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TUNING OF PID CONTROLLER FOR A SYNCHRONOUS MACHINE CONNECTED TO A NON-LINEAR LOAD

Gowrishankar Kasilingam and Jagadeesh Pasupuleti
Department of Electrical Power Engineering, UNITEN, Malaysia
E-Mail: gowri200@yahoo.com

ABSTRACT

This paper proposes a method of determining the optimal proportional integral derivative (PID) controller parameters using the particle swarm optimization (PSO) technique. The stability of the power system is an important factor in the operation of any electric system. A PID controller with a power system stabilizer (PSS) has been developed to maintain the stability and enhance the performance of the power system. Optimization of PID parameters is an important problem in control engineering. A PSO algorithm has been proposed to tune the parameters of the PID controller. The effectiveness of the PID-based PSS has been tested on a single-machine infinite-bus (SMIB) system having a three-phase thyristor-based non-linear load with different kinds of faults. Analysis shows that the dynamic performance with the proposed method is better compared with the conventional trial-and-error method. The speed deviation, rotor angle deviation and load angle were compared in a Simulink-based MATLAB environment. The simulations show that the proposed method damps optimally and suppresses errors to a minimum.

Keywords: power system stabilizer, PID controller, PSO algorithm, non-linear load.

1. INTRODUCTION

As the science and technology of health become more sophisticated, the world's population increases each day, imposing greater demands on the electric power supply. Different types of loads, such as domestic loads, commercial loads and industrial loads, are connected to multiple generators in a complex power system. Hence, there is a need for more efficient power systems that respond quickly to match the supply dynamically with the demand dynamically, which changes non-linearly.

The transient stability, also known as the synchronizing torque, is improved through the use of alternator excitation systems with high gains and fast response times. However, the use of such systems reduces the small-signal stability. To overcome this disadvantage, a power system stabilizer (PSS) is installed in the excitation system of a synchronous generator. The small-signal stability of the power system is improved by damping the swings in the generator rotor angle. To do this, supplementary perturbation signals are provided in a feedback path to the alternator excitation system. Small-signal stability analysis is becoming popular among researchers in the field of power system stability because such analysis can provide information about the ability of an electric system to withstand minute changes or disturbances due to non-linear loading without the loss of synchronism among the synchronous machines in the system. A PSS is most commonly used to resolve oscillatory stability problems [1].

A conventional PSS used to damp out small oscillations is designed on the basis of a model that is linearized around a particular operating point [2]. As a result, such a device has the disadvantage that is it unable to provide a good response over a wide operating range. This drawback can be overcome by integrating the PSS with a proportional integral derivative (PID) controller or using a controller with the PSS. Shaoru Zhang and Fang Lin Luo [3] proposed the use of a proportional integral (PI) adaptive control method with a PSS for a single machine connected to an infinite-bus system. PID controllers have existed for about 80 years. They were commercially introduced in the 1930s. Even today, industries use PID controllers to increase the efficiency of power systems. These controllers perform robustly over a wide range. The PID controller is chosen over other types of controllers such as on/off controllers, proportional controllers and proportional derivative controllers.

Gowrishankar *et al*. [4] analysed the effectiveness of combining a PID controller with a PSS under different operating conditions in a MATLAB Simulink environment. K.R. Sudha *et al*. [5] proposed a combination of a PID and a fuzzy logic PSS (FLPSS). If the PID parameters are not tuned appropriately, recovery may be slow and cyclic, and the system may not be robust. The system could even stop operating and collapse [6]. Researchers are therefore searching for the best method of optimizing the PID parameters.

Among the many strategies that have been proposed are those of Ziegler-Nichols [7] and Cohen-Coon [8], who are pioneers in PID tuning. They proposed methods based on trial and error and the process reaction curve. Tan Qian Yi *et al*. [9] used the Ziegler-Nichols (ZN) tuning method and the trial-and-error method to obtain different PID gains and analysed the performance of synchronous machines with these gains. Their analysis suggests that the dynamic performance is better with the ZN method compared with the conventional trial-and-error method. For complex systems of high order and those with time delays, non-minimum phases and non-linear processes, ZN tuning methods are not very effective. Other methods that have been used include the Refined Ziegler-Nichols Method [10], pole placement [11] and the use of heuristic techniques such as population-based incremental learning, genetic algorithms (GAs), simulated

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annealing and particle swarm optimization (PSO) [12]. In heuristic optimization, good solutions are searched for at a reasonable computational cost. Heuristic techniques cannot guarantee feasibility or optimality. In many cases it is not possible to state how close a particular feasible solution is to optimality [13].

GAs, among the most important optimization methods, has been studied extensively. With GAs, the chance of being trapped in a local minimum is low. GAs use a stochastic global search method that mimics natural evolution [14].

