Design and Application of Optimally-Tuned Variable Parameters PID Controller for Nonlinear Engineering Systems

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Abstract

The goal of this article is to investigate the implementation of the Cuckoo Search Algorithm (CSA) as an optimization technique to determine the parameters of variable parameters PID (VP-PID) controller. The VP-PID has three parameters that have to be optimally evaluated. A case of three physical imbedded nonlinearities in a single area electric power system has been selected to test the suitability of the proposed technique. The integral-square error (ISE) criterion has been considered as a part of the objective function together with the percentage overshoot and settling time. Matlab/Simulink software has been used in the simulation process. The simulation results show that the proposed VP-PID controller furnishes a better performance than the conventional PID controller.

Keywords: Proportional-Integral-Derivative controllers (PID); Variable Parameters PID controller (VP-PID); Cuckoo Search Algorithm; Nonlinear physical Systems; Matlab/Simulink

Introduction

In recent years, the problem of maintaining the power and frequency of a power system free from oscillations has become rapidly crucial need because of irregular load variations and imbedded system nonlinearities [1]. The unexpected load variations result in many undesired behaviours such as the mismatch of generated power and load demand for consumption. This can be achieved by the load frequency control (LFC) methods. Nowadays, plenty research work is going on to make the systems intelligent so the systems can successfully serve the benefits of all customers [2].

Several optimization approaches have been recorded in literature that can be applied to tune the conventional PID controller. This includes but not limited to:

Particle Swarm Optimization (PSO),

Genetic Algorithm (GA),

Bacterial Foraging Optimization (BFO) [2].

Furthermore, the LFC and AGC of a single area power system been investigated by a variety of techniques such as gravitational search algorithm [3], the modified particle swarm optimization [4], the artificial neural network [5], optimal control design [6], fuzzy controllers [23], proportional-integral-observer techniques [7], as well as LQR and Legendre wavelet function [8]. Also, the AGC control of single area power system with distributed generation has been investigated in [9]. All these researches deal only with no nonlinearities in the control loops.

On the other hand, the application of VP-PID controller has been studied in different fields by many research workers. The contribution of the variable parameters class of controllers is the cope the desired characteristic of dynamic systems. Based on the desired behavior of the system output, we can assume variable parameter controller. In general, most of the systems will start their response with peak overshoot and sustained oscillations. This can be reduced by implementing a conventional PID controller [10]. The tuned parameters of this class of controllers may be reduced after sometime when the response tends to have steady state. This is the philosophy behind the use of VP-PID controller [11-12].

In this paper, a new evolutionary optimization technique has been used for tuning the variable parameters PID controller. This algorithm is inspired by lifestyle of a bird family called cuckoo. Specific breeding and egg laying of cuckoos bird is the main basis of this optimization algorithm [13-14].

THE CLASSICAL PID CONTROLLER

The PID controller is considered to be an important component in industrial control systems because of its capability of reducing the steady state error and enhancing the dynamic response and other static characteristics of systems. The PID controller is defined, mathematically, by the next equation [15-17]:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d\,e(t)}{dt} \qquad (1)$$

Where $e(t)$ is the system error, K_i is the integral constant, K_p is the proportional constant, K_d is the derivative constant and $u(t)$ is the controller output.

On the other hand, the VP-PID controller can be described by changing controller gains as follows

Case I : The proportional gain parameter (*Kp*) must be high firstly and then decrease to the normal value in order to accelerate system response. Under these conditions, the basic formula of *Kp* is:

$$K_p = C_1 + C_2 * e_{f(i)} \qquad (2)$$

Where C_1 and C_2 are considered constants achieving the following bounderies

$$C_{1_{min}} \leq C_1 \leq C_{1_{max}} \qquad (3)$$

$$C_{2_{min}} \leq C_2 \leq C_{2_{max}} \qquad (4)$$

and $e_{f(i)}$ is the final value of the system error at optimal tuning step *i*.

Case II : The derivative gain parameter (K_d) is increased to prevent the oscillation and overlapping. But, this increase causes the slowdown of the system response. Thus, change of K_d must be from the highest value to the lowest. K_d can be formulized as

$$K_d = C_3 + C_4 * e_{f(i)} \qquad (5)$$

Where C_3 and C_4 are considered constants achieving the following bounderies

$$C_{3_{min}} \leq C_3 \leq C_{3_{max}} \qquad (6)$$

$$C_{4_{min}} \leq C_4 \leq C_{4_{max}} \qquad (7)$$

Case III : Integral gain parameter (K_i) is provided to initialize the steady state error but big values of this parameter causes oscillation and higher overshoot. Thus, change of K_i must be from the highest value to the lowest. K_i can be formulized as

$$K_i = C_6 - C_5 * e_{f(i)} \qquad (8)$$

Where C_5 and C_6 are considered constants achieving the following boundaries

$$C_{5_{min}} \leq C_5 \leq C_{5_{max}} \qquad (9)$$

$$C_{6_{min}} \leq C_6 \leq C_{6_{max}} \qquad (10)$$

CUCKOO SEARCH ALGORITHM (CSA)

