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Design of Particle Swarm Optimization Based PI Controller for an Isolated Wind - Diesel Hybrid Power System with Superconducting Magnetic Energy Storage Unit

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Abstract

A design of particle swarm optimization based PI controller for an isolated wind-diesel hybrid power system with superconducting magnetic energy storage unit is proposed in this work. The hybrid power system is normally equipped with a control system, which functions to reduce the system frequency oscillations and makes the wind turbine generator output follow the performance curve when the system is subjected to wind/load disturbances. Usually PI controllers are employed in these systems. Since the operating point continuously changes depending on the demand of consumers, these constant gain PI controllers are unsuitable for other operating points. Hence the problem of tuning of PI controller is formulated as an optimization problem which is solved by particle swarm optimization (PSO) technique that has a strong ability to find the most optimistic results.

1.Introduction

Electrical energy demand is increasing constantly and this demand has to bemet by a planned electrical power generation programme. Although electrical energy is environmentally the most benign form of energy, its production is routed through burning of conventional fossil fuels or nuclear energy or hydro resources. All of these, in addition to other disadvantages, give rise to environmental issues of varied nature. To minimize the environmental degradations, one of the solutions is to utilize wind energy in favorable remote sites, away from the centralized energy supply systems [1].

However, the wind power generation has its own characteristics that are different from the existing generation systemssuch as the wind dependence caused inconsistency in the generation of electric power. A wind power station may be fully supplying an 'autonomous' load at one moment and may be in considerable power deficitonly seconds later. Thus wind power generation introduces uncertainity in operating a power system and it is continuously variable and difficult to predict. Since wind power varies randomly there must be a stand-by power source to meet load demand. Hence there is a need for some magic formula such as wind combined with diesel [2].

Wind and diesel system is one of thehybrid systems utilizing more than one energy source. Hybrid power systems area combinationof twoor more electrical powersources where at least one of them is a renewable one. A hybrid wind and diesel system is quite reliable because the diesel acts as a cushion to take care of variation in wind speed and would always provide power equal to load power minus the wind power. Usually, diesel generator installed capacity is sized to meet the peak power demand, but is used in practice to supply power only when the wind power is insufficient to meet the load demand. But a simple diesel back-up may not be sufficient.

The operation of diesel generator set for extended periods at low power level (less than 50%)could result in engine damage together with a reductionin engine life time. So, a simple diesel generator back – up may not be sufficient and there is a need for reliable energy storage medium. In case of strong wind or less demand the excess energy can be stored in energy storage unit which can share the sudden changes in power requirements.

Energy storage is an attractive option to augment demand side management implementation. By using energy storage systems, a low cost source of electricity can be efficiently provided to meet the peak demand. An energy storage device can be charged during off-peak periods and the stored energy is used during peak periods [3].

SMES is suggested as storage unit for improving the dynamic performance of wind-diesel hybrid power systems. An SMES unit is a device that stores energy in the magnetic field generated by the dc current flowing through a superconducting coil [4]. During high wind speed and less load demand the excess energy will be stored in themagnets with superconductive windings of SMES unit. A Fast acting energy storage such as SMEScan effectivelydamp out electromechanical oscillations in a power system, because it provides storage capacity in addition to kinetic energy of the generator rotor, which can share the sudden changes in power requirement.

The isolated wind- diesel hybrid power system with superconducting magnetic energy storage unit is normally equipped with a control system, which functions to reduce the system frequency oscillations and makes the wind turbine generator power output follow the performance curve when the system is subjected to wind / loaddisturbances. Usually PI controllers are employed in these systems. These PI controllers result in relatively large overshoots in transient frequency deviations. Further, the settling time of the system frequency deviation is also relatively high.

