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Design of Decentralized Controller Gain Scheduling For Power System Restoration Assessment in an Interconnected Power System

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Abstract

The problem of restoration assessment in a Two-Area Two-Unit thermal Reheat Interconnected Power System (TATURIPS) has been investigated with spinning reserves such as Super conducting Magnetic Energy Storage device (SMES) and Gas Turbine (GT) units. The Proportional Integral (PI) controller gains are tuned using an Evolutionary Algorithm (EA) Particle Swarm Optimization (PSO) technique to find best parameter for the tuning of controller. Thus to exemplify the optimal parameter search PSO is used in an uncertainity area of the controller. Simulation results emphasis on the better settling time based stability performance of optimized PI controller in the TATURIPS with SMES / GT units when compared with that of the conventional controller in an interconnected power system.

Keywords: Particle Swarm Optimization, Multi-Area power systems, Gas Turbine, Super Conducting Magnetic Energy Storage Device, settling time.

1. Introduction

In an extremely complex and highly meshed power system the disturbances may be propagated over a vast area within a very short period of time. Even a simple incident may degenerate the system very rapidly into a large-scale breakdown. Therefore, it is necessary to anticipate any critical situation within a very few hours or minutes before the real time operation, preventing cascading and limiting its consequences for restoration of power system, which has to be carried out by implementing remedial actions [1]. Generally, ordinary controllers are designed with Proportional-Integral (PI) controllers. However, since the “I” control parameters are usually tuned, it is incapable of obtaining good dynamic performance for various load and system change scenarios. In literatures, many control strategies have been suggested based on conventional linear control theory, variable structure control, a lot of artificial intelligence based robust controllers such as genetic algorithm, tabu search algorithm, fuzzy logic and neural networks based robust controller are used for PI controller parameters tuning [2], [3]. Since, Particle Swarm Optimization algorithm is an optimization method that finds the best parameters for controller in the uncertainty area of controller parameters and obtained controller is an optimal controller, it has been used in almost all sectors of industry and science. One of them is the load-frequency control. In this study, it is used to determine the parameters of a PI controller according to the system dynamics, control over frequency, deviations, control the input and inter-area tie-power oscillations. By optimizing the values of proportional (K_p) and integral (K_i) gains, the output of the system frequency seems to be improved. In this simulation study the proposed controller is simulated for a TATURIPS. To show effectiveness of proposed method and also compare the performance of these two controllers, several changes in demand of first area, demand of second area and demand of two areas simultaneously are applied. Simulation results indicate that the overshoots and settling times with the proposed PSO-PID controller are better than the output of the conventional controller [4-9]. PSO controllers guarantee the good performance under various load conditions

The expert system, which is used to bring up the faulted power system to the target system which allows the estimation and observation of the real restoration time, the degree of stability, the observation of the system voltage profile, power to be transmitted is done by following tools [10].

1.1Generation Management: This tool is responsible for connecting generators. Firstly, it started by finding the smallest black start generator in the solution and then it connects the generators in accordance with the generator sequence given by the PSO-solution.

1.2 Restoration Path Management: In every step of connecting a generator or load, an optimized path algorithm is used to find the shortest path. Moreover the Path Management is used to check the loading limits of every line proposed for connection.

1.3 Time Management: Since one of the main goals of using the expert system is to estimate the real restoration time, great attention has been given to the time required for every element in every stage of restoration.

1.4 Load management: During restoration, loads are restored based on the load priorities and system security considerations. The priorities of loads are calculated in accordance to the load importance. If two loads are in the same degree of priority, the nearest one is picked. Moreover, if two or more loads are in the same degree of priority and in the same distance, the load with the highest level of connectivity is picked.

1.5 Role of expert system in this proposed work: The main objectives of expert system in knowledge based restoration are

- By providing initial source of power immediately to the interconnected power system with SMES and Gas Turbine units.
- By optimizing the gain values of the PI controller using PSO technique for the two-area interconnected power system with SMES and Gas Turbine units for system restoration.
- The primary function of the expert system is to restore the interconnected thermal reheat power system even for small disturbances and to avoid excess under frequency deviations.

