varepsilon_{16} \ge 0.2$ then the system is vulnerable and the system becomes unstable and may result to blackout. Small blackouts, involving only a few substations, can often be handled rather easily since they occur more often than the larger blackouts so the operators has more experience with them and the load can often be reconnected as soon as the operational reserves are able to meet the demand. Larger blackouts, affecting the whole or significant parts of the power system, are much harder to restore since large parts of the power system need to be energized and a significant part of the generating units will not be available. In order to handle restoration situations the operators have prepared restoration plans and guidelines for some typical blackout situations. The operators have to adopt these to the current situation with the consideration of two major strategies in power system restoration which can be defined as bottom up and top down. Bottom up means that several smaller electrical islands are started in parallel; these are then used to energize the transmission system. The need to synchronize the islands can slow down the process. Top down means that the transmission system is energized from one point and all the lower voltage levels are energized from the transmission system and the whole energized power system is kept synchronized.

Table 1 Optimized Controller parameters of the TAHTRIPS using Electrical hydro governor for the corresponding Load demand change

TAHTRIPS using Electrical hydro governor	PI controller gain of AREA 1		PI controller gain of AREA 2		Load demand in pu.MW				Uncontracted load demand pu.MW	
	K_{P1}	K_{i1}	K_{P2}	K_{i2}	Disco$_1$	Disco $_2$	Disco $_3$	Disco $_4$	Area1	Area 2
Case 1	0.082	0.162	0.192	0.077	0.1	0.1	0.0	0.0	0.0	0.0
Case 2	0.117	0.196	0.197	0.083	0.1	0.1	0.0	0.0	0.1	0.0

Case 3	0.095	0.169	0.212	0.101	0.1	0.1	0.0	0.0	0.0	0.1
Case 4	0.126	0.212	0.218	0.104	0.1	0.1	0.0	0.0	0.1	0.1
Case 5	0.015	0.226	0.118	0.124	0.15	0.05	0.15	0.05	0.0	0.0
Case 6	0.317	0.485	0.218	0.171	0.15	0.05	0.15	0.05	0.1	0.0
Case 7	0.278	0.424	0.285	0.195	0.15	0.05	0.15	0.05	0.0	0.1
Case 8	0.347	0.489	0.244	0.187	0.15	0.05	0.15	0.05	0.1	0.1
Case 9	0.395	0.227	0.282	0.162	0.12	0.08	0.14	0.06	0.0	0.0
Case 10	0.401	0.251	0.215	0.175	0.12	0.08	0.14	0.06	0.1	0.0
Case 11	0.392	0.263	0.221	0.137	0.12	0.08	0.14	0.06	0.0	0.1
Case 12	0.412	0.285	0.258	0.144	0.12	0.08	0.14	0.06	0.1	0.1

Table 2 Optimized Controller parameters of the TATRIPS for the corresponding Load demand change

TATRIPS	PI controller gain of AREA 2		PI controller gain of AREA 2		Load demand in pu.MW				Uncontracted load demand pu.MW	
	K_{P1}	K_{i1}	K_{P2}	K_{i2}	Disco $_1$	Disco $_2$	Disco $_3$	Disco $_4$	Area1	Area 2
Case 1	0.341	0.459	0.191	0.081	0.1	0.1	0.0	0.0	0.0	0.0
Case 2	0.384	0.315	0.121	0.051	0.1	0.1	0.0	0.0	0.1	0.0
Case 3	0.411	0.489	0.284	0.112	0.1	0.1	0.0	0.0	0.0	0.1
Case 4	0.386	0.352	0.256	0.127	0.1	0.1	0.0	0.0	0.1	0.1
Case 5	0.316	0.512	0.127	0.296	0.15	0.05	0.15	0.05	0.0	0.0
Case 6	0.393	0.575	0.131	0.305	0.15	0.05	0.15	0.05	0.1	0.0
Case 7	0.324	0.492	0.214	0.362	0.15	0.05	0.15	0.05	0.0	0.1
Case 8	0.381	0.563	0.249	0.368	0.15	0.05	0.15	0.05	0.1	0.1
Case 9	0.421	0.685	0.247	0.183	0.12	0.08	0.14	0.06	0.0	0.0
Case 10	0.438	0.696	0.255	0.178	0.12	0.08	0.14	0.06	0.1	0.0
Case 11	0.416	0.671	0.252	0.172	0.12	0.08	0.14	0.06	0.0	0.1
Case 12	0.435	0.678	0.261	0.186	0.12	0.08	0.14	0.06	0.1	0.1

