

Decentralized controller gain scheduling using PSO for power system restoration assessment in a two-area interconnected power system

R. Jayanthi^{1*}, I. A. Chidambaram², C. Banusri³

^{1*} Department of Electrical Engineering, Annamalai University, Annamalainagar -608002, INDIA

² Department of Electrical Engineering, Annamalai University, Annamalainagar -608002, INDIA

³ Department of Electrical Engineering, Jaya College of Engineering, Avadi, Chennai, INDIA

* Corresponding Author: e-mail: rrj_pavi@yahoo.co.in, Tel +91-4144-237092

Abstract

Load Frequency Control (LFC) is one of the most important issues in electrical power system design/operation and is becoming much more significant recently with increasing size, changing structure and complexity in restoration of interconnected power systems. In practice, LFC systems are used with simple Proportional-Integral (PI) or Integral (I) controllers. However, since the PI or I control parameters are usually tuned based on classical or trial-and-error approaches, they are incapable of obtaining good dynamic performance if the power system is more vulnerable due to various load changing scenarios in multi-area power system. For this reason, in this study the P and I control parameters are tuned based on Particle Swarm Optimization (PSO) algorithm for a better Load-Frequency Control in a Two-Area Two-Unit Thermal Reheat Power System (TATURIPS) with step load perturbation. To exemplify the optimum parameter search PSO is used as it is an optimization method, therefore, even in the uncertainty area of controller parameters, finds the best parameters for controller and obtained controller is an optimal controller. This makes a trade-off between exploration and exploitation of search space to find global optimum in less number of generations. A TATURIPS is taken for the study to illustrate the proposed method. To show effectiveness of proposed method, the performance of optimized PI controller is obtained with several time-domain simulations for various load changes scenarios and is presented. Simulation results emphasis on the better settling time based stability performance of optimized PI controller in the TATURIPS with GT unit when compared with that of the SMES and the conventional system two-unit two-area interconnected power systems.

Keywords: Load Frequency Control, Particle Swarm Optimization, TATURIPS, Gas Turbine, Super Conducting Magnetic Energy Storage Device.

1. Introduction

Large-scale power systems are normally composed of interconnected subsystems or control areas. The connection between the control areas is done using tie-lines. Each area has its own generator or group of generators and it is responsible for its own load and scheduled interchanges with neighboring areas. Because loading of a given power system is never constant and to ensure the quality of power supply, a load frequency controller is needed to maintain the system frequency at the desired nominal value. It is known that changes in real power affect mainly the system frequency and the input mechanical power to generators is used to control the frequency of the output electrical power. In a conventional power system, each control area contains different kinds of uncertainties and various disturbances due to increased complexity, system modeling errors and changing power system structure. A well designed power system should not only cope up with changes in load but also with system disturbances and it should provide acceptable high level of power quality while maintaining both voltage and frequency within tolerable limits (Wang Y, et al, 1998). During the last three decades, various control strategies for LFC have been proposed. This extensive research is due to the fact that LFC constitutes an important function on power system operation where the main objective is to regulate the output power of each generator at prescribed levels while keeping the frequency fluctuations within pre-defined limits. Robust adaptive

control schemes have also been developed (Yamashita. et al, 1991, Pan et al., 1989, Aldeen et al., 1991) to deal with changes in system parametric under LFC strategies. Viewing a multi-area power system under LFC as a decentralized control design for a multi-input multi output system, it has been shown that a group of local controllers with tuning parameters can guarantee the overall system stability and performance. The result reported in Lim et al. (1996) demonstrates clearly the importance of robustness and stability issues in LFC design. The applications of artificial neural networks, genetic algorithms, fuzzy logic and optimal control to LFC have been reported in (Shayegi et al, 2007, Shayeghi. et al., 2007, Chao ou, et al, 2006). The objective of this study is to investigate the load frequency control, of a multi-area power system taking into consideration of various level of step sized loading to assess the requirements for power system restoration. An optimal control scheme based particle swarm optimization (PSO) Algorithm method is used for tuning the parameters of PI controller (S.P. Ghoshal, 2004). The proposed controller is simulated for a two-area two-unit thermal reheat power system and the output responses of the system with respect to the settling time has been studied. To show the effectiveness of proposed method and also to 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 controllers designed using PSO approach guarantees good performance under various load conditions. The expert system, which is used to bring up the vulnerable power system to a normal 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 can be done using the following tools (Adibi et al., 1994).