The use of GAs to auto-tune PID controllers was proposed by A. Jones and P. Oliveira [15]. Continuous GAs were proposed to improve the operation time and efficiency of PID adjustment [16, 17]. An improved GA method was proposed by Kim [18] to tune a PID controller for optimal control of an RO plant. Their method had a fast settling time compared with the conventional tuning method, and it had minimal overshoot. GAs were used successfully by Yin *et al.* [19] to tune a PID controller for low damping of a slow-response plant. Md Zain *et al.* [20] used a GA to optimize PID parameters. They used these parameters to control the vertical motion of a single-link flexible manipulator. The vibration of the manipulator was found to be reduced well in simulations. Although the performance of GAs in obtaining globally optimum solutions is excellent, some deficiencies have been pointed out: (i) poor premature convergence, (ii) loss of the best solution found and (iii) no absolute assurance that a global optimum will be found [21].

Giriraj Kumar *et al*. [22] used a PSO algorithm to tune the PID gains of a high-performance drilling machine. A PSO algorithm has a better performance index (based on various error criteria) compared with a controller tuned using conventional methods. Dashti *et al*. [23] proposed the use of the PSO method to tune a digital PID controller. They analysed the criteria used to assess the performance. Shayeghi *et al*. [24] proposed the use of the PSO method for multi-objective design of multi-machine power system stabilizers. Even though methods of tuning PIDs using GAs and PSO have been extensively studied, the implementation details are not clear.

The objective of this work is to use the trial-and-error method and a PSO algorithm for tuning a PID controller in combination with a PSS for a single-machine infinite-bus system. Gaining a better understanding of how a PID controller is tuned using a popular heuristic approach with PSO is another objective. The experimental results demonstrate that the PSO-PID PSS is effective with synchronous machines.

2. PRELIMINARY WORK

A. Power system stabilizer (PSS)

The disturbances occurring in a power system induce electromechanical oscillations of electrical generators. These oscillations, also called power swings, must be effectively damped to maintain the stability of the system. A solution to the problem of oscillatory instability is to damp the oscillations of the generator by providing a PSS, which is a supplementary controller in the excitation system. The PSS damps the oscillations of the rotor of a synchronous machine by controlling its excitation using an auxiliary stabilizing signal or signals. A block diagram is provided in Figure-1 to explain the operation of a PSS. The excitation system is controlled by an automatic voltage regulator (AVR) and a power system stabilizer (PSS). The output of the PSS-PID is used as an additional input (u) to the automatic voltage regulator (AVR) block. The input of the PSS is the deviation of the speed of the machine (Δω).

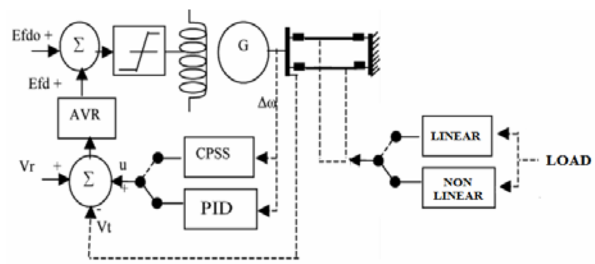

Figure-1. General control model of SMIB power system.

A block diagram of a conventional lead-lag PSS is shown in Figure-2. A generic PSS may be modeled as a non-linear system with a stabilizer gain, wash-out term, phase compensation system and output limiter [4].

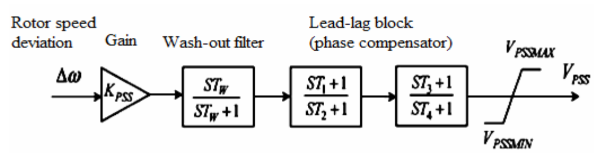

Figure-2. Conventional power system stabilizer (PSS).

a) Gain

The overall gain (K) of the generic PSS determines the extent of damping the stabilizer imposes. K can be chosen in the range between 20 and 200.

b) Wash-out time constant

The wash-out high-pass filter eliminates low frequencies that are present in the speed deviation signal and allows the PSS to respond only to speed changes. The time constant, T_w, can be chosen in the range between 1 and 2 for local modes of oscillation. However, if inter-area modes are also to be damped, then T_w must be chosen in the range between 10 and 20.

c) Lead-lag time constants (phase compensation system)

T1 and T3 are the time constants in the numerator and T2 and T4 are the time constants in the denominator, in seconds, of the first and second lead–lag transfer functions, respectively. The phase-compensation system is represented by a cascade of two first-order lead–lag transfer functions, which are used to compensate for the

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phase lag between the excitation voltage and the electrical torque of the synchronous machine.

d) Limiter

The output of the PSS must be limited to prevent it from countering the action of the AVR. The PSS must provide greater feedback when the signal deviation increases above the desired value, compared with the feedback to be provided when the deviation is below the desired value. A typical value of the lower limit is -0.05, and the higher limit can vary between 0.1 to 0.2.