Table 3 Feasible Restoration Indices for TAHTRIPS using Electrical hydro governor with different types of case studies

TAHTRIPS using Electrical hydro governor	FRI based on Settling time (ς_s)			FRI based on Peak over/ under shoot (m_p)			FRI based on control input deviation (ΔP_c)	
	ε_1	ε_2	ε_3	ε_4	ε_5	ε_6	ε_7	ε_8
Case 1	1.281	0.942	45.63	0.551	0.416	0.152	0.085	0.035
Case 2	1.563	0.994	46.14	0.843	0.523	0.201	0.182	0.045
Case 3	1.345	1.269	49.09	0.586	0.564	0.109	0.123	0.112
Case 4	1.736	1.592	56.67	0.851	0.723	0.153	0.181	0.113
Case 5	0.956	0.922	42.59	0.657	0.583	0.043	0.133	0.083
Case 6	1.289	0.959	43.54	0.853	0.732	0.113	0.204	0.092
Case 7	1.412	1.241	47.78	0.881	0.753	0.146	0.145	0.121
Case 8	1.782	1.445	58.36	0.933	0.762	0.153	0.218	0.172

Table 4 Feasible Restoration Indices for TATRIPS with different types of case studies

TATRIPS	FRI based on Settling time (ς_s)			FRI based on Peak over/ under shoot (m_p)			FRI based on control input deviation (ΔP_c)	
	ε_1	ε_2	ε_3	ε_4	ε_5	ε_6	ε_7	ε_8
Case 1	0.871	0.861	42.63	0.351	0.316	0.042	0.149	0.113
Case 2	0.936	0.875	43.54	0.562	0.402	0.053	0.234	0.124
Case 3	0.901	0.943	46.23	0.432	0.459	0.062	0.143	0.252
Case 4	1.212	1.375	53.63	0.624	0.716	0.081	0.225	0.236
Case 5	0.923	0.896	40.78	0.357	0.456	0.012	0.153	0.093
Case 6	0.949	0.912	41.96	0.553	0.513	0.043	0.264	0.146
Case 7	0.931	0.986	45.51	0.381	0.653	0.051	0.159	0.162
Case 8	1.245	1.312	52.29	0.633	0.991	0.055	0.258	0.178

Table 5 Comprehensive Restoration Indices for TAHTRIPS using Electrical hydro governor with different types of case studies

TAHTRIPS	CRI based on Settling time (ς_s)			CRI based on Peak over / under shoot (m_p)			CRI based on control input deviation (ΔP_c)	
	ε_9	ε_{10}	ε_{11}	ε_{12}	ε_{13}	ε_{14}	ε_{15}	ε_{16}
Case 9	1.625	1.612	57.69	0.856	0.804	0.161	0.173	0.153
Case 10	1.811	1.682	58.71	1.036	0.856	0.177	0.179	0.159
Case 11	1.725	1.894	62.65	0.956	1.021	0.179	0.181	0.164
Case 12	1.945	1.881	63.87	1.489	1.354	0.183	0.194	0.173

Table 6 Comprehensive Restoration Indices for TATRIPS with different types of case studies

TATRIPS	CRI based on Settling time (ς_s)			CRI based on Peak over / under shoot (m_p)			CRI based on control input deviation (ΔP_c)	
	ε_9	ε_{10}	ε_{11}	ε_{12}	ε_{13}	ε_{14}	ε_{15}	ε_{16}
Case 9	1.431	1.537	55.48	0.678	0.719	0.156	0.185	0.161
Case 10	1.715	1.678	56.39	0.691	0.701	0.167	0.193	0.167
Case 11	1.525	1.823	59.36	0.705	0.929	0.168	0.187	0.173
Case 12	1.747	1.867	59.29	1.317	1.252	0.173	0.218	0.186