1.1 Generation Management: This tool is responsible for making the generators to commit for the optimal generation. 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 provided 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 unit.
- By optimizing the gain values of the PI controller using PSO technique for the two-area interconnected power system with SMES unit 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. Figure 1 represents the transfer function model of a two-area reheat thermal system.

The state variable equation of the minimum realization model of the ‘N’ area interconnected power system is expressed as (Chidambaram et al., 2005).

$$\dot{X} = Ax + Bu + \Gamma d \tag{1}$$

$$Y = Cx \tag{2}$$

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

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

$$u = [u_1, \dots, u_N]^T = [\Delta P_{c1}, \dots, \Delta P_{cN}]^T \quad N - \text{Control input vector}$$

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

N – Disturbance input vector

$$y = [y_1, \dots, y_N]^T$$

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.

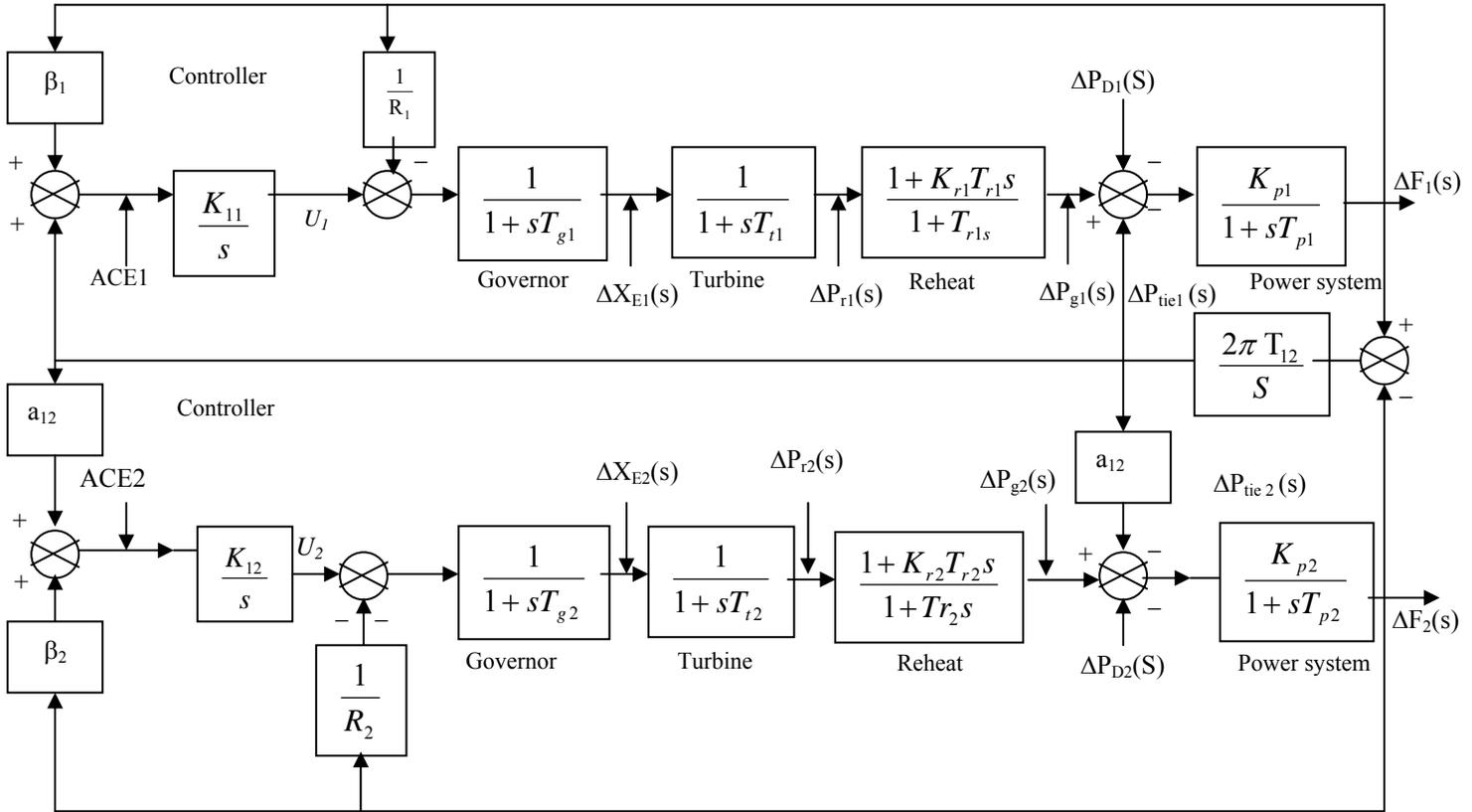


Figure 1. Transfer function model of two-area reheat thermal system

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 with 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. The gain values and their respective settling time for both 1% and 4% in area1 and area 2 are given in tables 2,3,4 & 5 respectively.

