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A New Method to Design of PID Controller for Load Frequency Control of Hydro Power Plant based Total Cost Function

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Abstract

This paper presents a novel approach to design of PID controller of Load Frequency Control (LFC) in hydro power plant by selection of PID parameters with a new method. In the conventional power systems the automatic generation control (AGC) of hydro power plants has widely used in frequency control due to having the fast response and high capability for supplying the network against to large demand variation or following disturbance. So, it is important to best performance of frequency control section in hydro power plants. In the suggested method to conducting the simulation, the total cost function is considered which included the time domain characteristics, frequency domain characteristics and Integral of Absolute Error (IAE). Consequently to selection of PID parameters, the Particle Swarm Optimization (PSO) has successfully employed due to finding the global optimum PID parameters based total cost function. Finally, the response of LFC with PID controller based this method is compared with response of LFC without PID controller and with other methods in frequency control of hydro power plant such as transient droop compensation.

Keywords: Hydro Power Plant, Load Frequency Control, PID Controller, Particle Swarm Optimization, Total Cost Function, Transient Droop Compensation.

Introduction

In the modern day power systems, there is several control area that are interconnected to its neighboring areas. Each control area has to generate the requisite load and system losses in a predetermined system frequency. As the load changing in each area the generating energy in power plants must be changed to remain the frequency of system at rated value (i.e. in UK and US the frequency is 50 and 60 Hz respectively). Consequently, the automatic generation control (AGC) or in other words, load frequency controller (LFC) is designed[1].

In recent years, with development of power systems and funding of private sectors in electric markets, having a desirable and reliable electric energy with constant frequency and voltage for delivering to consumers is important for competitionin electric markets. For mentioned reason, it’s necessary to consider preparations for quality improvement of generation and delivering of electrical energy. In the conventional power systems the AGC of hydro power plants have an important role in frequency control due to having the fast response and high capability for supplying the network against to large demand variation or following disturbance happened from generation unit of load section. Although the LFC of others power plants supply the network in hard condition too, but their role in partial load variations is more obvious. Therefore, the control system of hydro power plant is important for stability of network.

On the other hand, due to the system of a hydro power plant is unstable without any controller, it is important to design a control system to have a suitable stability margin in addition of a fast response to a load variation[2]. Another characteristic of hydro power plant control system is to have a non-oscillation response, because of the limitation of position gate.

A proportional integral derivative (PID) controller is used in hydro-generators speed control systems, commonly[1-3]. The PID controller has an adequate system response considering the stability requirements and the performance of its regulating units. The speed deviation is processed by the PID term into a command signal to a series of hydraulic valves and servos to produce a change in gate position of prime mover.A PID controller calculates an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs[2].

There are several methods for determining of coefficients of a PID controller that are proposed in lectures. An H_∞, controller with a PID structure has been proposed by[4]. Based on the D-partition; a graphical technique for tuning PID-type controllers has been described[5]. A constrained optimization has been proposed[6]. The pole placement technique applied to PID control has been discussed[6-8]. Based on a control signal specification and the use of one or two points of the process frequency response, a frequency-domain design method has been presented[9].

In this paper a novel method for suitable design of PID controller is suggested. This method is based on system response features in time and frequency domain, so that a goal function is formed of this characteristics with its own weight factor, then it is optimized by using particle swarm optimization (PSO) method. Kennedy and Eberhart[10] proposed a swarm-intelligence-based parallel optimization algorithm, Particle Swarm Optimization (PSO) in 1995. PSO shows a realistic performance on pattern classification, optimization and controller parameters design[10-11].

Formulation of load frequency controller

The essential elements of the hydraulic plant are described in Figure-1.

The turbine power output changes when the gate opening of turbine changes. The classical transfer function of a hydraulic turbine can be described as below:

$$\frac{\Delta \overline{P_m}}{\Delta \overline{G}} = \frac{1 - T_W s}{1 + \frac{1}{2} T_W s} \tag{1}$$

Where: T_w is water starting time that varies with load so that at full load lies between 0.5s and 4s.