Particle swarm optimization (PSO) as one of the modern heuristic algorithms is a population based evolutionary algorithm. Unlike population based evolutionary algorithms, PSO is motivated by the simulation of social behavior instead of survival of the fittest, and each candidate solution is associated with a velocity. The candidate solution called the “particles” then “fly” through the search space. The velocity is constantly adjusted according to the corresponding particle’s experience and the particle’s companion’s experiences. It is expected that the particles will move towards better solution areas. Hence this thesis describes the application of particle swarm optimization (PSO) based PI controller for an isolated wind – diesel hybrid power system with superconducting magnetic energy storage unit.

2. Development of mathematical model of an isolated wind-diesel hybrid power system with SMES unit

2.1 Transfer function model

Since the system is exposed to a small change in load during its normal operation, the linear model will be sufficient for its dynamic representation. Therefore, a small perturbation transfer function model block diagram ofisolated wind – diesel hybrid power system with SMES unit is shown in Fig.1 [4].

The SMES unit has a natural tendency ofcurrent restoration which is a very slow processand artificial enhancement of rate of restoration isrequired. Use of inductor current deviationfeedback in the SMES unit control loop isconsidered here. The inductor current deviation can be sensed and used as a negative feedback signal in the SMES unit control loop to achieve quick restoration of current. The transfer function model block diagram representation of such a control scheme is shown in Fig. 2.

2.2 Continuous – time dynamic model

The continuous – time dynamic model ofthe isolated wind – diesel hybrid power system with SMES unit is developed in this section.

2.2.1Model of isolated wind power systems in the hybrid power system with SMES unit

The state variable equations of the wind power system may be expressed as follows by inspection of the block diagram shown in Fig.1.

$$\Delta\omega_1 = \frac{1}{2H_w\, s}\,[\Delta P_M - K_{FC}\Delta\omega_1 + K_{FC}\Delta\omega_2 + \Delta P_w] \qquad (1)$$

$$\Delta P_M = \frac{K_{pc}\,K_{p3}}{1+s}\,\Delta P_{M1} \qquad (2)$$

$$\Delta P_{M1} = \frac{1}{1+sT_{p2}}\,[\Delta P_{M2'} + K_{P2}T_{P1}\,u] \qquad (3)$$

$$\Delta P_{M2'} = \left[\frac{K_{P2} - K_{P2}T_{P1}}{1+s}\right] u \qquad (4)$$

2.2.2 Model of diesel power system in the hybrid power systems with SMES unit

The state variable equations of the diesel generator are expressed by inspection of the block diagram shown in Fig.1.

$$\Delta\omega_2 = \frac{1}{2H_d\, s}\,[K_{FC}\Delta\omega_1 - K_{FC}\Delta\omega_2 - I_{d0}\Delta E_d - \Delta I_d\Delta E_d - \Delta P_{load} + \Delta P_f\,] \qquad (5)$$