3. Modeling of a Gas turbine

Amid growing concerns about Green house emissions, Gas turbines have been treated 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(Soon klat yee et al, 2008). 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.,

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 (S. Barsali, et al 2008, M. Nagpal, et al, 2001). 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 fig 2 has been incorporated in the system under study.

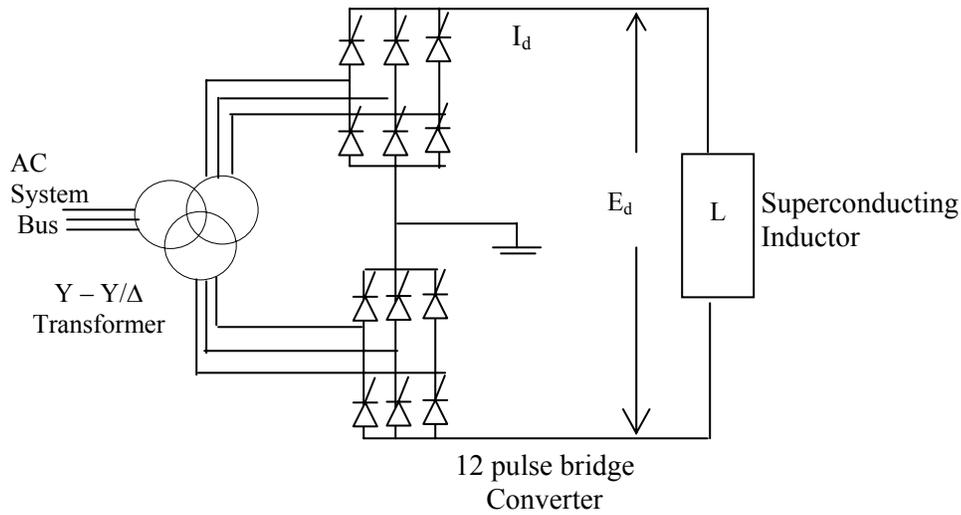


Figure 3. The schematic diagram of SMES unit

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

$$W_L = LI_d^2 / 2 \quad \text{MJ} \quad (4)$$

Where L = inductance of SMES, in Henry

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

$$\Delta E_{di}(s) = \left(\frac{K_{SMES}}{1 + sT_{dei}} \right) [\beta_1 \Delta F_1(s) + \Delta P_{tie1}(s)] - \frac{K_{id}}{1 + sT_{dei}} \Delta I_{di}(s) \quad (5)$$

$$\Delta I_{di}(s) = (1/sL_i) * \Delta E_{di}(s) \quad (6)$$

Where

$\Delta E_{di}(s)$ = converter voltage deviation applied to inductor in SMES unit

K_{SMES} = Gain of the control loop SMES

T_{dei} = converter time constant in SMES unit

K_{id} = gain for feedback ΔI_d 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

$$\Delta P_{SMESi} = \Delta E_{di} I_{doi} + \Delta I_{di} \Delta E_{di} \quad (7)$$

Figure 4 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 feedback signal in the SMES control loop.

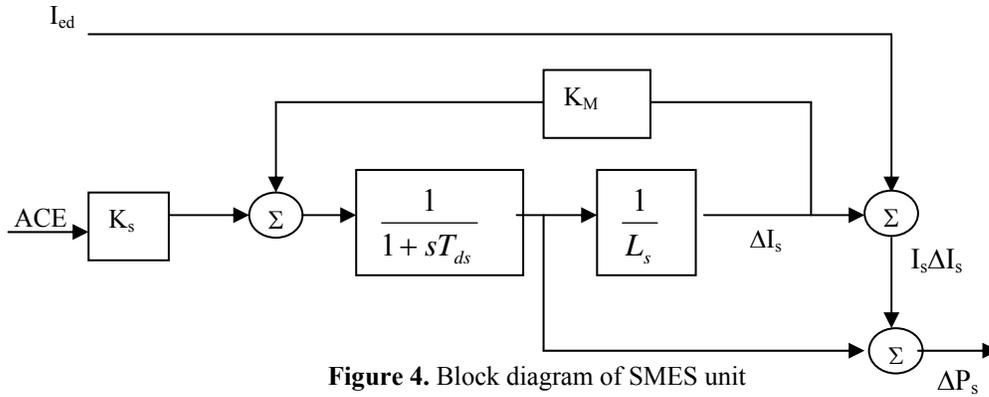


Figure 4. Block diagram of SMES unit

In a two-area interconnected thermal power system under study (as shown in Fig 5) with the sudden small disturbances which continuously disturb the normal operation of power system.