As can be seen, the (1) is a non-minimum phase system. Also, in response to a change in gate position, the initial power surge will be appeared in direct opposite of it. This is take placed due to the pressure across the turbine will be reduced, when the gate is opened, then with accelerating of water with a time constant (T_w), the power output will increase. This means that with increasing the power demand or outing of the one unit, disturbance in network, the hydro power plant output first decreases, then with a specific time constant will increase and supply the power system. This behavior of hydro power plant is important, because, it will be caused to reduce the total generating power and consequently reducing the frequency of system and if the generation unit in area didn't recover loss of generation by increasing the generation power in order to keep the frequency on acceptable range, the frequency protection in area will activate and trip the unit, that will case loss of generation in both units so that even may it cause of loss of whole system and consequently black out. This matter will be important in a small system with less inertia. Therefore the response time and amplitude of hydro power will be important in design of power plant control system.

The basic function of governor is to control the speed/load. When the electrical power demand increase, it will be cause to the mechanical power input of power plant will be less than electrical type and reduce the speed generator (frequency of system) according to Newton's Law of Motion that is given in (2). The governor senses the speed and compares it with reference speed (ω_{ref}).

$$T_{turbine} - T_{electrical} = J_T \frac{d\omega}{dt} \tag{2}$$

Where: J_T is the sum of the moments of inertia in the shafts, $T_{turbine}$ is the sum of all turbine driving torques, and $T_{electrical}$ is the sum of all the counter-torques of the generators.

As mentioned earlier, the hydro turbines have a specific response, for this reason a large transient droop with a high resetting time is added to control system. The term transient droop implies that, for fast deviations in frequency, the governor exhibits high regulation (low gain) while for slow changes and in the steady state the governor exhibits the normal low regulation (high gain). The compensator transfer function is [2]:

$$G_C(s) = \frac{1 + T_R s}{1 + \left(R_T / R_P\right) T_R s} \tag{3}$$

Where: T_R and R_T are obtained using the equations given in 2 as follows:

$$R_T = \left[2.3 - (T_W - 1)0.15\right] \frac{T_W}{T_M} \tag{4}$$

$$T_R = \left[5.0 - (T_W - 1)0.5\right] T_W \tag{5}$$

in which T_M = 2H.

In the modern speed governor of hydraulic turbines the electrohydraulic systems is used. The operation of this type is similar to mechanical type. The electrical components in this model provide greater flexibility and improved performance with dead band and time lags. The speed sensing, permanent droop, temporary droop and other measuring and computing function are performed electrically and shown in figure-2[2-24].

In order to keep the frequency of system in nominal value, often a supplementary control system is required. Proportional integral (PI) and proportional integral derivative (PID) controller are used commonly in most power plants. These controllers have important advantage due to their simplicity and ability. These cause the possibility of a higher response speeds by providing transient gain reduction and transient increase[2].

Design of PID Controller Using PSO Based PID Controller

Problem Description: The typical feedback PID system is as showed at figure-3, where *r(t)* is reference input, *u(t)* is control signal, *y(t)* is output, *d(t)* is external disturbance, *e(t)* is the error of output and reference input, and also is the input signal of controller *C(s)* is PID controller as follow form :

$$C(s) = K_p + \frac{K_i}{s} + K_d s \tag{6}$$

Where K_p, K_i and K_d is proportion constant, integral constant and derivative constant respectively. The time domain of these parameters is as follows:

$$\Delta_f = \{(K_p, K_i, K_d) \in R^3 : K_p > 0, K_i > 0, K_d > 0\} \quad (7)$$

Therefore, the problem of designing the controller can be described as finding the global optimum PID parameters (i.e. K_p, K_i and K_d) to make a good performance for the objective system.

Total Cost Function: As you know, controllers could provide robust performance for a special system if they guarantee the closed-loop stability and achieve the desired performance[13]. In this paper, to obtain the best PID controller, common cost function, within which different typical criteria to design the PID controllers using Particle Swarm Optimization (PSO) are considered.