$$\Delta P_{f1} = \frac{-K_d}{s}\,\Delta\omega_2 \qquad (6)$$

$$\Delta P_f = \frac{1+s}{1+sT_1}\Delta P_{f1} \qquad (7)$$

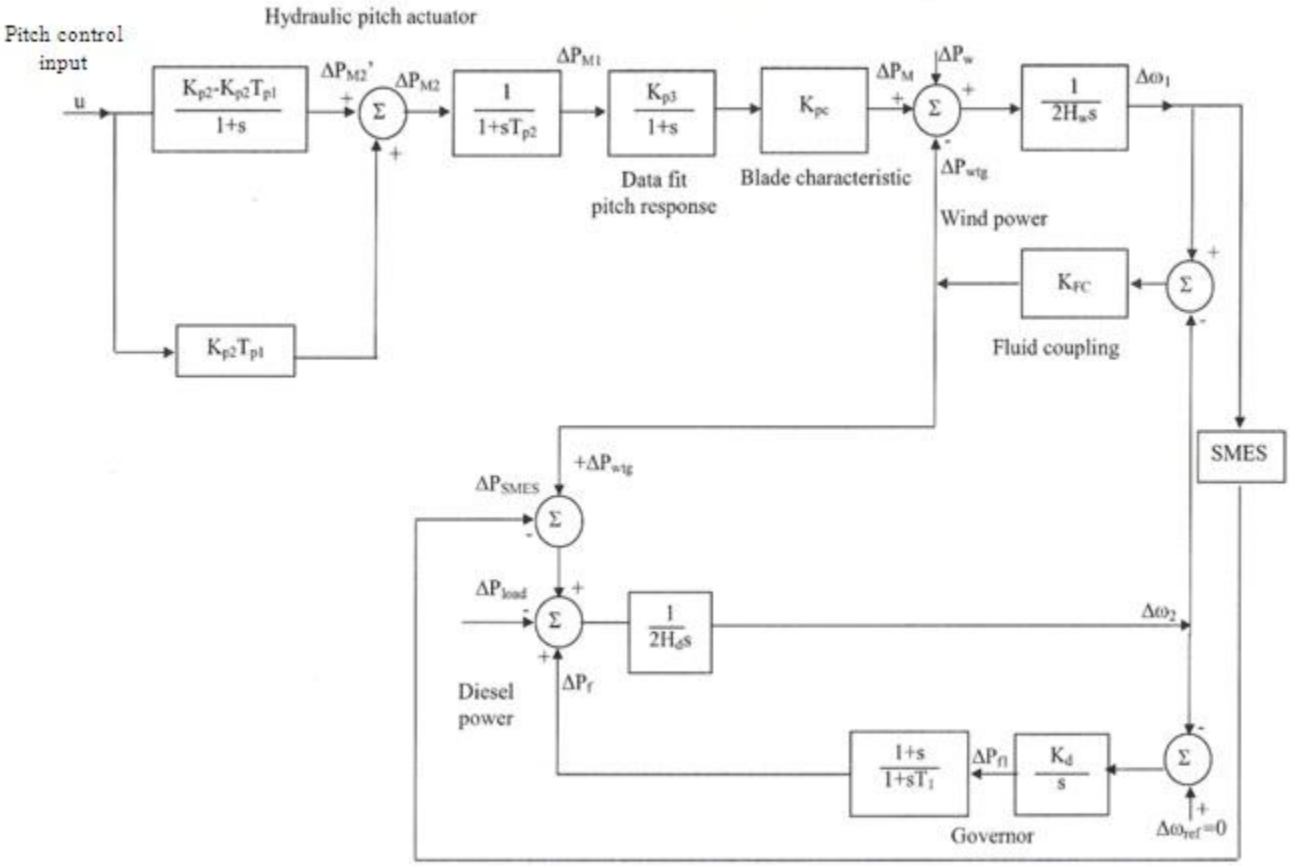

Fig. 1. Transfer function model block diagram of an isolated wind-diesel hybrid power system with SMES unit.