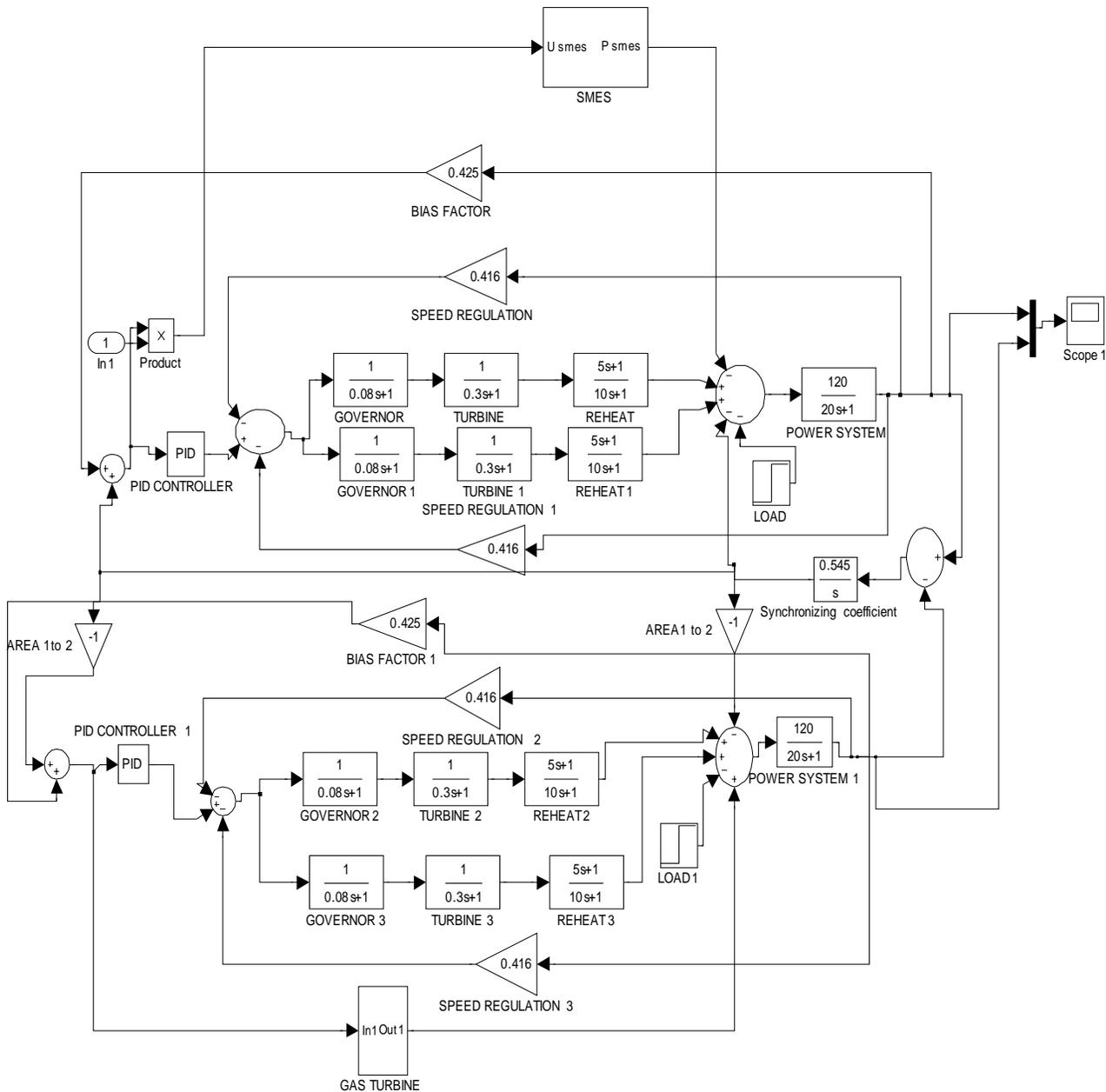


Figure 5. Simulink model of TATURIPS with SMES and Gas Turbine units

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 (Issarachi Nagamroo, 2005, A.Demiroren, et al, 2003, A. Demiroren et al 2004).

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

$$ACE_i = \beta_i \Delta f_i + \Delta P_{tie\ i} \quad (8)$$

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.