2. Modeling of a two-area interconnected thermal reheat power system

Due to the inherent characteristics of changing loads, the operating point of power system may change very much during a daily cycle. The generation changes must be made to match the load perturbation at the nominal conditions, if the normal state is to be maintained.

The mismatch in the real power balance affects primarily the system frequency but leaves the bus voltage magnitude essentially unaffected. In a power system, it is desirable to achieve better frequency constancy than obtained by the speed governing system alone. This requires that each area should take care of its own load changes, such that schedule tie power can be maintained. A two-area interconnected system dynamic model in state variable form can be conveniently obtained from the transfer function model.

The state variable equation of the minimum realization model of the 'N' area interconnected power system is expressed as [11].

$$\dot{X} = Ax + Bu + \Gamma d \quad (2.1)$$

$$Y = Cx \quad (2.2)$$

Where, the system state vector x consists of the following variables as:

$$[x] = \left[\int ACE_1 dt, \int ACE_2 dt, \Delta F_1, \Delta P_{g1}, \Delta X_{e1}, \Delta P_{tie}, \Delta F_2, \Delta P_{g2}, \Delta X_{e2}\right]^T$$

$$u = [U_1, \ldots . U_N]^T = [\Delta P_{C1}, \ldots . \Delta P_{CN}]^T$$

N – Control input vector

$$d = [d_1, \ldots . d_N]^T = [\Delta P_{D1}, \ldots . \Delta P_{DN}]^T$$

N – Disturbance input vector

$$y = [y_1, \ldots . y_N]^T$$

2N – Measurable output vector

A is system matrix, B is the input distribution matrix and Γ disturbance distribution matrix, x is the state vector, u is the control vector and *d* is the disturbance vector of load changes of appropriate dimensions.The typical values of system parameters for nominal operation condition are given in appendix. This study focuses on optimal tuning of controllers for LFC and tie-power control, settling time based optimization using PSO algorithm to ensure a better power system restoration assessment. The aim of the optimization is to search for the optimum controller parameter setting that maximizes the minimum damping ratio of the system. On the other hand in this study the goals are control of frequency and inter area tie-power with good oscillation damping and also obtaining a good performance under all operating conditions and various loads and finally designing a low-order controller for easy implementation.

3. Modeling of a Gas turbine

Amid growing concerns about Green house emissions, Gas turbines have been touted as a viable option, due to their higher efficiency and the lower green house gas emissions compared to other energy sources and fast starting capability which enables them to be often used as peak units that respond to peak demands [12]. Also, they can be profitably used in power system restoration for supplying power to the restoration areas as they have the advantages like, Quick start-up/shut-down, Low weight and size, Cost of installation is less, Low capital cost, Black-start capability, High efficiency, Requires low cranking power, Pollutant emission control etc.

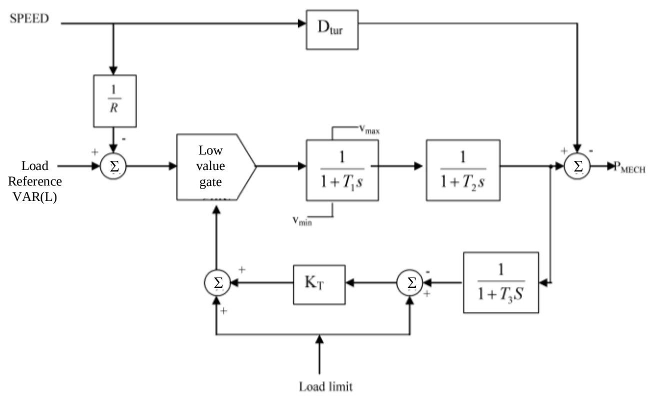


Figure 1. Gas Turbine Model

The continuous power plant output of a Gas turbine at the maximum depends upon frequency and temperature. It gives approximately two-thirds of the total power output of a typical combined cycle plant [13], [14]. When the load is suddenly increased the speed drops quickly, but the regulator reacts and increases the fuel flow to a maximum of 100% thereby improving the efficiency of the system. A model as shown in figure 1 has been implemented in the model used here.