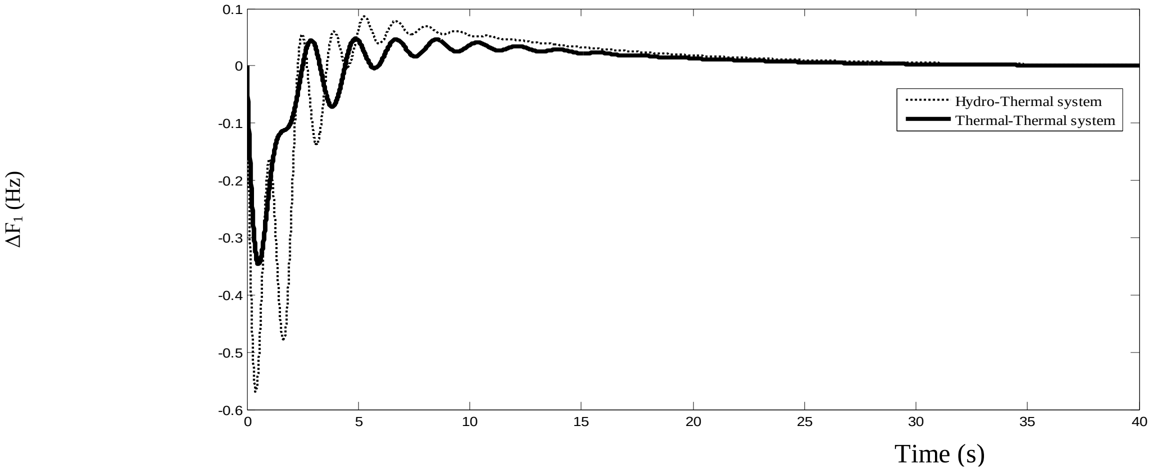

Fig. 3 (a) ΔF$_1$ (Hz) Vs Time(s)

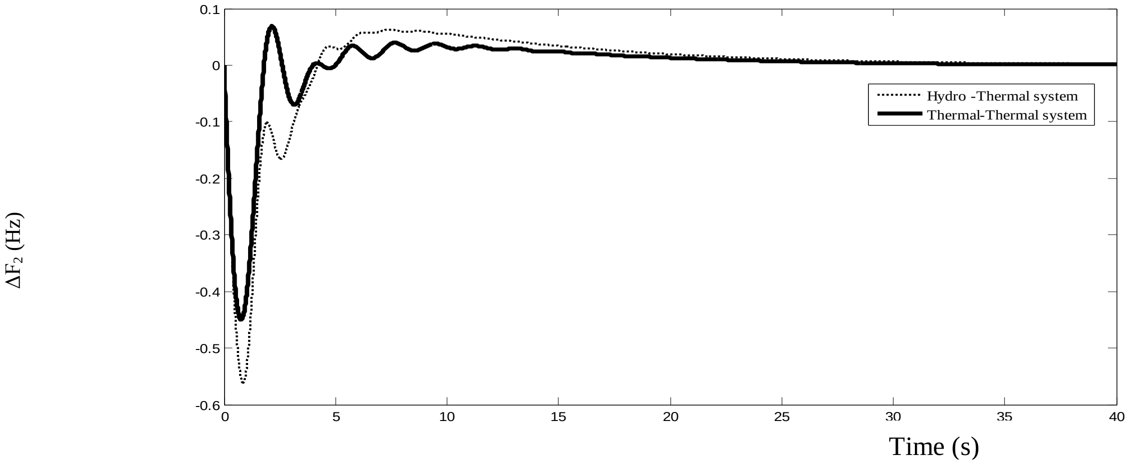

Fig. 3 (b) ΔF2 (Hz) Vs Time (s)