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 neighboring 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

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

Velocity $V_t^i = \{v_1^i, v_2^i, \dots, v_n^i\}$ in variable space 'S'

- Velocity and position of each particle in the next generation (time step) can be calculated as

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

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

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 (Y. Shi et al, 1998)

▪ 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’ (J. Kennedy et al, 2001)
- Generally, max velocity is set as 10-20% of dynamic range of each variable.
- Velocity can be controlled within a band

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

▪ **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

Figure 6. shows the simulink model of the plant with PSO algorithm 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 and Fig. 7 represents the corresponding flow chart:

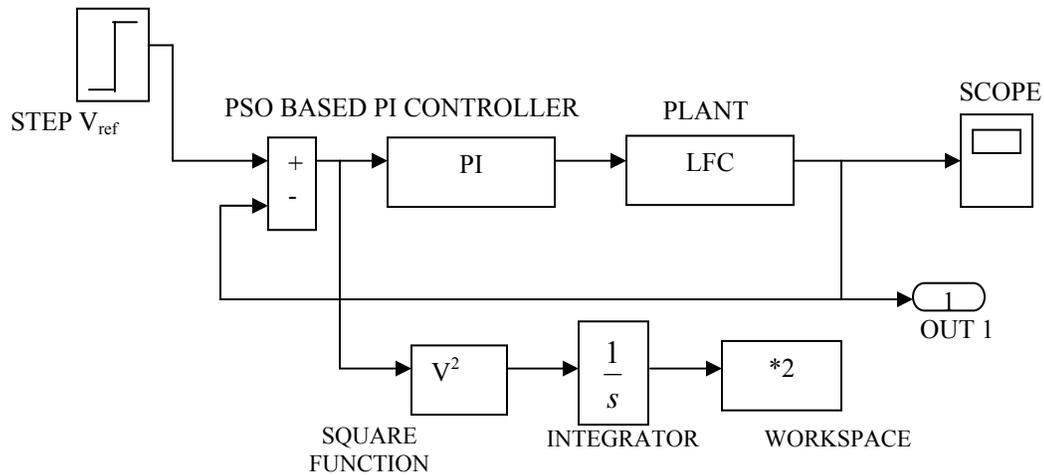


Figure 6. Simulink model of plant with PSO Algorithm based PI Controller

Table 1. Parameter values tuned for PSO algorithm

Parameters	Value
Population size	5
Number of generations	10
Inertia weight (ω)	0.8
cognitive coefficient (C1)	2.05
social coefficient (C2)	2.05