4. Super Conducting Magnetic Energy Storage (SMES) device

The normal operation of a power system is continuously disturbed due to sudden small load perturbations. The problem lies in the fact that the inertia of the rotating parts is the only energy storage capacity in a power system. Thus, when the load-end of the transmission line experiences sudden load-end of the transmission line experiences sudden small load changes, the generators need continuous control to suppress undesirable oscillations in the control to suppress undesirable oscillations in the system.

The superconducting magnetic energy system is a fast acting device can swallow these oscillations and help in reducing the frequency and tie-line Power deviations for better performance of system disturbances. The Super conducting magnetic energy system is designed to store electric energy in the low loss superconducting coil. Power can be absorbed or released from the coil according to the system requirement. A super conducting magnetic energy storage(SMES) which is capable of controlling active and reactive power simultaneously has been expected as one if the most effective stabilizers of power oscillations [15].

Besides oscillation control, a SMES allows a load leveling, a power quality improvement and frequency stabilization. A typical SMES system includes three parts namely superconducting coil, power conditioning system and cooled refrigerator. From the practical point of view, a SMES unit with small storage capacity can be applied not only as a fast compensation device for power consumptions of large loads, but also as a robust stabilizer for frequency oscillations.

4.1. SMES Unit:

The schematic diagram in Figure 2 shows the configuration of a thyristor controlled SMES unit [16]. The SMES unit contains DC superconducting Coil and converter which is connected by Y–D/Y–Y transformer. The inductor is initially charged to its rated current I_{d0} by applying a small positive voltage. Once the current reaches the rated value, it is maintained constant by reducing the voltage across the inductor to zero since the coil is superconducting. Neglecting the transformer and the converter losses, the DC voltage is given by

$$E_d = 2Vd0 \cos \alpha - 2 I_d R_c \qquad (4.1)$$

Where E_d is DC voltage applied to the inductor (kV), firing angle (α), I_d is current flowing through the inductor (kA). R_c is equivalent commutating resistance (V) and V_{d0} is maximum circuit bridge voltage (kV). Charge and discharge of SMES unit are controlled through change of commutation angle α.

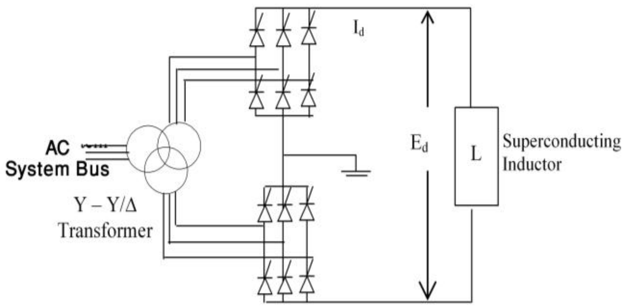


Figure 2. The schematic diagram of SMES unit

In AGC operation, the dc voltage E_d across the superconducting inductor is continuously controlled depending on the sensed area control error (ACE) signal. Moreover, the inductor current deviation is used as a negative feedback signal in the SMES control loop. So, the current variable of SMES unit is intended to be settling to its steady state value. If the load is used as a negative feedback signal in the SMES control demand changes suddenly, the feedback provides the prompt restoration of current. The inductor current must be restored to its nominal value quickly after a system disturbance, so that it can respond to the next load disturbance immediately . As a result, the energy stored at any instant is given by

$$W_L = L I_d^2/2 \quad MJ \qquad (4.2)$$

Where L = inductance of SMES, in Henry

Equations of inductor voltage deviation and current deviation for each area in Laplace domain are as follows:

$$\Delta E_{di}(s) = \left(\frac{K_{SMES}}{1+sT_{dci}}\right)\left[\beta_1 \Delta F_1(s) + \Delta P_{tie1}(s)\right] - \frac{K_{id}}{1+sT_{dci}} \Delta I_{di}(s) \qquad (4.3)$$

$$\Delta I_{di}(s) = (1/sL_i) * \Delta E_{di}(s) \qquad (4.4)$$

Where

- $\Delta E_{di}(s)$ = converter voltage deviation applied to inductor in SMES unit
- K_{SMES} = Gain of the control loop SMES
- T_{dci} = Converter time constant in SMES unit
- K_{id} = gain for feedback ΔId in SMES unit.
- $\Delta I_{di}(s)$ = inductor current deviation in SMES unit

The deviation in the inductor real power of SMES unit is expressed in time domain as follows:

$$\Delta P_{SMESi} = \Delta E_{di} I_{doi} + \Delta I_{di} \Delta E_{di} \qquad (4.5)$$

Figure 3 shows the block diagram of the SMES unit. To achieve quick restoration of the current, the inductor current deviation can be sensed and used as a negative feed back signal in the SMES control loop.

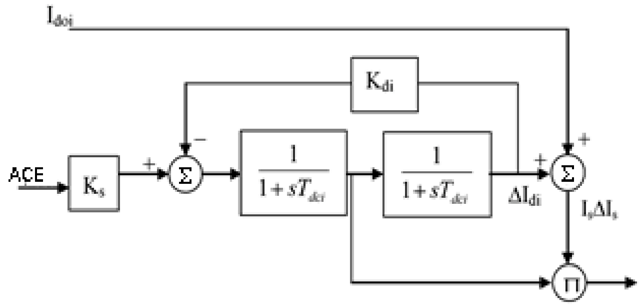


Figure 3. Block diagram of SMES unit

In a two-area interconnected thermal power system under study with the sudden small disturbances which continuously disturb the normal operation of power system. As a result the requirement of frequency controls of areas beyond the governor capabilities SMES is located in area1 absorbs and supply required power to compensate the load fluctuations.

Tie-line power flow monitoring is also required in order to avoid the blackout of the power system. The Input of the integral controller of each area is

$$ACE_i = \beta_i \Delta f_i + \Delta P_{tie\ i} \quad (4.6)$$

Where,

β_i = frequency bias in area i
Δf_i = frequency deviation in area i
$\Delta P_{tie\ i}$ = Net tie power flow deviation in area i

The application of energy storages to electrical power system can be grouped into two categories.

1. Like conventional pumped hydro plant storage meant for load leveling application.
2. To improve the dynamic performance of power system.

SMES have the following advantages like: The time delay during charge and discharging is quite short, Capable of controlling the both active and reactive power simultaneously, Loss of power is less, High reliability, High efficiency.

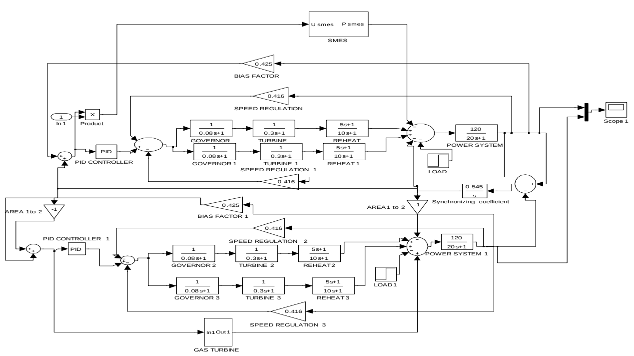


Figure 4. Simulink model of TATURIPS with SMES and GT units

5. Controller design using particle swarm optimization technique for the power system restoration problem

This is a population based search technique. Each individual potential solution in PSO is called particle. Each particle in a swarm fly around in a multidimensional search space based on its own experience and experience by neighbouring particles. Let in search space '*S*' in n-dimension with the swarm consists of 'N' particles. Let, at instant 't', the particle 'i' has its position defined by