There are many evaluation criteria for controller performance, such as Integral of Absolute Error (lAE), Integral of Squared-error (lSE) and Integral of Time Weighted- Squared-Error (ITSE) and so on. Though IAE and ISE cause small overshoot, they enlarge the settling time, because these two criteria gave same weight to error in the time horizon. The definition of these two criteria is as follow [11]:

$$IAE = \int_0^{\infty} |r(t) - y(t)| dt = \int_0^{\infty} |y(t)| dt \quad (8)$$

$$ISE = \int_0^{\infty} e(t)^2 dt \quad (9)$$

Recently, a new cost function is reported[8]. It use rising time T_r, settling time T_S and overshoot M_P % represent dynamic performance, use static state error e_{ss} to showing static state performance, use gain margin GM and phase margin PM represent frequency domain performance. Finally a sum of weighted criteria is formed as cost function:

$$J(\gamma) = w_1 T_r + w_2 T_s + w_3 e_{ss} + w_4 \int_0^{\infty} | e(t)^2 | dt + \frac{w_5}{PM} + \frac{w_6}{GM} \quad (10)$$

where γ is the PID controller parameters as follows:

$$\gamma = [K_p \;\; K_i \;\; K_d] \quad (11)$$

According to equation (10), Total cost function is the sum of weighted mutual of gain margin GM and phase margin PM used as supplementation when other cost function cannot satisfy design requirements .The weight factors must properly be set in order to attain the desired specification.

Implementation of Particle Swarm Optimization to Design of PID Controller: For SISO system, from the perspective of design purpose, controller design is a multi-object optimization problem, which involves the dynamic and static, time and frequency characteristics. But due to the un-decoupling feature between performance criteria, the affect on one performance criterion will unavoidably affects the others, thus the controller design problem is down to a single object problem that optimize a function who reflects comprehensive system performance[11]. To solve this problem, Particle Swarm Optimization (PSO) Algorithm is used to finding the global optimum of PID parameters.

Kennedy and Eberhart developed a PSO algorithm based on the behavior of individuals (i.e. particles or agents) of a swarm[13-14]. It has been perceived that members within a group seem to share information among them, a fact that causes to increased efficiency of the group. An individual in a swarm approaches to the optimum by its present velocity, previous experience, and the experience of its neighbors[10-22].

In a physical n-dimensional search space, parameters of PSO technique are defined as follows:

$X_i = (x_{i1}, ..., x_{i2})$: Position individual i.

$V_i = (v_{i1}, ..., v_{i2})$: Velocity individual i.

$Pbest_i = (X_{i1}^{Pbest}, ..., X_{in}^{Pbest})$: Best position of individual i.

$Gbest_i = (X_{i1}^{Gbest}, ..., X_{in}^{Gbest})$: Best position neighbors of individual i.

Using the information, the updated velocity of individual i is modified by the following equation in the PSO algorithm 15:

$$V_i^{k+1} = wV_i^k + c_1 rand_1 \times (Pbest_i^k - X_i^k) + c_2 rand_2 \times (Gbest_i^k - X_i^k) \quad (12)$$

where: V_i^k: velocity of individual i at iteration k, ω: weight parameter, c_1, c_2: weight factors, $rand_1$, $rand_2$: random numbers between 0 and 1, X_i^k: position of individual i at iteration k, $Pbest_i^k$: best position of individual i until iteration k, $Gbest_i^k$: best position of the group until iteration k, Each individual moves from the current position to the next position by equation (13) [15]:

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (13)$$

The search mechanism of the PSO using the modified velocity and position of individual i based on equations (12) and (13) is illustrated in Figure-4[15].

Case studies

For study of proposed method for optimum design of a hydro power plant's PID controller on stability and deviation of frequency, a standard test model is considered. The diagram block of a speed governor system of a hydraulic unit supplying an isolated load is shown in figure-5the speed governor representation include a transient droop compensation G_C and a governor time constant of T_G2.