B. Proportional integral derivative (PID) controller

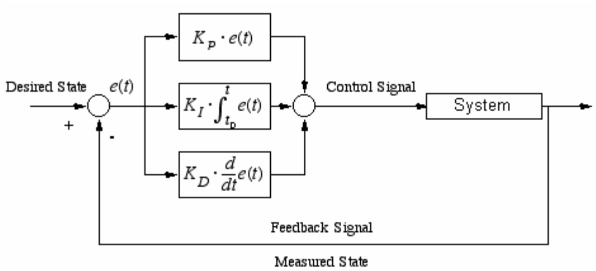

Figure-3. Block diagram of system with PID controller.

The PID was an essential element of early governors, and it became the standard tool when process control emerged. Nowadays more than 95% of the control loops in process control are of the PID type. The sequence of control in a system is shown in Figure-3. The controller can be represented in different forms, depending on the type of process. A PID controller often has logic, sequential functions, selectors and simple function blocks combined to build a complex automation system. The transfer function of a PID controller can be written as:

$$G_{PID}(s) = k_p + \frac{k_i}{s} + k_d s = \frac{k_d s^2 + k_p s + k_i}{s} \quad (1)$$

where

k_p is the proportional constant,

k_i is the integral constant.

k_d is the derivative constant and

S is the pole of the system in the complex plane.

Determination of the proportional, integral and derivative constants of the controller is called the tuning-in process. The control depends on the dynamic response of the plant. In PID control, the actuating signal consists of a proportional error signal added to the integral and derivative of the error signal. It is given by:

$$e_a(t) = e(t) + T_d \frac{d_e(t)}{dt} + k_i \int e(t)dt \quad (2)$$

A PID controller corrects the error difference between a measured process variable and the desired input or reference point or set point by calculating and giving as output a correction that adjusts the process accordingly [8]. To obtain the best response of the PID controller in a system, the PID controller must be tuned by optimizing the values of k_p, k_i and k_d. Ziegler-Nichols [6] proposed as the basis of their controller-tuning rules that the ratio of the amplitudes of subsequent peaks in a particular direction be approximately 0.25. However their proposed method of tuning the PID controller is only applicable to processes having a time delay or having a dynamic of order greater than 3. Many algorithms have been proposed by other researchers for obtaining the best PID parameter values for specific systems. Example of other types of algorithms includes GAs and PSO.

C. Particle swarm optimization (PSO)

PSO is an artificial intelligence (AI) method that uses a population-based stochastic approach to find approximate solutions of extremely difficult or numerically impossible maximization and minimization problems. It was developed by Dr. Eberhart and Dr. Kennedy in 1995 [25] to simulate the social behaviour displayed by flocking birds and schooling fish. These researchers found that birds flock together to search for food. Hence it can be assumed that information is shared among the individuals of a flock. In PSO, each particle in a swarm represents a solution to a particular problem, and it is defined by its position and velocity. The position of the *i*th particle in an N-dimensional search space can be represented by an N-dimensional vector, $x_i = (x_{i1}, \dots \dots x_{in} \dots, x_{iN})$.

The velocity of the particle can be represented by another N-dimensional vector, $v_i = (v_{i1}, \dots \dots v_{in}, \dots, v_{iN})$. The best position previously visited by the particles is denoted as $p_i = (p_{i1}, \dots \dots p_{in}, \dots . p_{iN})$, and p_g is the index of the particle that visited the best position in the swarm. The velocity and the new position are determined according to the following two equations, in which a weight *w* is added [26]:

$$v_{in} = wv_{in} + c_1 r(p_{in} - x_{in}) + c_2 R(p_{gn} - x_{in}) \quad (3)$$

$$x_{in} = x_{in} + v_{in} \quad (4)$$

where the factor c_1 is a constant called the cognitive weight and the factor c_2 is a constant called the social or global weight. Both are positive constants. *r* and *R* are random functions in the range [0,1], that is, they are greater than or equal to zero but strictly less than unity. The velocity of the particles depends on the three terms in equation (3). The symbol *g* represents the index of the best particle in the population [27]. Appropriate selection of the inertia weight provides a balance between global and local exploration and exploitation and results in fewer iterations on average to find an optimal solution. Its value is set according to the following equation:

$$w = w_{max} - \frac{w_{max} - w_{min}}{iter_{max}} \times iter \quad (5)$$

where w_{max} and w_{min} are both random numbers, called the initial weight and final weight, respectively. $iter_{max}$ is the maximum iteration number. $iter$ is the current iteration number. The termination criterion is defined by the maximum number of iterations that the PSO can perform. Once the PSO performs this preset number of iterations, the algorithm is automatically terminated. The individual that generates the latest value of p_{gn} is an optimal controller parameter.