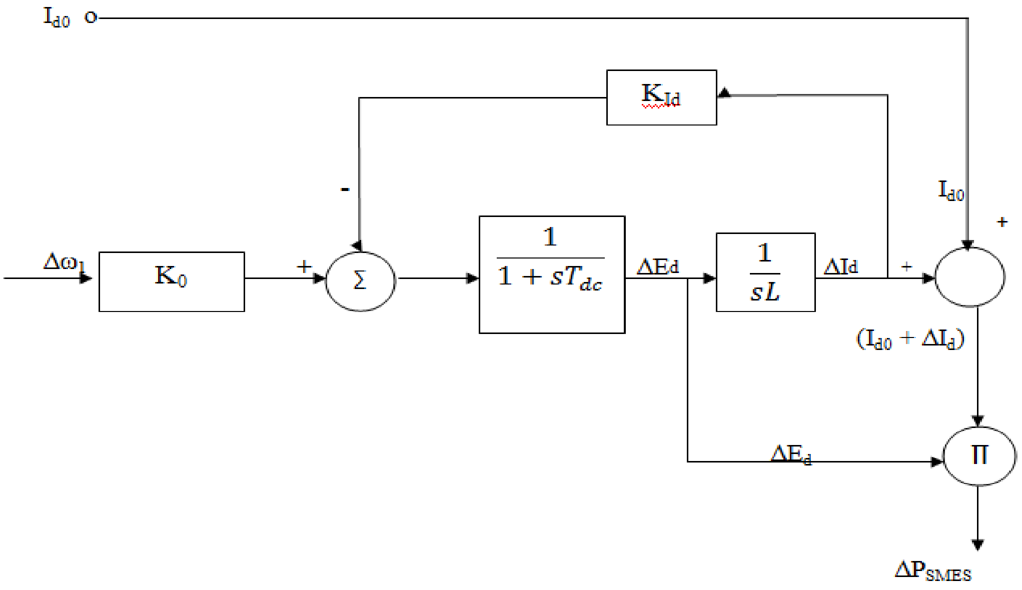

Fig. 2. Transfer function model block diagram of the SMES unit control with inductor current deviation feedback.

2.2.3 Model of the SMES unit in the hybrid power system

The state variable equations of the SMES unit are expressed by inspection of the block diagram shown in Fig. 2.

$$\Delta E_d = \frac{1}{1+sT_{dc}}\,[K_0\Delta\omega_1 - K_{Id}\Delta I_d] \qquad (8)$$

$$\Delta I_d = \frac{1}{sL}\,\Delta E_d \qquad (9)$$

2.2.4 Determination of the continuous – time state space model

By taking inverse Laplace transformation of the equations from (1) - (9), a linear continuous – time dynamic model can be described in the state space form as

$$\dot{x} = Ax + bu + \gamma d \qquad (10)$$

$$y = Cx \qquad (11)$$

Where,
$\dot{x}$= $[\Delta\omega_1\ \Delta P_M\ \Delta P_{M1}\ \Delta P_{M2'}\ \Delta\omega_2\ \Delta P_{f1}\ \Delta P_f\ \Delta E_d\ \Delta I_d]^T$ is the 9th order state vector.
d = $\Delta P_{load} + \Delta E_d \Delta I_d$ is the scalar disturbance input
u = is the scalar control input
y = ΔP_{wtg} is the scalar output
A = System state matrix
b = input distribution vector
γ = disturbance distribution vector
C = output distribution vector

3. Output feedback control scheme

It is known that by incorporating an integral controller the steady state requirements can be achieved. In order to introduce an integral function to the controller system the Eq. (10) is augmented with a new state variable defined as the integral of ΔP_{wtg} ($\int \Delta P_{wtg}\, dt$). The augmented equation of 10th order can be described as

$$\dot{\bar{x}} = \bar{A}\bar{x} + \bar{b}\bar{u} + \bar{\gamma}\bar{d} \qquad (12)$$

Where $\bar{x} = \begin{pmatrix} \int \Delta P_{wtg}\, dt \\ x \end{pmatrix}$, $\bar{A} = \begin{pmatrix} 0 & C \\ 0 & A \end{pmatrix}$, $\bar{b} = \begin{pmatrix} 0 \\ b \end{pmatrix}$ and $\bar{\gamma} = \begin{pmatrix} 0 \\ \gamma \end{pmatrix}$

As the newly addedstate variable ($\int \Delta P_{wtg}\, dt$) will also be available for feedback, the new measurable output $\bar{y}$ can be written as

$$\bar{y} = \bar{C}\bar{x} \qquad (13)$$

where $\bar{y} = [\int \Delta P_{wtg}\, dt\ ,\ \Delta P_{wtg}\ ]^T$ and $\bar{C} = \begin{pmatrix} 1 & 0 \\ 0 & C \end{pmatrix}$

For the design of decentralized controller, the augmented system should be controllable and should not have unstable fixed modes. It can be easily shown that the augmented system will be controllable if and only if the system is controllable and the matrix,

$\begin{pmatrix} 0 & C \\ b & A \end{pmatrix}$ is of the rank (1 + n)

The problem now is to design the output feedback control law,

$$u = k^T y \qquad (14)$$

to meet the desired output response of the system.