The generator is represented by its equation of motion with a mechanical starting time T_M. The parameters of governor system are given in table-1.

To assess the efficiency of proposed method on frequency response, the several cases is considered as below
Case 1:With no transient droop compensation i.e. G_C (s)= 1 in Figuge. Case 2: With a transient droop compensation. Case 3: With PID controller that proposed. Case4: With PID controller designed by proposed method in this paper.

Speed Governor System with No Transient Droop Compensation: The frequency and time response of this system are shown in figure-6 and figure-7 respectively. It can be seen from figure-6 that the gain margin (G.M) and phase margin (P.M) are -12.4 dB and -104 degree respectively. As for control theory for stability of the system the gain margin and phase margin must be positive while in this case both parameters are negative. Hence the uncompensated system is unstable and is not appropriate in hydro speed governing systems. The time response of system to step input shown in Figure-7confirm this matter.

Speed Governor System with a Transient Droop Compensation: In this case, transient droop compensation is added to speed governor system for stabilization. The reason of implementation of this particle has been explained earlier in section 2. In figure-8 and figure-9 the response of system in time and frequency domain is shown.

As can be seen in above responses, with adding the transient droop compensation to control system, system becomes stable. In this state, the G.M=5.3 dB and P.M=42.3 degree, are positive and consequently the closed loop system is stable. According to figure-9 the parameters of time response are such as, the time rise T_r=2.66s, the peak time T_P=9.94s, maximum overshoot M_P=34.7% and the settling time T_S=26.5s.

Speed Governor System with PID Controller Using 2: In this case the PID controller is placed in forward path. The PID parameters (K_P, K_I, and K_D) are same as have been considered in 2.

The frequency and time response of this system are calculated as shown in figure-10 and figure-11 respectively.

The gain margin and phase margin show the system in this case is stable too. The value of them is 6.04 dB and 37.1 degree respectively. The time response of system has the rise time T_r=3.36s, peak time T_P=10.4s, settling time T_S=115s and maximum overshoot M_P=20.5%.

The value of time and frequency of responses show that using the PID controller that proposed in 2 has been caused to the system became more appeasable than prior system. This matter is obtained by comparing the value of maximum overshoot and the time parameters with each other in to cases, that in this case the all times (T_r, T_S, T_P) is bigger than prior state, whereas the maximum overshoot has been decreased.

Speed Governor System with PID Controller Designed Using PSO Based Total Cost Function: The PSO is applied to objective function that explained earlier to find the optimum coefficient of PID controller for having a fast and stable response in speed governor control system.Figure-12 and Figure-13 show the frequency and time response of such system to a step input.

In this case the gain margin and phase margin will be 4.52 dB and 52 degree, respectively, that is say to, and thesystem is stable and has a suitable stability margin.

Figure-13 shows the step response of system, for which the rise time T_r=1.47s, peak time T_P=5.7s, settling time T_S=8.55s and maximum overshoot M_P=3.5%. As can be seen the response of system with PID controller that designed by proposed method in this paper, has the more suitable parameters than the previous cases. So this shows that the suggested method is a strong method to find the appropriate design of PID controllers, both in time and frequency domain.

Conclusion

This paper presents a new method to design of PID controller of Load Frequency Control (LFC) in hydro power plant by selection of PID parameters with a new approach. Due to the system of hydro power plant is unstable without any controller, it is important to design a control system to have a suitable stability margin in addition of a fast response to a load variation. To obtain good PID parameters in this paper, total cost function is considered which included the rising time, settling time, percent of overshoot, steady state error, Integral of Absolute Error (IAE), phase margin and gain margin. Then the Particle Swarm Optimization (PSO) method is employed to finding the global optimum PID parameters based total cost function.

Also, with adding the transient droop compensation to control system, system becomes stable. By comparing the obtained results, one can find out that total cost function has good efficiency to finding the most appropriate PID controller due to the importance of time domain parameters and frequency characteristics in performance of LFC in hydro power plants. Also, by comparing the simulations, it can be obtained that the PID controller obtained from PSO and total cost function could get the system stable with best characteristics.