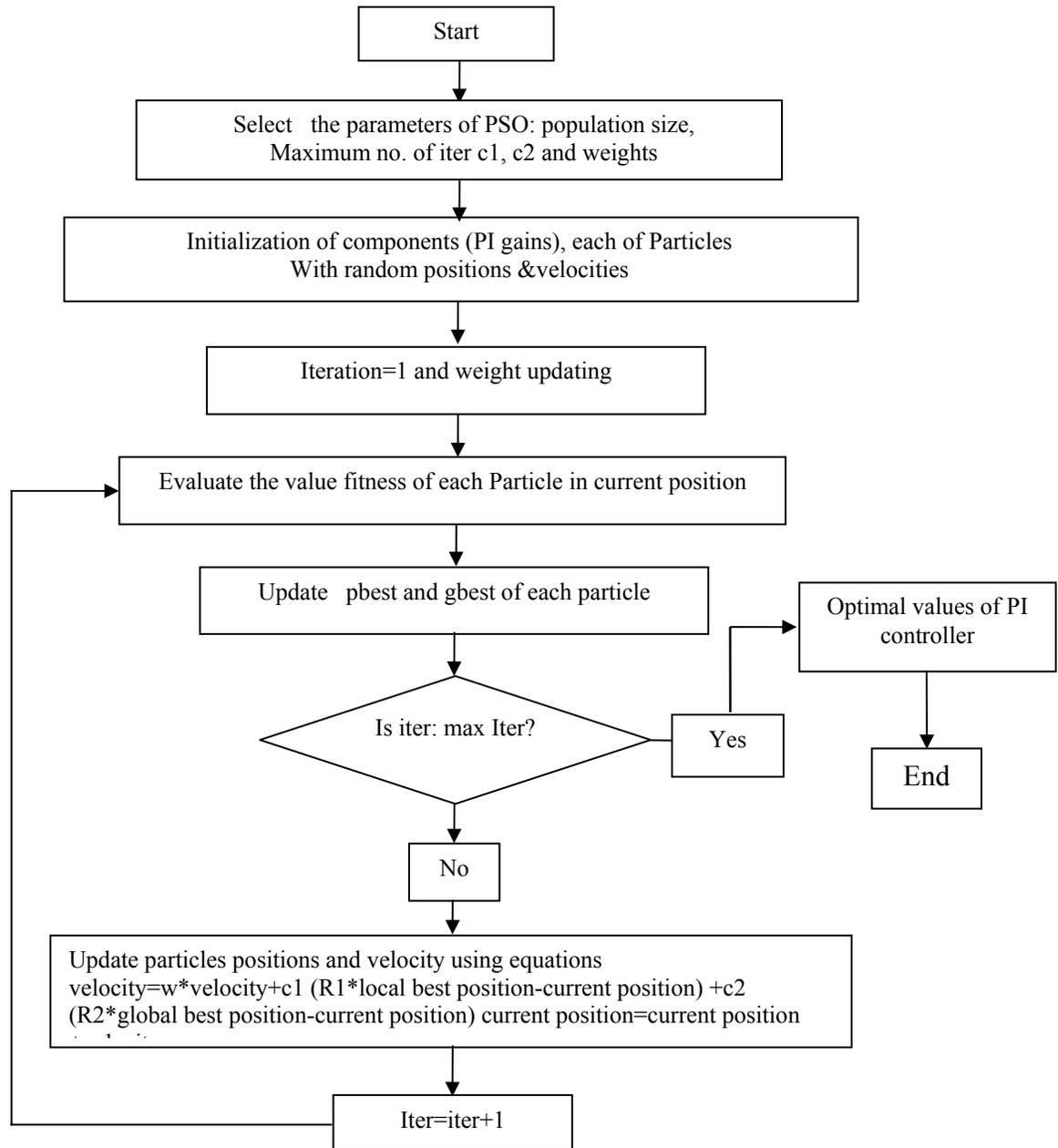
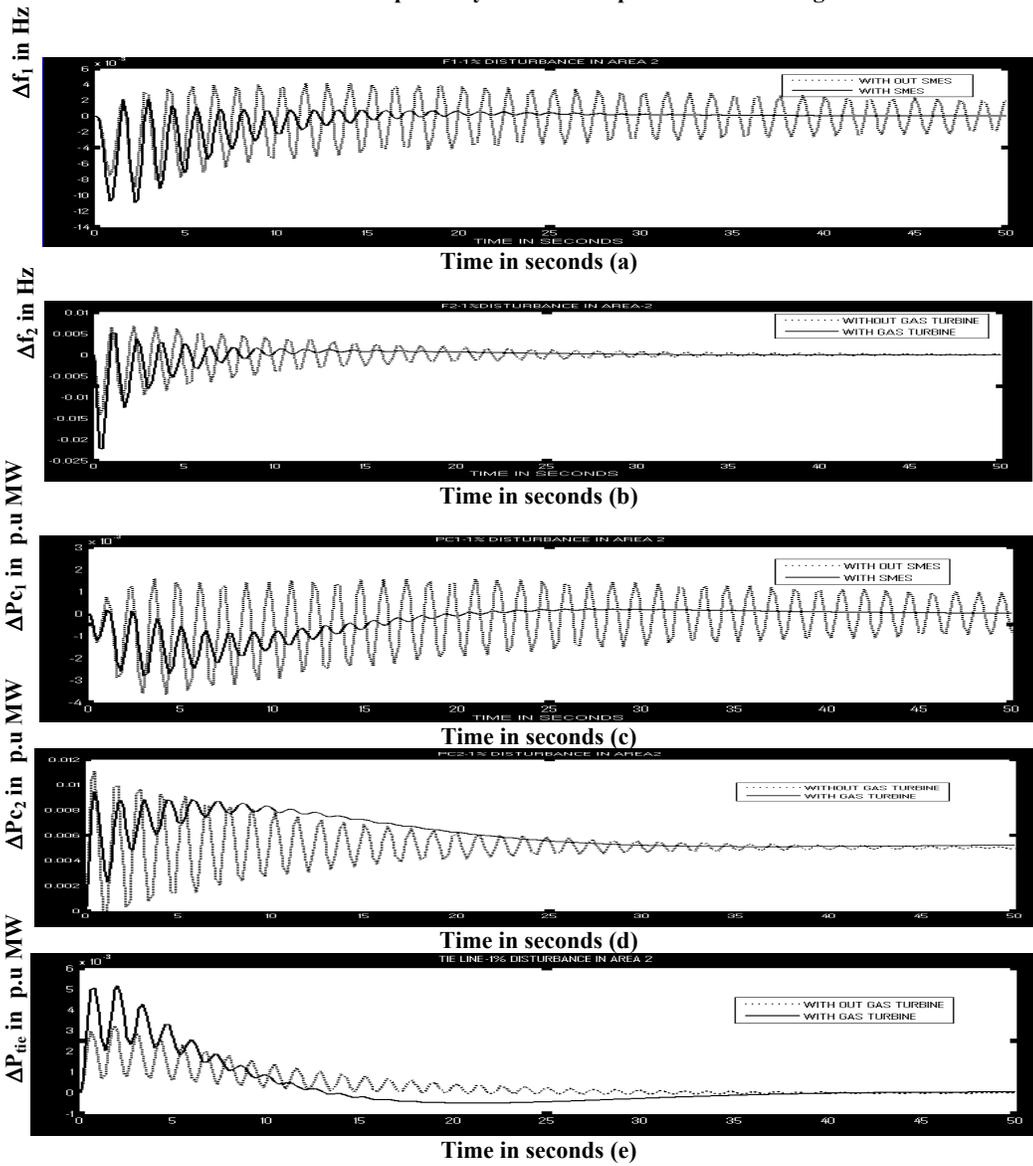