The control law Eq. (14) can be written in terms of ΔP_{wtg} as

$$u = -k_I \int \Delta P_{wtg}\, dt - k_p \Delta P_{wtg} \qquad (15)$$

where $k^T = [-k_I, -k_p]$ is a two-dimensional conventional integral and proportional controller constant feedback gain vector.

Unfortunately, since the operating point continuousy changes depending on the demand of consumers, this constant feedback gain output feedback control law is unsuitable to other operating points. Therefore, the problem of tuning of PI controller is formulated as an optimization problem which is solved by particle swarm optimization (PSO) technique that has a strong ability to find the most optimistic results.

4. Design of particle swarm optimization based PI controller for an isolated wind-diesel hybrid power system with SMES unit

4.1 Introduction

Particle swarm optimization (PSO) as one of the modern heuristic algorithms is also a population based evolutionary algorithm. Unlike population based evolutionary algorithms, PSO is motivated by the simulation of social behavior instead of survival of the fittest and each candidate solution is associated with a velocity. The candidate solutions, called "particles" then "fly" through the search space. The velocity is constantly adjusted according to the corresponding particle's experience and particles companion's experiences. It is expected that the particles will move towards the better solution areas.

In PSO, the inertia weight is used to balance the global and local search ability. A large inertia weight facilitates a global search while a small inertia weight facilitates a local search. By changing the inertia weight dynamically, the search ability is dynamically adjusted.

Since the search process of the PSO is non-linear and very complicated; it is hard to mathematically model the search process to dynamically adjust the inertia weight. Instead a fixed inertia weight or a linearly decreasing inertia weight is deployed (classical PSO). By linearly decreasing the inertia weight from a relatively large value to a small value through the course of a PSO run, PSO tends to have more global search ability at the beginning of the run while having more local search ability near the end of the run [9].

4.2 Basic elements of PSO

PSO is a flexible, robust population based stochastic search/optimization algorithm with implicit parallelism, which can easily handle with non-differential objective function, unlike traditional optimization methods. PSO is less susceptible to getting trapped on local optima unlike GA, SA, etc.

Kennedy,Eberhart and Shi developed PSO concept similar to the behavior of a swarm of birds. PSO is developed through simulation of bird flocking in multi-dimensional space. Each particle's present position is realized by the previous position and present velocity information.

The basic elements of PSO are:

(i) Particle or agent or candidate solution.
(ii) Population, which is set of n particles at certain iteration cycle t.
(iii) Swarm is an apparently disorganized population of moving particles that tend to cluster together while each particle seems to be moving in a random direction with different particle velocities v (t).
(iv) Inertia weight w: It is a control/strategy parameter that is used to control the impact of the previous velocities on the current velocity. Hence, it influences the tradeoff between the global and local exploitation abilities of the particles. For initial stages of the search process, large inertia weight to enhance the global exploitation is recommended while for last stages, the inertia weight is reduced for better local exploration.
(v) Individual best position X*(t): As a particle moves through the search space, it compares its fitness value at the current position to the best fitness value it has ever attained at any time up to the current time. The best position that is associated with the best fitness encountered so far is called the individual best position X*(t). For each particle in the swarm, X_j*(t) (jth particle, j=1,2,…population size, each having n components) is determined and updated during the search by its velocity.
$X_j^*(t) = [x_{j}^*{}_{,1}, x_{j}^*{}_{,2},\ldots\ldots,x_{j}^*{}_{,n}]$
(vi) Global best position X**(t): It is the best position among all of the individual best position achieved so far.
$X^{**}(t) = [x_1^{**}, x_2^{**},\ldots\ldots,xn^{**}]$
(vii) Stopping criteria: The number of iterations reaches the maximum allowable number N_m.