Table-1
The parameters of control system of hydro power plant

R_P	T_G	T_W	T_M	K_D
0.05	0.5	2	10	1

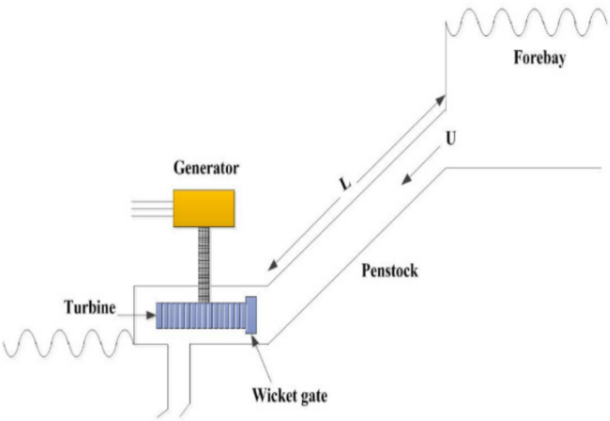

Figure-1
Essential elements of hydraulic power plant

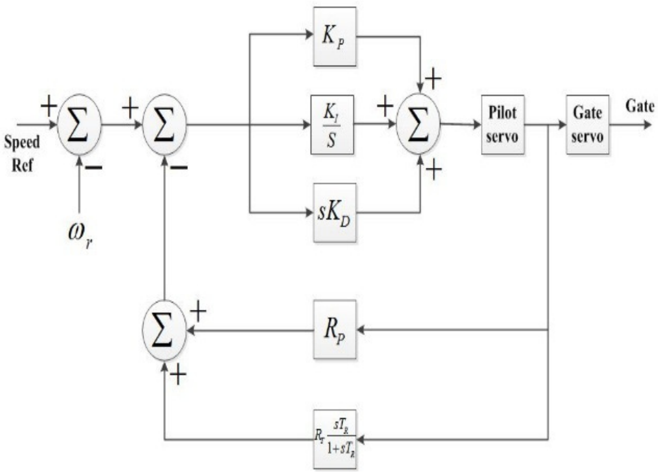

Figure-2
The control block diagram of hydro power plant

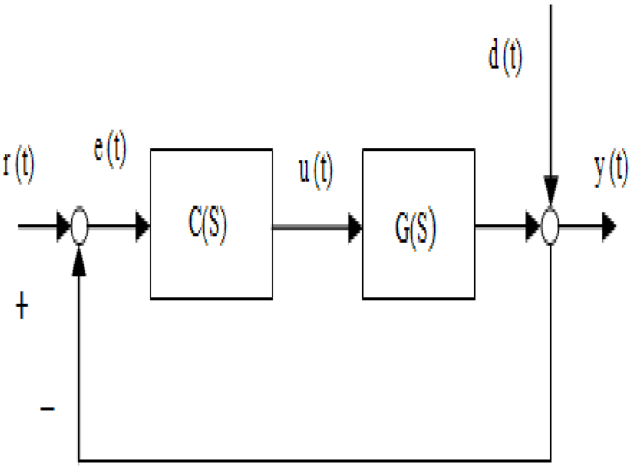

Figure-3
Control system diagram.