Steps in a PSO Algorithm:

a) Initialize an array of particles with random positions and their associated velocities to satisfy the inequality constraints.
b) Check whether the quality constraints are satisfied and modify the solution if required.
c) Evaluate the fitness function of each particle.
d) Compare the current values of the fitness function with the previous best value of the particle. If the current fitness value is smaller, then assign the current coordinates to p_{in}.
e) Determine the current global minimum fitness value among the current positions.
f) Compare the current global minimum with the previous global minimum. If the current global minimum is less than p_g, then assign the current coordinates to p_{gn}.
g) Change the velocities according to equation (3).
h) Move each particle to the new position according to equation (4) and return to step 2.
i) Repeat steps 2-8 until optimization or the maximum number of iterations is reached [28].

3. PROPOSED METHOD

The proposed system combines a PID controller with a PSS to guarantee robust performance over a wide range of operating conditions including linear and non-linear loads. Figure-4 shows a block diagram of the proposed system, which is connected to a three-phase thyristor-based non-linear load. The optimized values of the parameters of the generic PSS of the proposed system are the following:

K_{PSS} = 125; T_w = 2; Lead–lag time constants, T1 = 5000, T2 = 2000, T3 = 3 and T4 = 5.4; Limiter = -0.5 to 0.5.

The generator speed deviation, $\Delta\omega$, is provided as the input signal to the proposed stabilizer. The PSS provides the electrical damping torque in phase with the speed deviation to improve the damping of the power system. The PID controller is used to stabilize this system. The input of the stabilizer is the change in speed. The output of the controller is delivered to the excitation system. The aim is to control the phase difference between the generator and load. The objective of using a PID controller with a PSS is to provide a better solution to the stability problem compared with power systems utilizing either PSS or PID controllers alone.

In the proposed system, a novel PID tuning algorithm and PSO technique are used to improve the performance of the PID controller with a non-linear load. The initial values of K_p, T_i, T_d were determined using the trial-and-error method. The new proportional gain (K_p), the integral time (T_i), and derivative time (T_d) were determined using the PSO technique.

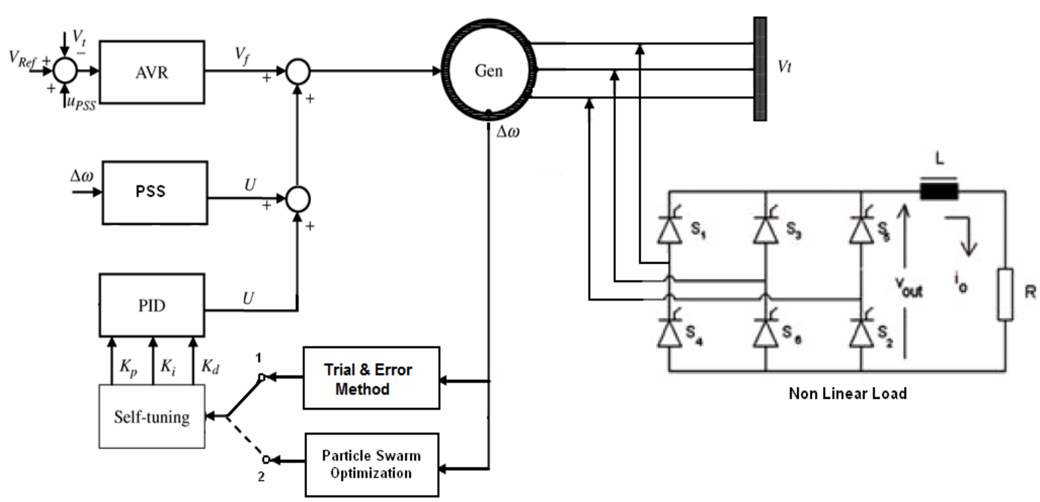

Figure-4. Proposed system.

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A. Non-linear loads

Non-linear loads are those AC loads in which the current is not proportional to the voltage. Loads that meet this definition include gas discharge lighting, which use saturated ballast coils and thyristors, namely silicon controlled rectifiers (SCRs). The nature of non-linear loads is to generate harmonics in the current waveform. This distortion of the current waveform leads to distortion of the voltage waveform. With these conditions, the voltage waveform is no longer proportional to the current. The non-linear loads create harmonic currents by drawing current in abrupt short pulses rather than in a smooth, sinusoidal manner.In our system, the non-linear load used is represented using a six-pulse converter with SCRs (Figure-5 and Figure-6).