4.3 Classical particle swarm optimization

Mathematically the particles are manipulated according to the following equation:

The velocity of $i$thcomponent of jth particle of the swarm is updated in current iterationcycle (iter) as:

$$v_{j,i}(\text{iter}) = w(\text{iter})\, v_{j,i}(\text{iter}-1) + c_1 \text{Rnd}_1 (x^*_{j,i}(\text{iter}-1) - x_{j,i}(\text{iter}-1)) + c_2 \text{Rnd}_2 (x^{**}_j(\text{iter}-1) - x_{j,i}(\text{iter}-1))$$

The position of ith component of jth particle is updated/manipulated as:

$$x_{j,i}(\text{iter}) = x_{j,i}(\text{iter}-1) + v_{j,i}(\text{iter})$$

wherec_1 and c_2 are positive constants and Rnd_1 and Rnd_2 are uniformly distributed random numbers in [0,1].

4.4 Optimization of PI gains

Optimization of PI gains by any of the optimization techniques corresponds to minimum of undershoot (US), minimum overshoot (OS), minimum settling time (t_s) and minimum *df/dt*, i.e. overall minimum figure of demerit.

Figure of demerit = $(OS \times 1000^2 + (US \times 100)^2 + (t_s)^2 + [(\frac{df}{dt})x100]^2$

Because overshoot, undershoot and d*f*/dt values are small compared with settling time, these are weighted by large multipliers so that the reduction of these values may compete with reduction of settling time during optimization process.The flowchart for optimization of PI gain using PSO is shown in Fig.3.