Figure 7: Flowchart for PSO

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

Power system	Gain values	
	K _p	K _i
Conventional in Area1 & 2	0.95	0.30
With SMES in Area-1	0.52	0.26
With GT 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-2.



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

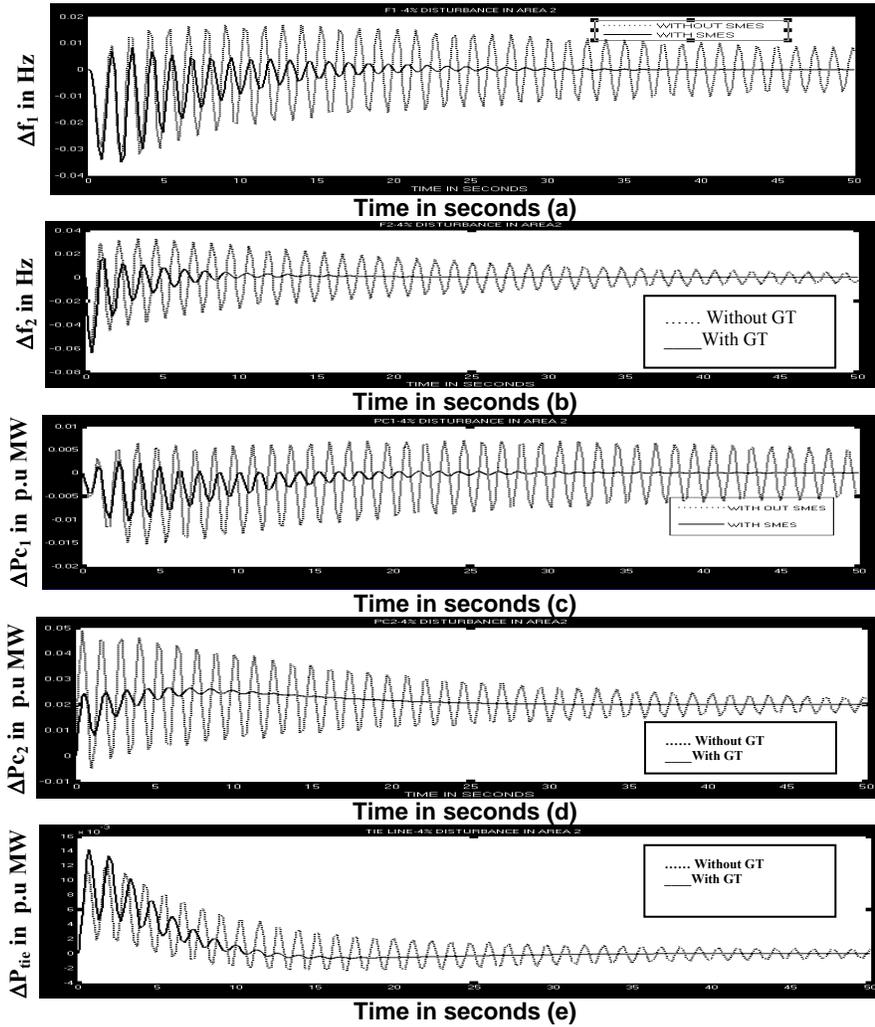
Table 3: Settling Time (in seconds) of the output response without and with GT For 0.01p.u. MW step load change in area-2

Power System	Change in frequency H.Z	ΔP_{tie1}
Without GT	More than 45 sec. (ΔF_2)	More than 50 sec
With GT in area-2	13 sec. (ΔF_2)	12 sec
Without SMES	More than 50 sec. (ΔF_1)	More than 50 sec
With SMES in area-1	25 sec. (ΔF_1)	13 sec.