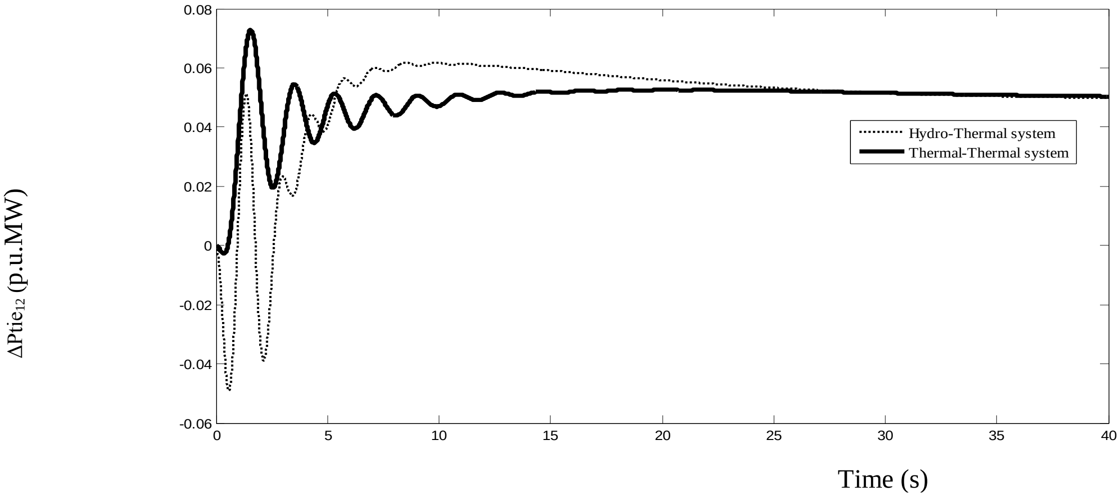

Fig. 3 (c) $\Delta Ptie_{12,\ actual}$ (p.u.MW) Vs Time (s)

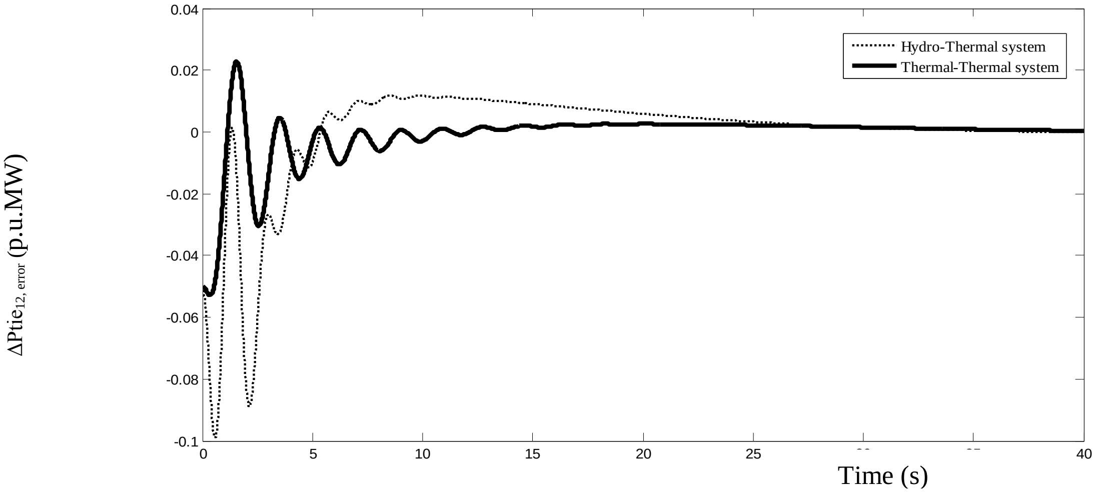

Fig. 3 (d) $\Delta Ptie_{12,\ error}$ (p.u.MW) Vs Time (s)