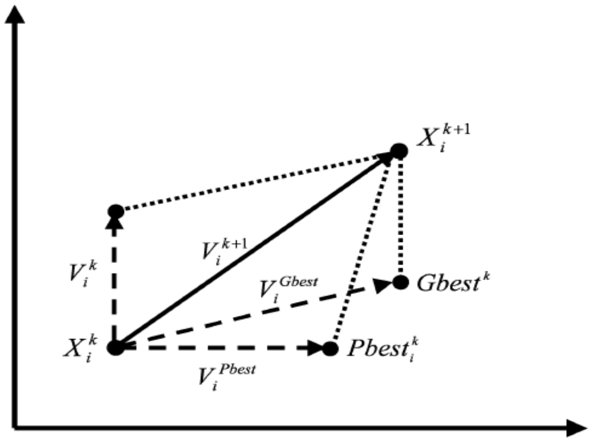

Figure-4
The search mechanism of the particle swarm optimization

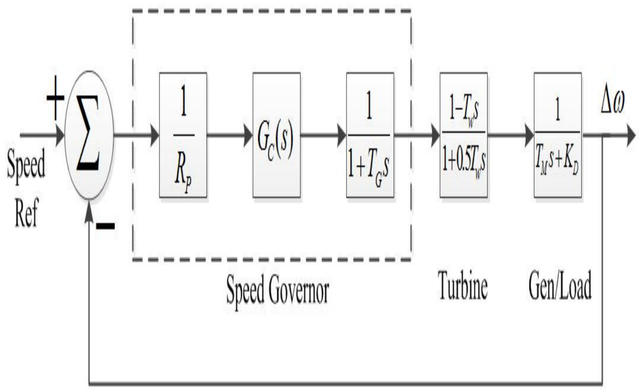

Figure-5
The diagram block of a speed governor system of a hydraulic unit

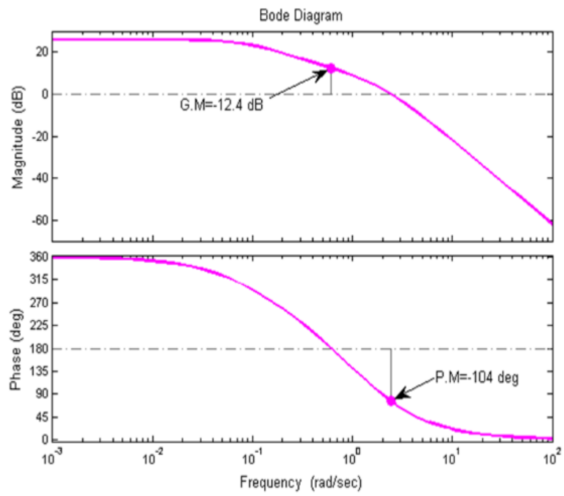

Figure-6
Open loop frequency response with no transient droop compensation

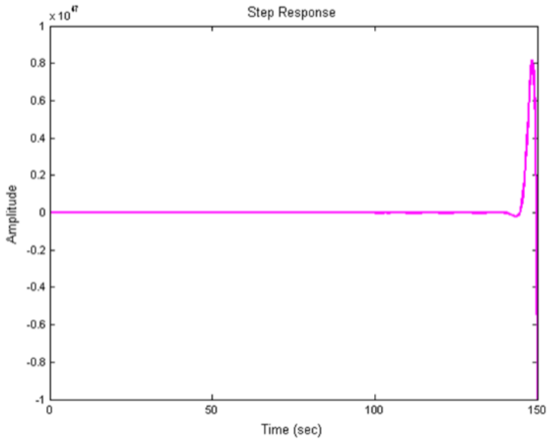

Figure-7
Closed loop time response with no transient droop compensation to step input