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

Power system	Gain values	
	K_p	K_i
Conventional in Area 1 & 2	0.98	0.22
With SMES in Area-1	0.64	0.15
With GT in Area-2	0.7	0.26

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



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

Table 5: Settling Time (in seconds) of the output response without and with GT For 0.04p.u. MW step load change in area-2

Power System	Change in frequency H.Z	ΔP_{tie1}
Without GT	More than 45 sec. (ΔF_2)	More than 50 sec
With GT	12 sec(ΔF_2)	13 sec
Without SMES	More than 50 sec. (ΔF_1)	More than 50 sec
With SMES	35 sec. (ΔF_1)	18 sec.

6. Conclusion

In this work a novel heuristic search technique (i.e.) PSO based controllers are designed and implemented in a two-area two-unit thermal reheat power system with GT in area 2 and SMES in area 1 by optimizing the gain values of the PI controller to restore the frequency and tie-line power deviations due to various step-load changes in area 2. The output response of the system reveals that reduced peak overshoots, minimum settling time are obtained thereby maintaining the stability of the system under study to greater extent when comprised with GT unit. Using this global optimization controller the improvement of the dynamic performance of TATURIPS is found to be very clear in attaining the restoration of the system under consideration. The proposed controller yields good transient response with a minimum settling time. Further, this work is being extended with the consideration of the system non-linearities.

APPENDIX

Data for the two-area interconnected thermal power system with reheat turbines (Chidambaram I.A et al., 2005)

$P_{r1}=P_{r2}=2000\text{MW}$
 $K_{p1}=K_{p2}=120\text{Hz/p.u}$
 $T_{p1}=T_{p2}=20\text{sec.}$
 $T_{t1}=T_{t2}=0.3\text{ sec.}$
 $T_{g1}=T_{g2}=0.08\text{sec.}$
 $K_{r1}=K_{r2}=0.5$
 $T_{r1}=T_{r2}=10\text{ sec.}$
 $R_1=R_2=2.4\text{Hz/p.u MW.}$
 $a_{12}=-1$
 $T_{12}=0.545\text{ p.u MW/Hz}$
 $\beta_1 = \beta_2 = 0.425\text{ p.u. MW/Hz}$

Data for the SMES unit (Demiroren.A 2002)

$L=2.65\text{H}$
 $T_{dc}=0.03\text{ sec}$
 $I_{d0}=4.5\text{KA}$
 $K_{id}=0.2\text{ KV/KA}$
 $K_{SMES}=100\text{KV/unit MW}$

Data for the Gas turbine model (Soon klat yee et al., 2008)

$T_1=10\text{ sec}$
 $T_2=0.1\text{sec}$
 $T_3= 3\text{sec}$
 $K_t=1$
 $K_r=0.04$
 $D_{turb}=0.03$

Maximum and minimum valve position = 1 and -0.1

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Biographical Notes

R. Jayanthi received her B.E and M.E degrees from Faculty of Engineering and Technology, Annamalai University, Annamalai Nagar, Chidambaram, India in 1994 and 2007 respectively. Currently working as an Assistant Professor in Department of Electrical and Electronics Engineering since 2007. She is currently working towards the Ph.D degree. Her research interest includes power system operation and control.

Dr. I. A. Chidambaram (1966) received Bachelor of Engineering in Electrical and Electronics Engineering (1987) Master of Engineering in Power System Engineering (1992) and Ph.D in Electrical Engineering (2007) from Annamalai University, Annamalainagar. During 1988 - 1993 he was working as Lecturer in the Department of Electrical Engineering, Annamalai University and from 2007 he is working as Professor in the Department of Electrical Engineering, Annamalai University, and Annamalai Nagar. He is a member of ISTE and Indian Science Congress (ISC). His research interests are in power systems, electrical measurements and control systems. (Electrical Measurements Laboratory, Department of Electrical Engineering, Annamalai University, Annamalai Nagar-608002, TamilNadu, India, Tel: -91-04144-238501, Fax:-91-04144-238275) driacdm@yahoo.com/ driacdm@gmail.com

C. Banusri is currently working as a Lecturer in Jaya College of Engineering, Avadi, Chennai, and received her B.E and M.E. degrees from Mailam Engineering College affiliated to Madras University (2002) and Annamalai University (2010) respectively. Her areas of interest are power system modeling and control.

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