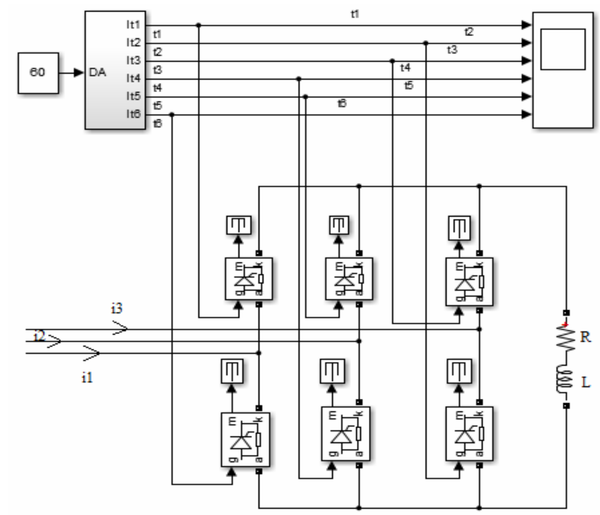

Figure-5. Simulink model of fully controlled line-commutated six-pulse converter.

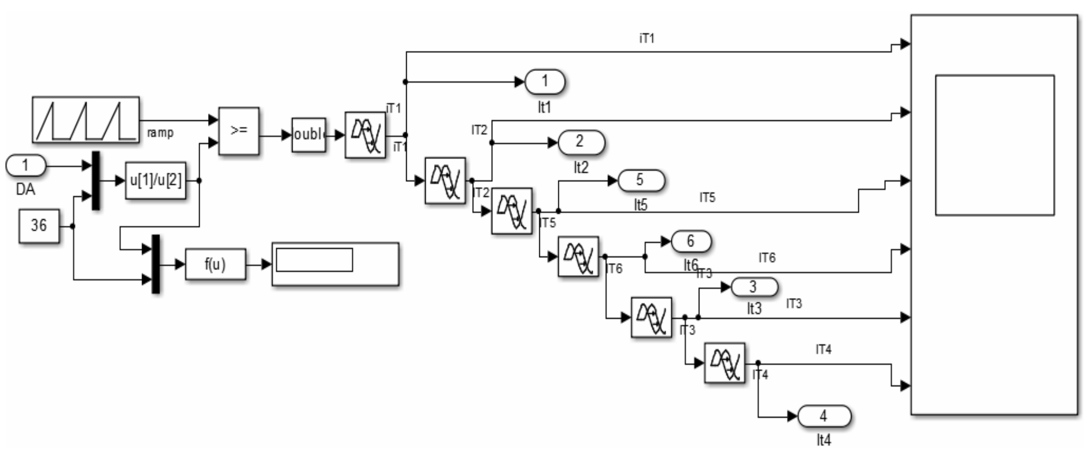

Figure-6. Simulink model of triggering circuit.

In Figure-5, i1, i2 and i3 are the currents of the three phases, and there are six SCRs. Each pair of thyristors is triggered (firing angle) by a triggering current. The currents are denoted as It1, It2, It3, It4, It5 and It6 and they are produced by ramp input signals. Each triggering pulse is delayed as shown in Figure-6. Hence, the thyristors are triggered and conduct until they are reverse-biased. If a thyristor is triggered at zero firing angles, it acts exactly like a diode. The term 'line-commutated converter' refers to the fact that the load actually turns thyristors off rather than them being turned off by external control circuits. The ideal AC current waveform for a six-pulse converter is on for 120° and off for 60° [29]. During the on period, the DC load current is assumed to be constant in the ideal case due to the assumed existence of a large series DC inductor. Assuming no commutations overlap and that there is balanced three-phase operation, it can be shown that the phase a current is

$$i_a(t) = \sum_h \frac{I_1}{h}\sin(h\omega_1 t + \delta_h) \quad (6)$$

where h = 1, 5, 7, 11, 13,… We see that the AC harmonic currents generated by a six-pulse converter include all odd harmonics except triplens. Harmonics generated by converters of any pulse number can be expressed by h = pn ± 1, where n is any integer and p is the pulse number of the converter. For the ideal case, converter harmonic current magnitudes decrease according to the 1/h rule. The total harmonic distortion (THD) is defined as the ratio of the rms value of all the harmonic components to the rms value of the fundamental frequency, and it can be calculated as [30]:

$$\text{THD} = \frac{\left(I_{1(rms)}^2 + I_{2(rms)}^2 + I_{3(rms)}^2 + \cdots + I_{n(rms)}^2\right)^{1/2}}{I_{1(rms)}} \quad (7)$$

B. Fitness function

Control tuning has different functions, such as the following:

a) Minimization of a performance index such as the integral of squared error (ISE)
b) Adjusting time specifications
c) Obtaining robustness properties

The objective of an optimal PID design is to maximize damping - in other words, minimize the overshoots and settling time in system oscillations. Integral error is usually used as the performance index of PID system parameter tuning, while the ISE is often used in optimal analysis and design. The fitness function is given by

$$J = \int_0^{\infty} (\Delta\omega)^2 \, dt \qquad (8)$$

where Δω is the deviation in the speed of the generator, obtained from time domain simulation. The proposed approach uses PSO to solve this optimization problem and search for the optimal set of PID parameters. At first PID parameters are evaluated the using trial-and-error method to get a smaller search space, for example $k_P = 3$, $k_I = 0.6$ and $k_D = 1.2$. Therefore we get a larger parameter search space: $0 \le k_P \le 9$, $0 \le k_I \le 1.2$ and $0 \le k_D \le 1.9$.