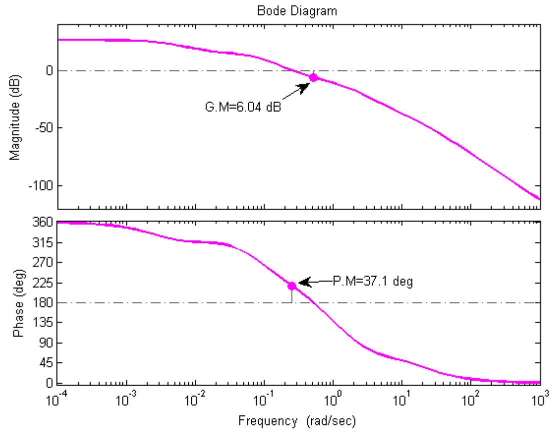

Figure-10
Open loop frequency response with PID controller that proposed in 2

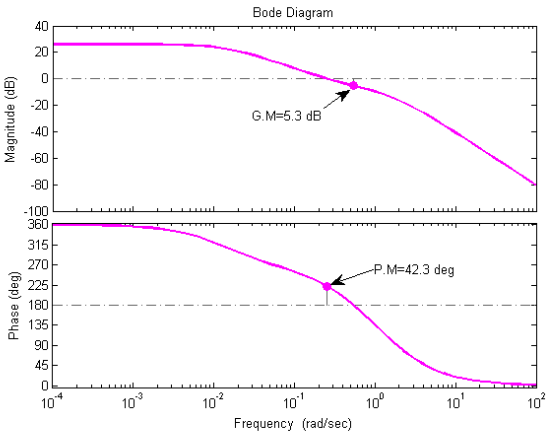

Figure-8
Open loop frequency response with a transient droop compensation

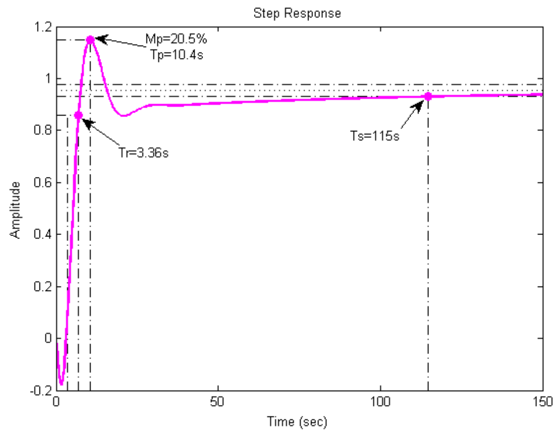

Figure-11
Closed loop time response with PID controller that proposed in 2 to step input

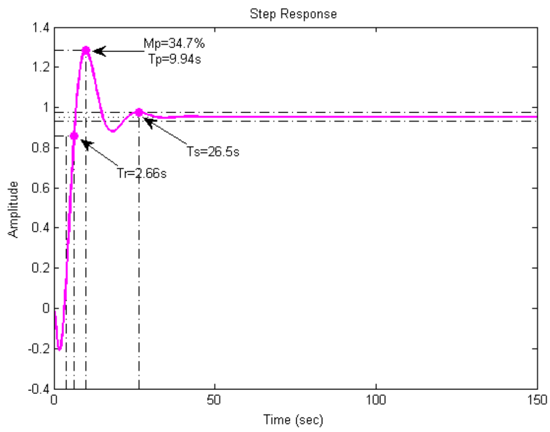

Figure-9
Closed loop time response with a transient droop compensation to step input

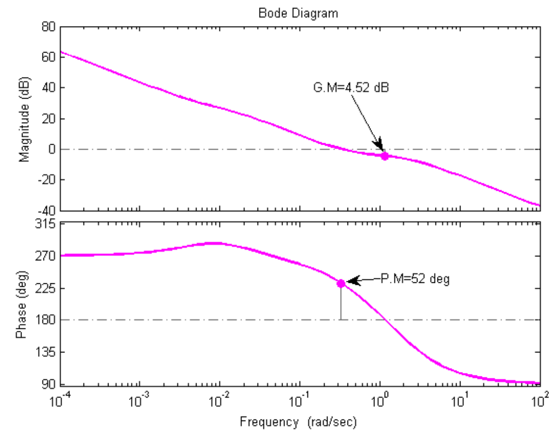

Figure-12
Open loop frequency response with PID controller designed by proposed method in this paper

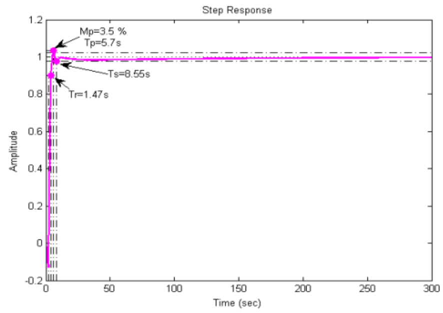

Figure-13
Closed loop time response with PID controller designed by PSO-PID to step input

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