$$X_t^i = \{x_1^i,\ x_2^i,\ \ .\ \ .\ \ .x_n^i\}$$

Velocity $V_t^i = \{v_1^i, v_2^i,\ \ .\ \ .\ \ .v_n^i\}$ in variable space '*S*'. Velocity and position of each particle in the next generation (time step) can be calculated as

$$V_{t+1}^i = \omega V_t^i + C_1.rand().\left(P_t^i - X_t^i\right) + C_2\ Rand()\left(P_t^g - X_t^i\right)$$

$$X_{t+1}^i = X_t^i + V_{t+1}^i$$

Where,

N - number of particle in swarm
ω - inertia weight
$C_1,\ C_2$ - acceleration constant
$rand()\ Rand()$ - Uniform random value in the range [0, 1]
P_t^i - best-position that particle '*i*' could find so far
P_t^g - global best at generation 't'

Performance of PSO depends on selection of inertia weight (ω), Max velocity ($V_{\max}$) and acceleration constant (C_1, C_2).

Effect of Inertia weight (ω)

Suitable weight factor helps in quick convergence. Large weight factor facilitates global exploration (i.e. searching of new area). While small weight factor facilitates local exploration (so wise to choose large weight factor for initial iterations and gradually smaller weight factor for successive iterations). Generally, ω 0.9 at beginning and 0.4 at end [17].

Effect of Max velocity ($V_{\max}$)

With no restriction on the max velocity of the particle, velocity may become infinitely large. If $V_{\max}$ is very low particle may not explore sufficiently. If $V_{\max}$ is very high it may oscillate about optimal solution. Therefore, velocity clamping effect has to be introduced to avoid '*swarm explosion*' [18]. Generally, max velocity is set as 10-20% of dynamic range of each variable. Velocity can be controlled within a band

$$V_{\max} = V_{ini} - \frac{V_{ini} - V_{fin}}{iter_{\max}}\ iter$$

Effect of Acceleration constant (C_1, C_2)

C_1 is called ***Cognitive Parameter*** which pulls each particle towards local best position. C_1, C_2 is called ***Social Parameter*** which pulls the particle towards global best position. Generally, C_1, C_2 are chosen between 0 to 4. The design steps of PSO based PI controller is as follows.

1. The algorithm parameters like number of generation, population, inertia weight and constants are initialized.
2. The values of the parameters K_P and K_i initialized randomly.
3. The fitness function of each particle in each generation is calculated.
4. The local best of each article and the global best of the particles are calculated.
5. The position, velocity, local best and global best in each generation is updated
6. Repeat the steps 3 to 5 until the maximum iteration reached or the best solution is found.

5.1 Simulink model of PSO Based PI Controller

The PSO algorithm is used to search an optimal parameter set containing K_p and K_i . The parameters used for tuning the PSO algorithm and simulink models are tabulated in table below:

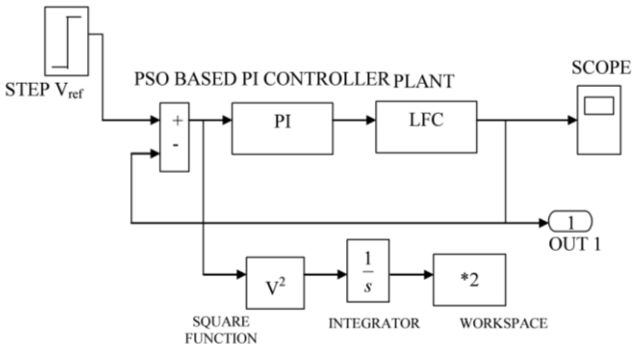


Figure 5. Simulink model of plant with PSO Algorithm based PI Controller

Table 1: ***Parameters values tuned for PSO***

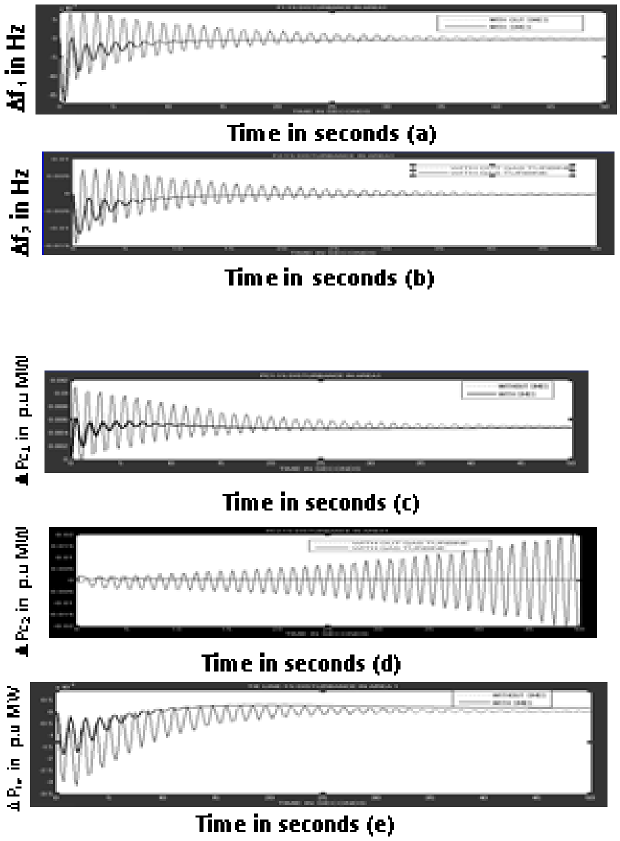
Parameters	**LFC**
Population size	5
Number of generations	10
Inertia weight (w)	0.8
Cognitive coefficient (C1)	2.05
Social coefficient (C2)	2.05

6. SIMULATION RESULTS

Table 2: Proportional plus Integral controller gains for 0.01p.u. MW step-load change in Area-1 and Area-2

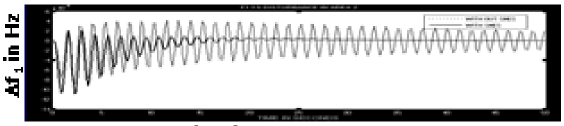
Power System	**Gain values**	
	K_P	**K_I**
Conventional in Area1&Area 2	0.95	0.30
With SMES in Area-1	0.52	0.26
With Gas Turbine in Area-2	0.65	0.24

CASE 1: Comparison of frequency deviations, control input requirements and tie-line power deviations in a two-area interconnected thermal reheat power system for 0.01p.u. MW load change in area-1.

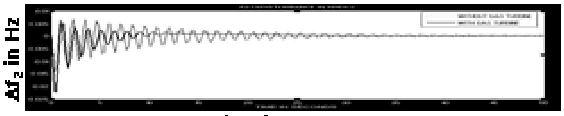


(a) Frequency deviation without and with SMES
(b) Frequency deviation without and with GT
(c) Control input requirement without and with SMES
(d) Control input requirement without and with GT
(e) Tie-line power deviations without and with SMES

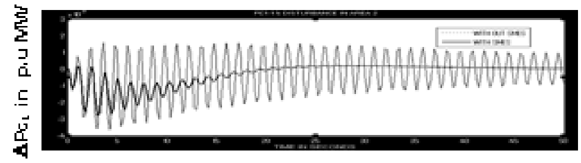
CASE 2: Comparison of frequency deviations, control input requirements and tie-line power deviations in a two-area interconnected thermal reheat power system for 0.01p.u. MW load change in area-2.