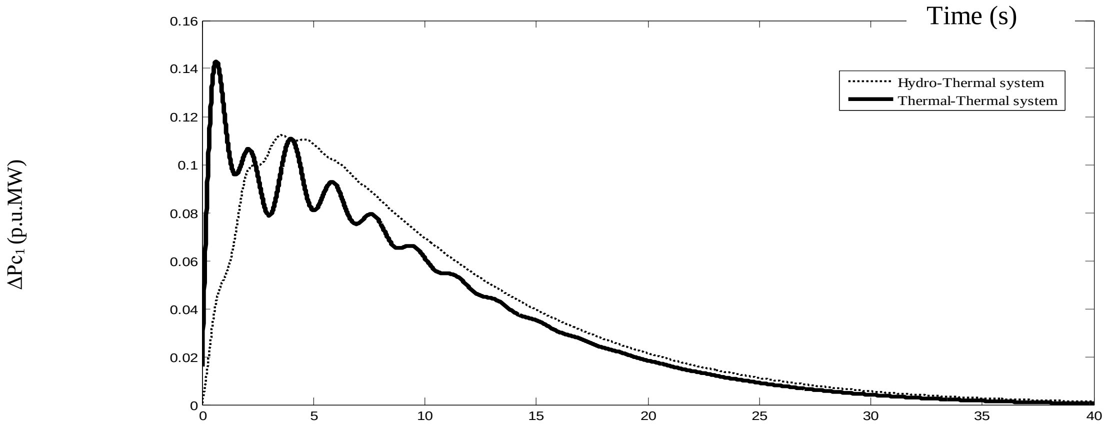

Fig. 3 (e) ΔPc1 (p.u.MW) Vs Time (s)

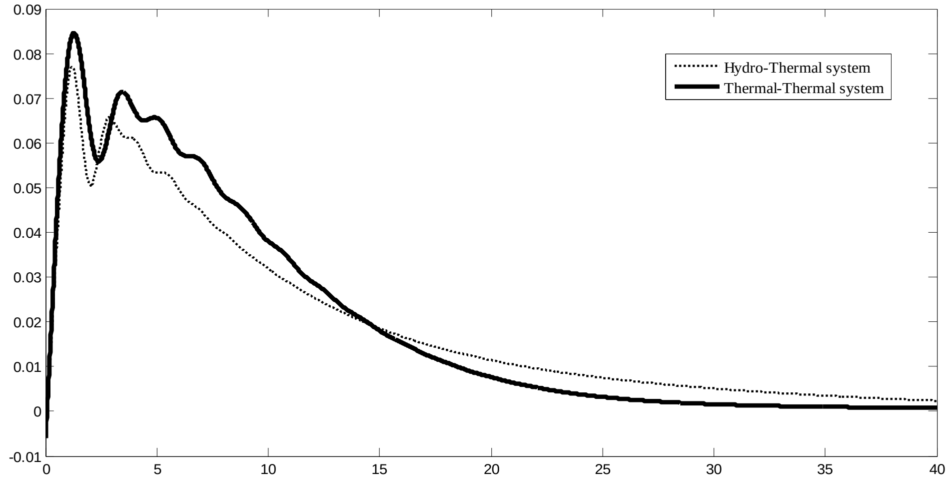

Fig. 3 (f) ΔPc_2 (p.u.MW) Vs Time (s)

Fig. 3: Dynamic responses of the frequency deviations, tie- line power deviations, and Control input deviations for a two area LFC system in the restructured scenario-2 (bilateral based transactions)