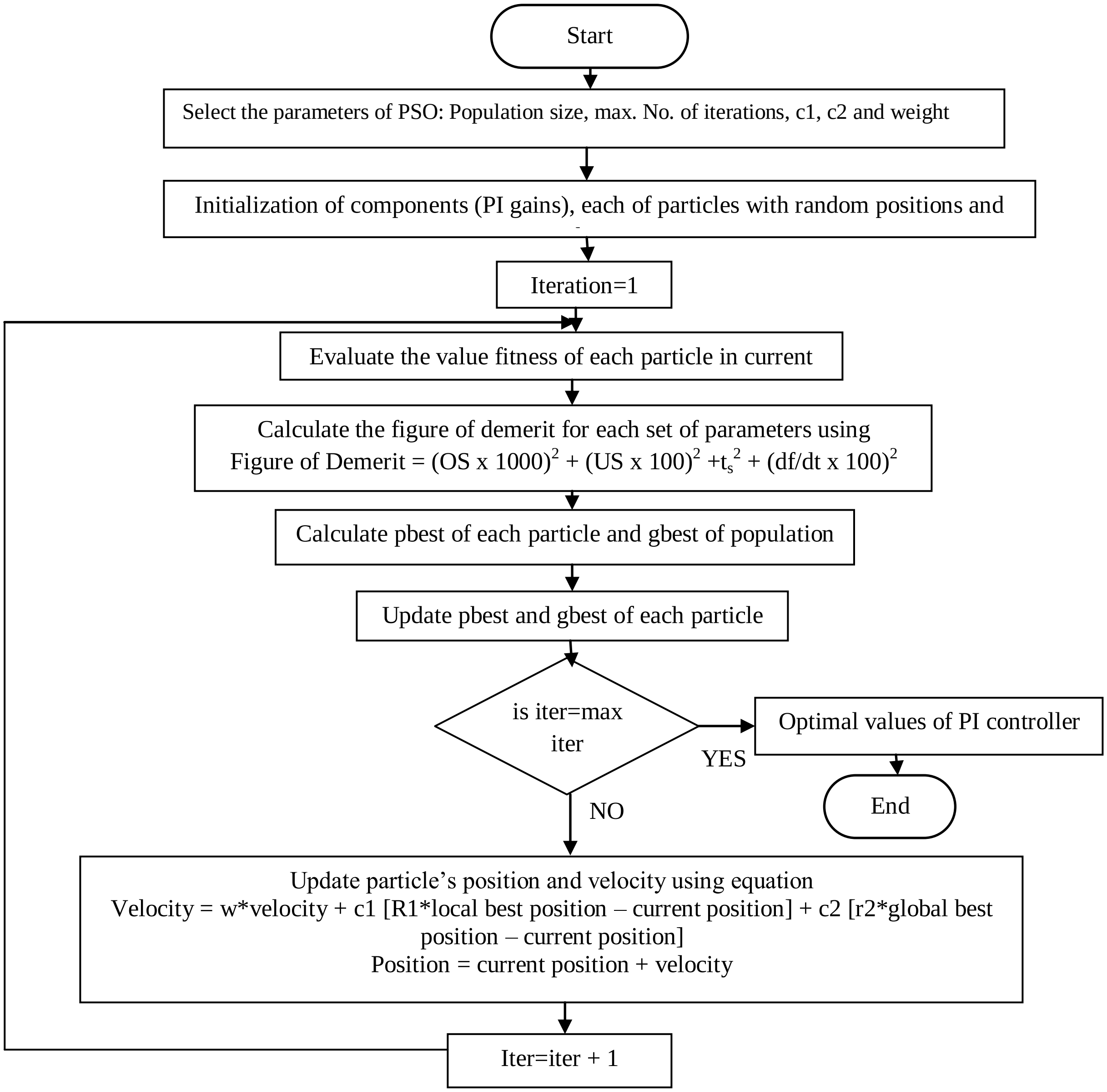

Fig.3. Flowchart for Optimization of PI gain using PSO.

4.5Simulation results and discussions

Optimization of PI gains by particle swarm optimization discussed above is implemented to an isolated wind – diesel hybrid power system with SMES unit. Simulations are carried out for a step load change of 1% disturbance and the resulting wind generator frequency deviation ($\Delta\omega_1$), diesel generator frequency deviation ($\Delta\omega_2$), wind generator power deviation (ΔP_{wtg}) and diesel generator power deviation (ΔP_f) are shown in Fig. 4 to 7. The results are also compared with fixed gain PI controller. It is found that the particle swarm optimization based PI controller has better transient and steady state performance over fixed gain PI controllers.

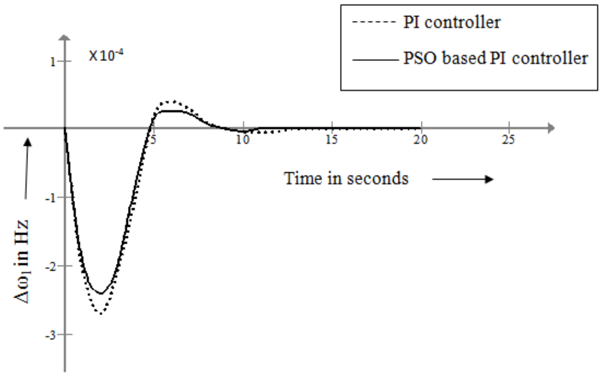

Fig.4. Wind generator frequency deviation ($\Delta\omega_1$) of wind diesel power system with SMES unit with fixed gain PI controller & with PSO based PI controller for a step load disturbance of 1%.

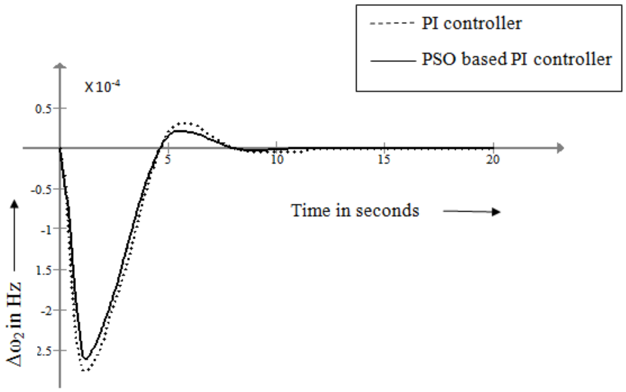

Fig.5. Diesel generator frequency deviation ($\Delta\omega_2$) of wind diesel power system with SMES unit with fixed gain PI controller & with PSO based PI controller for a step load disturbance of 1%.