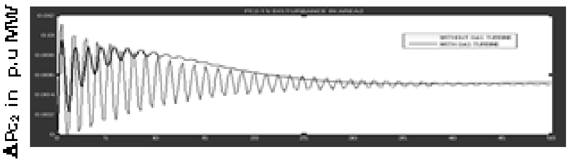


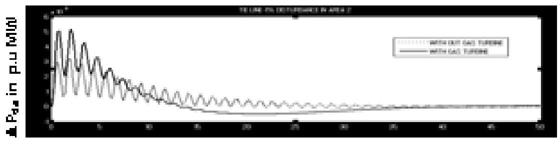
Time in seconds (a)



Time in seconds (b)







Time in seconds (e)

(a) Frequency deviation without and with SMES
(b) Frequency deviation without and with GT
(c) Control input requirement without and with SMES
(d) Control input requirement without and with GT
(e) Tie-line power deviations without and with GT

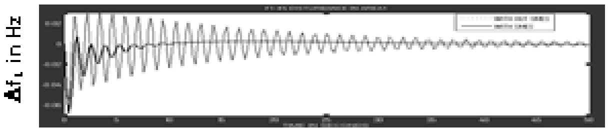
Area1 and Area2	Change in frequency H.Z	$\Delta Ptie_1$
Without SMES	More than 50 sec(ΔF_1)	More than 50 sec
With SMES	8 sec(ΔF_1)	12 sec
Without Gas turbine	More than 50 sec(ΔF_2)	More than 50 sec
With Gas turbine	15 sec(ΔF_2)	25 sec

Table 3: Settling Time (in seconds) of the output response without and with SMES and GT For 0.01p.u. MW step load change in area-1 and area-2 respectively.

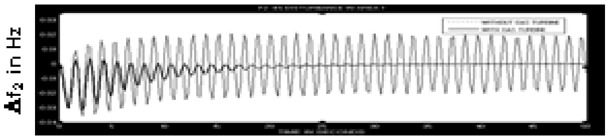
Table 4: Proportional plus Integral controller gains for 0.04p.u.MW step load change in Area-1 and Area-2

Power system	Gain values	
	K_P	K_I
Conventional in Area1&Area 2	0.98	0.22
With SMES in Area-1	0.64	0.15
With Gas turbine in Area-2	0.7	0.26

CASE 3: Comparison of frequency deviations, control input requirements and tie-line power deviations in a two-area interconnected thermal reheat power system for 0.04p.u. MW load change in area-1.



Time in seconds (a)



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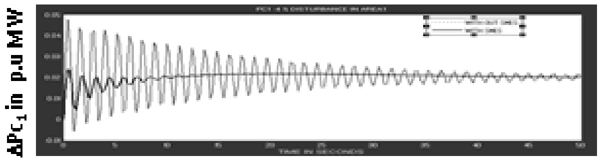
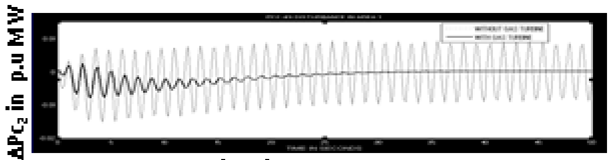
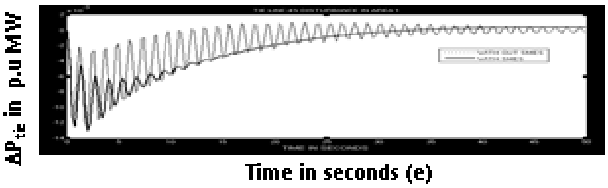


Time in seconds (c)



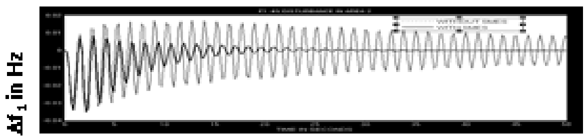
Time in seconds (d)



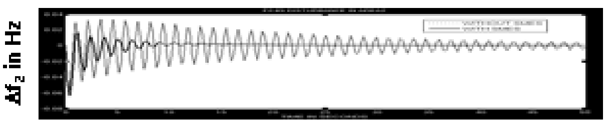
Time in seconds (e)

(a) Frequency deviation without and with SMES
(b) Frequency deviation without and with GT
(c) Control input requirement without and with SMES
(d) Control input requirement without and with GT
(e) Tie-line power deviations without and with SMES

CASE 4 : Comparison of frequency deviations, control input requirements and tie-line power deviations in a two-area Interconnected thermal reheat power system for 0.04p.u. MW load change in area-2.