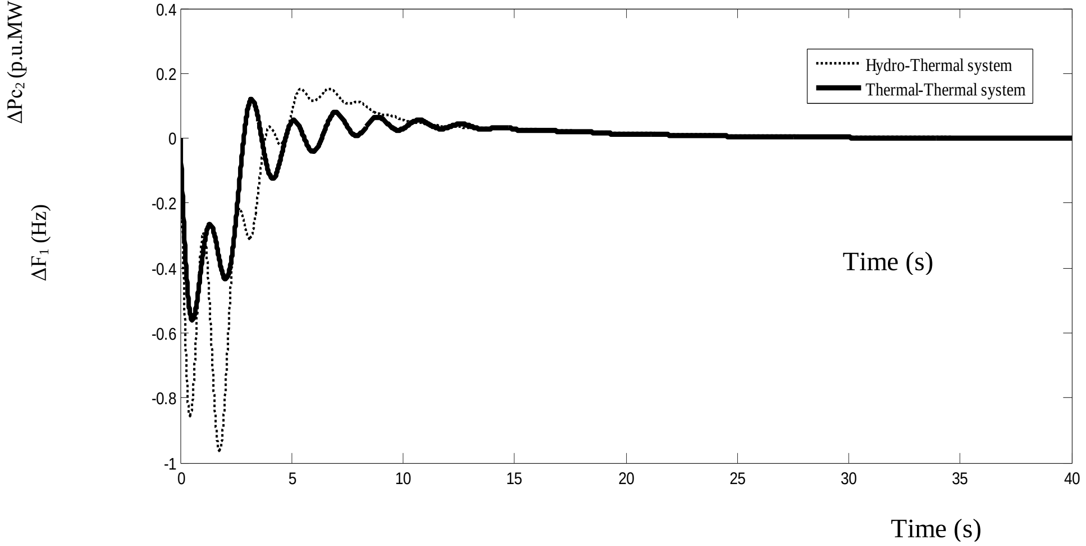

Fig. 4 (a) ΔF_1 (Hz) Vs Time (s)

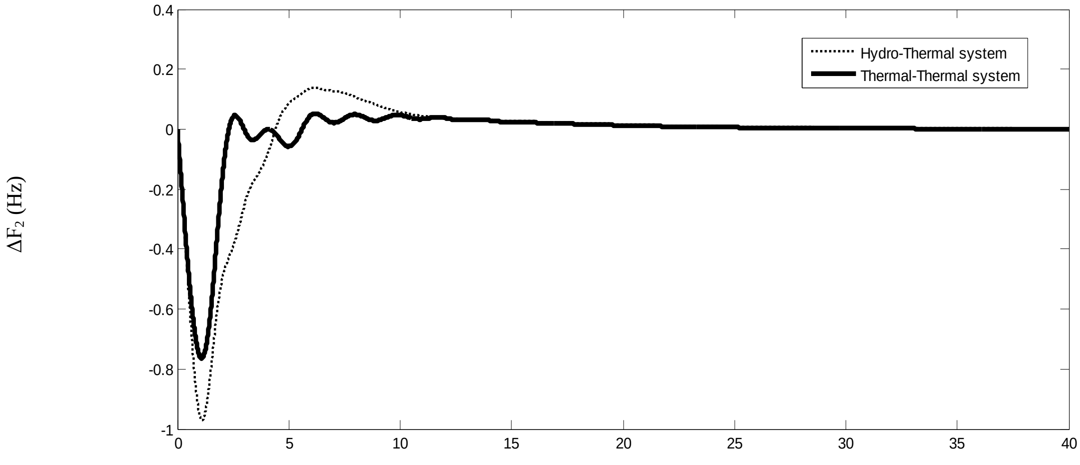

Fig. 4(b) ΔF_2 (Hz) Vs Time (s)

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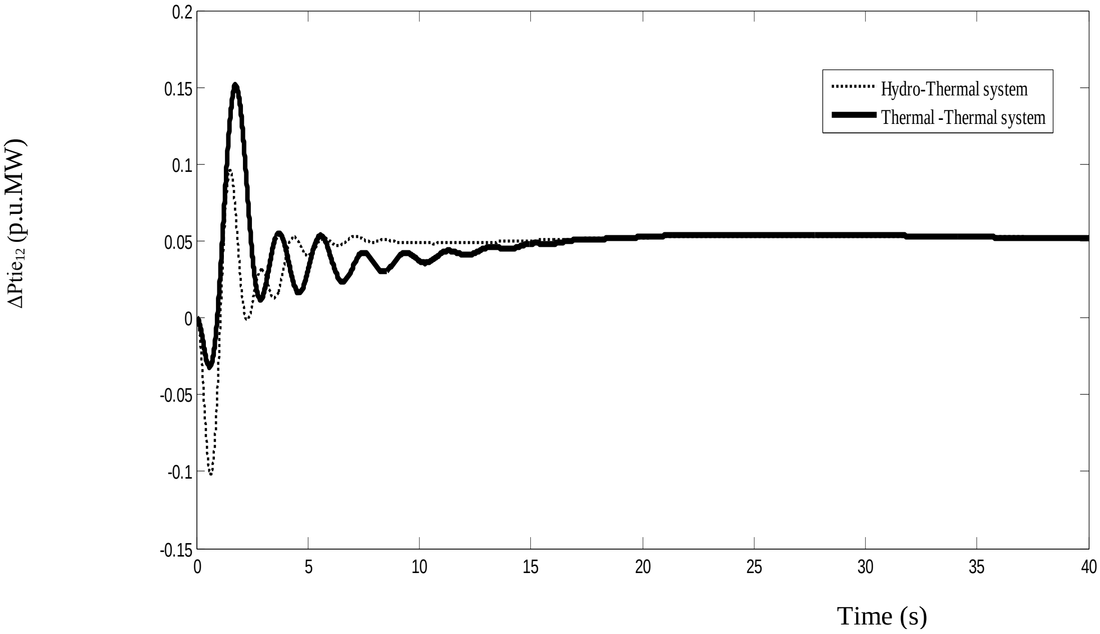