C. Tuning of PID based on PSO algorithm

The advantage of the PSO algorithm is its simplicity of implementation and the fact that it converges quickly to a solution. The searching speed should be high when the parameters are being determined if much iteration is involved. Based on the convergence rate of the fitness function, the PSO-PID algorithm adaptively changes the parameters K_P, K_I and K_D.

The optimum values of K_p, K_i and K_d that minimize an array of different performance indexes are accurately computed using PSO. The performance index is the ISE.

$$ISE = J = \int_0^{\infty} (\Delta\omega)^2 \, dt \qquad (9)$$

It is clear that a controller with a lower performance index is better than other controllers. To compute the optimum parameter values, a 0.1 step change in the reference mechanical torque (ΔT_m) is assumed, and the performance index is minimized using PSO. To improve the performance, the number of particles, particle dimension, number of iterations, c1 and c2 are chosen as 50, 3, 100, 2 and 2, respectively. Also, the inertia weight, *w*, decreases linearly from 0.9 to 0.4. It is clearly shown in Table-1.

Table-1. Parameters used for PSO algorithm.

PSO parameters	Value/type
Number of particles	50
Number of swarms	3
Number of iterations	100
c1, c2	2, 2
w_{max}, w_{min}	0.9, 0.4

4. RESULTS AND DISCUSSIONS

Experiments were conducted to verify the efficiency of the proposed PSO-PID algorithm and to compare the PSO-PID and conventional tuning methods.

Numerical simulations of a single-machine infinite-bus power system were carried out for different operating conditions. The tuning methods were tested with

a) a non-linear load with a three-phase fault
b) a non-linear load with a ground fault

The variation of the speed deviation, the rotor angle and the load angle were analysed for each of these faults. The simulations were carried out using MATLAB 7.1 and Simulink (R2013b).

A. Implementation of PSO-PID

The trial-and-error method was used with the same system to verify the advantages of the proposed method. The initial ranges of the PID parameters were [0, 6], [0, 1] and [0, 2].

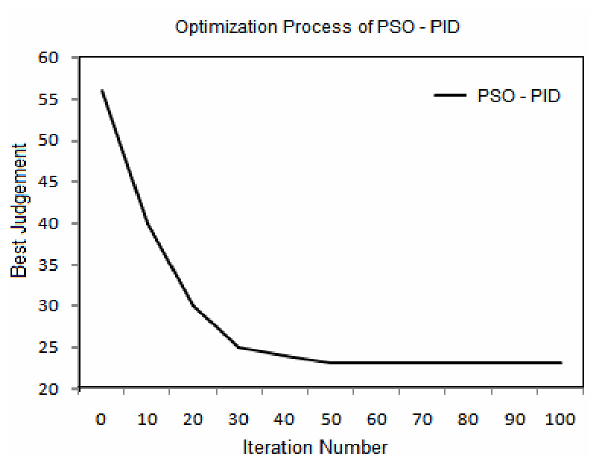

Figure-7. Optimization process.

Figure-7 shows the values of the fitness function for different numbers of iterations. It may be seen that the value of J for the PSO-PID is less than the local minimum. It may also be seen that the PSO-PID attains the best value after 50 iterations itself. Therefore, the PSO-PID controller obtains the optimal parameters more quickly and efficiently. Table-2 shows the values of the PID gains, K_P, K_I and K_D.

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Table-2. Controller parameters.

Method	PID gains		
	K_p	K_i	K_d
Trial and error	3.8	0.84	1.41
Particle swarm optimization	5.14	0.9	1.63

B. Non-linear load with three-phase fault

In this case, the three-phase fault is assumed to be at the transmission line. The system response for this contingency is shown in Figures 8-10. From Figures 8 and 9, it can be seen that the PSO-PID controller greatly improves the settling time of the speed deviation and rotor angle deviation, within 2.2 seconds, compared with 3.5 seconds with the other method. Figure-10 shows that the load angle performance is much better with the PSO-PID controller, with the settling time just a little more than 2 seconds. The comparison shows that the use of PSO to tune the PID controller leads to better performance in every aspect when the power system is connected to a non-linear load with three-phase fault conditions.