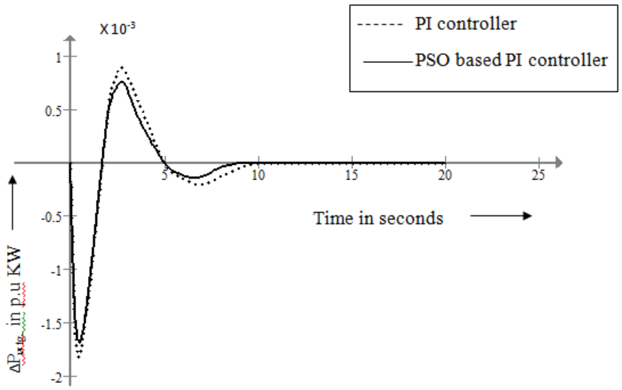

Fig.6. Wind generator power deviation (ΔP_{wtg}) of wind diesel power system with SMES unit with fixed gain PI controller & with PSO based PI controller for a step load disturbance of 1%.

turbance of 1%.

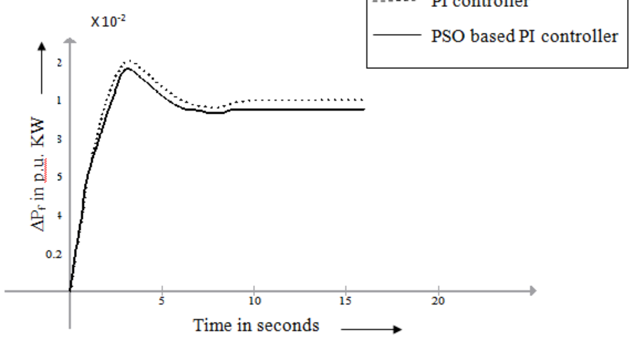

Fig.7. Diesel generator power deviation (ΔP_f) of wind diesel power system with SMES unit with fixed gain PI controller & with PSO based PI controller for a step load disturbance of 1%.

CONCLUSION

This paper presents a new design of particle swarm optimization based PI controller for an isolated wind-diesel hybrid power system with superconducting magnetic energy storage unit. Since the operating point continually changes depending on the demand of consumers, the constant gain PI controller are unsuitable to other operating points. Optimal Matrix – Riccati based controller or state adaptive controllers involve large computational burden and time. Fuzzy logic has been used for designing a controller. But gains are suboptimal in some cases.PSO is a flexible, robust population based stochastic search/optimization algorithm with implicit parallelism, which can easily handle with non-differential objective function, unlike traditional optimization methods. PSO is less susceptible to getting trapped on local optima unlike GA, SA, etc. Hence in this paper, particle swarm optimization based PI controller is carried out and the results are compared with fixed gain PI controllers.Theresults show that particle swarm optimization based PI controller has good transient and steady state performance over fixed gain PI controllers.

Appendix

- *System Parameters*

P_R	=350kW	H_w	=3.5 Seconds
H_d	=8.5 Seconds	K_F	=16.2 p.u.kW/Hz
K_{p3}	=1.4	ΔP_{load}	=0.01 p.u.kW
ΔP_w	=0.0 p.u.kW	T_1	=0.025 Seconds
K_d	=16.5 p.u.kW/Hz	T_{p2}	=0.041 Seconds
T_{p1}	=0.6 Seconds	K_{pc}	=0.08

- *SMESunit data*

I_{do}	=2.0kA	L	=10.0 H
K_o	=6000kV/Hz	K_{Id}	=5.0 kV/kA

- *PSO Input data and parameters*

The parameters required for the optimization algorithm are as follows:

Maximum number of iteration cycles = 50, Population =50, Maximum gain (g_{max}) =2.0, Minimum gain (g_{min}) = 0.2, Initial gains = 0.25 x Rnd_1, Where, Rnd_1 is uniformly distributed random number in [0, 1], Initial velocities of gains = 0.4, Inertia weight ω = 0.65.

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