Fig.4 (c) ΔPtie$_{12, actual}$ (p.u.MW) Vs Time (s)

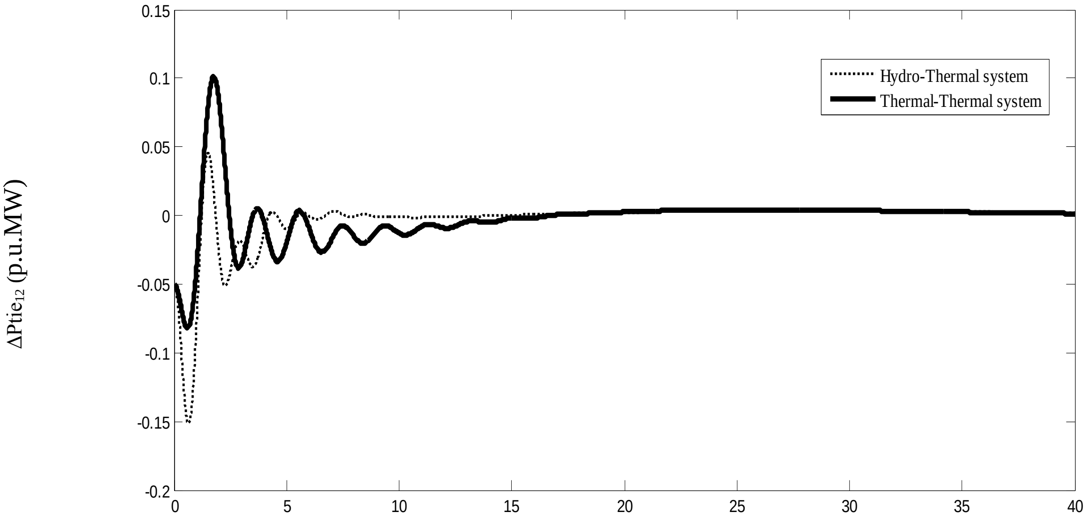

Fig.4(d) ΔPtie$_{12, error}$ (p.u.MW) Vs Time (s)

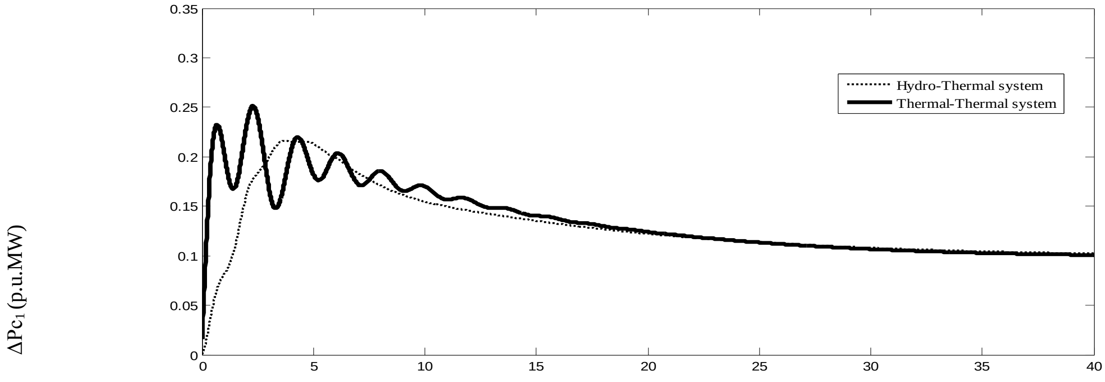

Fig.4 (e) ΔPc$_1$ (p.u.MW) Vs Time (s)