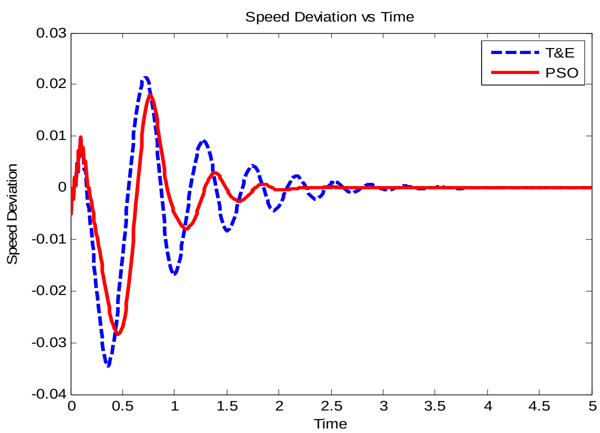

Figure-8. Speed deviation.

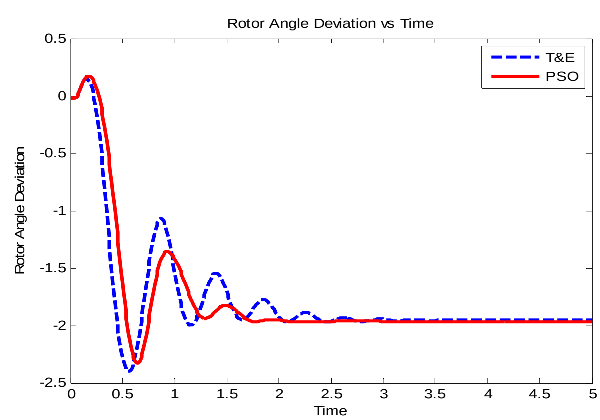

Figure-9. Rotor angle deviation.

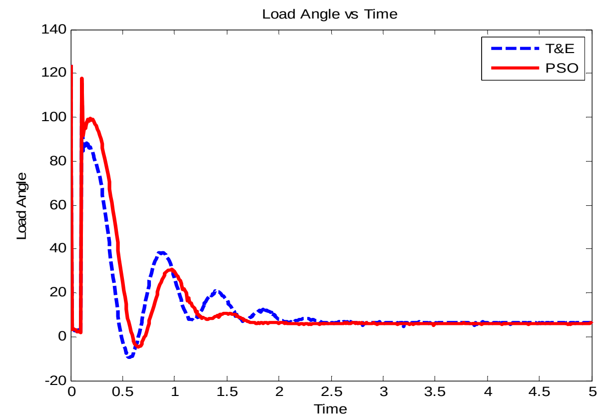

Figure-10. Load angle.

C. Non-linear load with ground fault

In this case, the synchronous machine was connected to a non-linear load with a ground fault condition. The following observations relate to the stability of the system. Figures 11-13 show the variation of the speed deviation, rotor angle deviation and load angle with respect to time under these conditions. Figure-11 shows that the rise time (T_r) with the trial-and-error method is smaller but that the settling time (T_s) with the PSO method is very low. From Figures 12 and 13, it may be seen that tuning using the PSO method reduces the rotor angle deviation and load angle settling time by around 2 seconds. Hence, the PID controller with PSO tuning significantly suppresses the oscillations in the system and provides good damping characteristics, particularly at low frequencies, by stabilizing the system much faster.

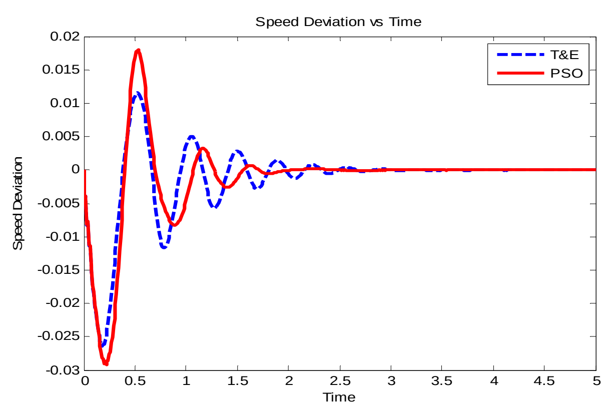

Figure-11. Speed deviation.

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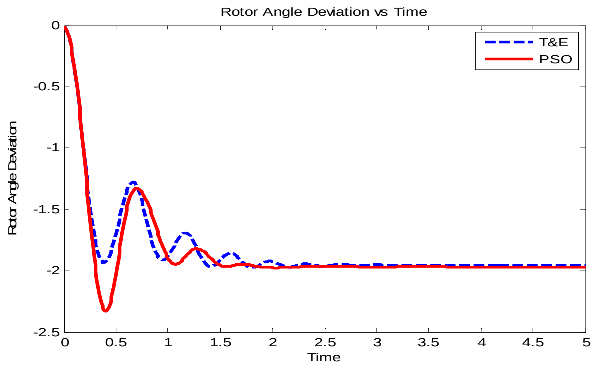

Figure-12. Rotor angle deviation.