Time in seconds (a)



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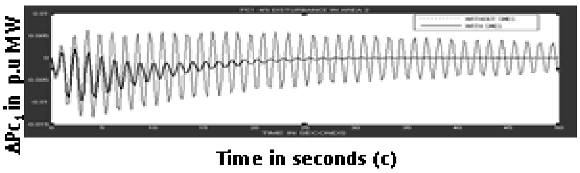
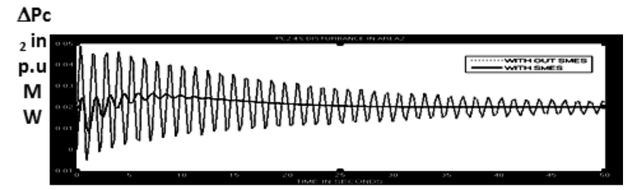
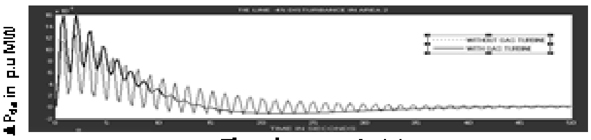


Time in seconds (c)



Time in seconds (d)



Time in seconds (e)

….. WITHOUT GAS TURBINE
—— WITH GAS TURBINE

(a) Frequency deviation without and with SMES
(b) Frequency deviation without and with GT
(c) Control input requirement without and with SMES
(d) Control input requirement without and with GT
(e) Tie-line power deviations without and with GT

Area1 and Area 2	**Change in frequency H.Z**	**$\Delta Ptie_1$**
Without SMES	More than 50 sec(ΔF_1)	More than 50 sec
With SMES	9 sec(ΔF_1)	18sec
Without SMES	More than 50 sec(ΔF_2)	More than 50 sec
With SMES	10 sec(ΔF_2)	18 sec

5Table 5: Settling Time (in seconds) of the output response without and with SMES and Gas turbine. For 0.01p.u. MW step load change in area-1 and area-2 respectively.

CONCLUSION

In this paper a PSO controller by considering SMES and GT units as spinning reserves for power system restoration problem has been designed. It is clear from the simulation results that the transient responses of frequency and tie-line, better system control has been achieved using the spinning reserves along with the global optimization controller for restoring the system. There is improvement of the dynamic performance of TATURIPS attaining the restoration of the system under consideration in a short duration of time. Hence, the proposed controller yields good transient response with a minimum settling time and further, this work is being extended with the consideration of the system non-linearity.

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Appendix

Data for TATURIPS [11]

$Pr_1=Pr_2=2000MW$
$Kp_1=Kp_2=120Hz/p.u$
$Tp_1=Tp_2=20sec.$
$Tp_1=Tt_2=0.3$ sec.
$Tg_1=Tg_2=0.08sec.$
$Kr_1=Kr_2=0.5$
$Tr_1=Tr_2=10$ sec.
$R_1=R_2=2.4Hz/p.u$ MW.
$a_{12}=-1$
$T_{12}=0.545$ p.u MW/Hz
$\beta_1 = \beta_2 = 0.425$ p.u. MW/Hz

Data for the SMES unit [15]

L=2.65H
$T_{dc}=0.03$ sec
$I_{do}=4.5KA$
$K_{id}=0.2$ KV/KA
$K_{SMES}=100KV/unit$ MW

Data for the Gas turbine model [12]

$T_1=10$ sec
$T_2=0.1sec$
$T_3= 3sec$
$K_t=1$
$K_r=0.04$
Dturb=0.03
Maximum and minimum valve position = 1and -0.1

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