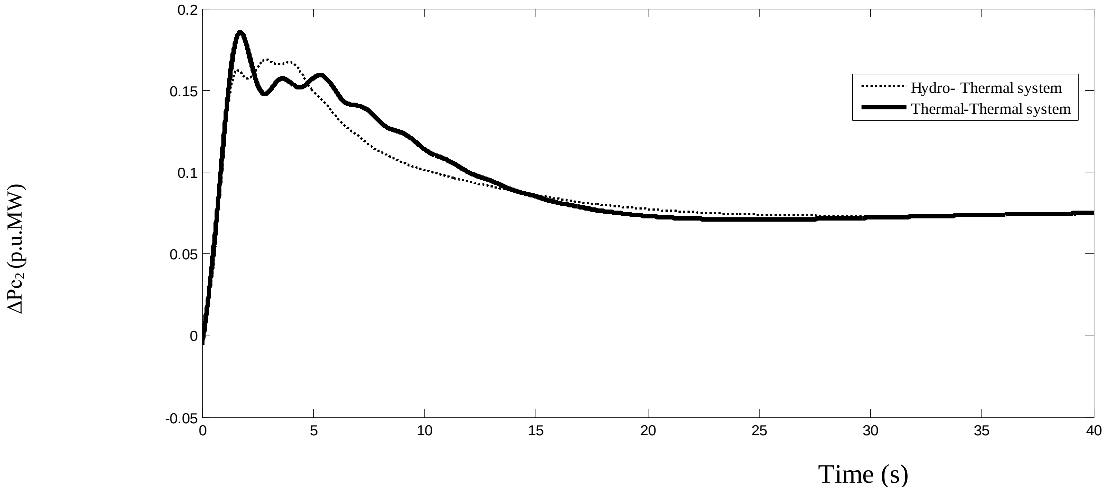

Fig.4 (f) ΔPc_2 (p.u.MW) Vs Time (s)

Fig. 4: Dynamic responses of the frequency deviations, tie- line power deviations, Control input deviations for a two area LFC system in the restructured (outage of Genco $_2$)

VII. CONCLUSION

The PI controllers are designed using BFO algorithm and implemented in two types of power system such as TAHTRIPS and TATRIPS. The effectiveness of the proposed method is tested on a two-area deregulated power system for a wide range of load demands and disturbances under different operating conditions. This BFO Algorithm is easy to implement without additional computational complexity, with quite promising results and ability to jump out the local optima. This paper proposes the design of various PSRI which indicates the requirements to minimize the frequency deviations, tie-line power deviation in a two-area interconnected restructured power system to ensure the reliable operation of the power system. In these PSRI can be utilized to help system operators in real time by suggesting relevant actions taken to completely automate the power system restoration. From the simulated results it is also observed that the restoration process for the Thermal generating unit requires more sophisticated control for a better restoration of the power system output responses and to ensure improved Power System Restoration Assessment Indices (PSRAI) in order to provide good margin of stability.

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A1. Control Area parameter [10]

Parameters	Area 1	Area 2
k_p (Hz/p.u.MW)	120	72
T_p (sec)	20	14.3
β (p.u.MW / Hz)	0.8675	0.785
T_{ij} (p.u.MW / Hz)	$T_{12} = 0.545$	
F (Hz)	60	
a_{12}	-1	

A2 Gencos Parameter (Thermal generating unit) [10]

MVA_{Base} (1000 MW) Parameters	Gencos (k in area i)			
	1-1	1-2	2-1	2-2
Rate (MW)	1000	1100	800	900
T_g (sec)	0.06	0.06	0.07	0.08
T_t (sec)	0.36	0.44	0.42	0.4
T_r (sec)	10	10	10	10
K_r	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

A3 Gencos Parameter (Hydro generating unit) using Electrical hydro governor [25]

Parameters	Value
Capacity (MW)	1000
R_2 (Hz /p.u.MW)	2.4
T_w (sec)	1.0
K_p	1.0
K_i	5.0
K_d	4.0