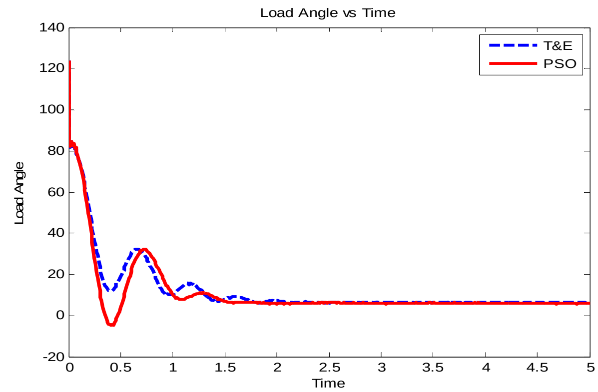

Figure-13. Load angle.

Tables 3-5 compare the performance of the proposed PSO-PID method and that of the trial-and-error method under the conditions studied. The performances are compared in relation to the speed deviation, rotor angle deviation and load angle.

Table-3. Response characteristics of the speed deviation with the PSO method.

	Non-linear load with ground fault			Non-linear load with three-phase fault			Fitness function (J)
Method	**Ts** (seconds)	**Tr** (seconds)	**Tp** (seconds)	**Ts** (seconds)	**Tr** (seconds)	**Tp** (seconds)	
Trial and error	3.1	0.26	0.01161	3.5	0.46	0.02058	-
PSO	2	0.31	0.0177	2.2	0.53	0.017	23.41

Table-4. Response characteristics of the rotor angle with the PSO method.

	Non-linear load with ground fault		Non-linear load with three- phase fault	
Method	**Ts (seconds)**	**Tp** (seconds)	**Ts** (seconds)	**Tp** (seconds)
Trial and error	2.4	0.01	3.1	0.028
PSO	1.8	0.012	2	0.037

Table-5. Response characteristics of the load angle with the PSO method.

	Non-linear load with ground fault		Non-linear load with three-phase fault	
Method	**Ts** (seconds)	**Tp** (seconds)	**Ts** (seconds)	**Tp** (seconds)
Trial and error	2.1	0.01	2.7	0.143
PSO	1.6	0.017	2.1	0.214

T_p is the peak time, measured in seconds. From Table-3, it can be seen that the PSO-PID has a lower overshoot and settling time, which means that it damps better compared with the other method. It can be clearly seen that the PSO-PID achieves a steady state faster than the other method, indicating better stability. From the analysis, it is evident that the dynamic performance with the proposed PSO method of tuning a PID controller is better compared with conventional methods with a three-phase thyristor-based non-linear load. The value of the fitness function, J, is also less. The performance of the PSO method may be superior because of the use of the technique of updating the global best position and increased communication between particles. Thus the proposed PSO method is a simpler method provides a better solution and may be used practically.

5. CONCLUSIONS

A PID PSS using PSO has been proposed to enhance dynamic stability. The proposed method was successfully used with a typical single-machine infinite-bus power system having a three-phase thyristor-based non-linear load under different kinds of faults. A Simulink model of the combination of a PID controller and PSS was found to be effective for this load and these fault conditions. The settling time was reduced compared with conventional techniques such as the trial-and-error method. From the machine parameters, it may be concluded that the proposed system is efficient and ensures stability and its performance is better than that of a traditional PID controller.

APPENDIX

Generator parameters (per unit)
Nominal power, Pn = 200 × 10^6 VA
Frequency, fn = 50 Hz
Xd = 1.305; Xq = 0.474
Time constants: T_d = 1.01 seconds; T_d = 0.053 seconds; T_{q0} = 0.1 seconds
Stator resistance, Rs = 2.8544 × 10^{-3}
Inertia coefficient, H = 3.2 seconds

Exciter parameters (per unit)
Low-pass filter time constant, T_r = 20 × 10^{-3}seconds
Regulator gain and time constants: KA = 300; TA = 0.001 seconds
Exciter: KE = 1; TE = 0 seconds
Damping filter gain and time constant: KF = 0.001; TF = 0.1 seconds
Regulator output limits and gain: E_{fmin} = -11.5; E_{fmax} = 11.5; K_p = 0
Initial values of terminal voltage and field voltage: V_{t0} = 1.0; V_{f0} = 1.0

Distributed line parameters
Number of phases, N = 3
Frequency used for RLC specification = 50 Hz
Resistance per unit length (ohms/km): 6.365 × 10^{-3} to 0.1932
Inductance per unit length (H/km): 13 × 10^{-4} to 3 × 10^{-3}
Capacitance per unit length (F/km): 10 × 10^{-9} to 4 × 10^{-9}
Line length (km) = 100

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