The cuckoo search algorithm (CSA) is inspired by the cuckoos breeding behavior [13]. Cuckoos select a random nest for laying their eggs; and a cuckoo can place only one egg at the time. Only the eggs with the highest quality (solutions) are carried over to the next generation. The available number of host nests must be fixed. The host can detect an alien egg with a probability $P_a \in [0, 1]$. In this case, the host bird can either throw the egg out or give up the nest so as to construct a fully new nest in a new location.

In the case of generating new solutions x^{t+1} for a cuckoo i, an Lévy flight method is applied as follows [14].

$$x_i^{(t+1)} = x_i^{(t)} + \alpha \oplus \text{Lévy}(\lambda) \quad (11)$$

Where α is the step size (α≥ 0) and it must be related to the scales of the studied problem. In most cases, it may be selected to be as α = O($\frac{L}{10}$) where L refers to the studied problem characteristic scale. λ is a variable such that $1 < \lambda \leq 3$.

In fact, the Lévy flight in essence presents a random walk whose random step length is drawn from an Lévy distribution. It has an infinite variance with an infinite mean.

$$\text{Lévy} \backsim u = t^{-\lambda}, (1 < \lambda \leq 3) \quad (12)$$

A number of the new solutions should be generated by Lévy around the best solution obtained so far. This will speed up the local search.

The objective function J_i at iteration *i* is given as

$$J_i = \frac{1}{ISE_i} \quad (13)$$

so that

$$ISE_i = \int_0^\infty e_i^2(t)\, dt + \text{Settling Time}_i + \text{P.O.}_i \quad (14)$$

Where P.O.$_i$ and Settling Time$_i$ represent the percentage overshoot and settling time at iteration *i* of optimization procedure [15].

APPLICATION

The controllers described in this research work can be applied on a single area power system. The system consists of the governor; the turbine and the generator; and the load. The block diagrams implementing the conventional PID and the VP-PID controllers is delineated in Fig. 1. The parameters for this system as well as the characteristics of the turbine saturation (GRC), the GDB and the time delay as non-linear elements are listed in [1]. The system is subjected to a sudden load change of 0.05 p.u. The parameters of the Cuckoo Search Algorithm (CSA) are delineated in Table 1. The flow chart of the algorithm is illustrated in Fig. 2.

Table 1. The parameters of the Cuckoo Search Algorithm (CSA)

Parameter	Value
Number of individuals	10
Number of generations	100
The probability (P_a)	0.25

Results and Discussion

The frequency control single area power system with GRC, GDB, and time delay nonlinearities incorporating the classical and VP-PID controllers has been studied in this research. The Cuckoo Search Algorithm has been utilized to tune the proposed controllers. The tuning process of the two controllers has been achieved using the Matlab/Simulink software. The results of the tuning procedure using the ISE criterion are summarized in Table 2.

As stated in the literature, a proportional controller (K_p) will reduce the rise time and will decrease, but never eliminate, the steady-state error. An integral control (K_i) will eliminate the steady-state error, but it may make the transient response worse. A derivative control (K_d) will increase the stability of the system, reducing the overshoot, and improving the transient response [15-17].

As mentioned earlier, the first alternative is to implement the conventional PID controller as noted in Fig. 3. The parameters of the first controller (K_p, K_d, and K_i) are tuned using the Cuckoo Search Algorithm but those of the second controller, PID(s), are obtained a special optimization technique assigned to this block in Matlab.

The frequency deviation curve of the PID controller as shown in Fig. 3 is somewhat acceptable. There are two main notes. The first is the irregular effect at steady state. Second is the high value of ISE. The estimated optimal parameters of this controller are shown in Table 2. The tuning procedure using the CSA gives zero value for the integral gain K_i.

On the other hand, the frequency deviation given by the VP-PID controller is shown in Fig. 4. The estimated parameters variation of the VP-PID using CSA are delineated in Fig. 5. This controller will yield a smaller value for the ISE compared with the conventional PID controller as shown in Table 2. This, of course, can be achieved with little high computation time.

The frequency deviations obtained by the classical and VP-PID controllers are illustrated in Fig. 3 and 4. These curves illustrate that we cannot arrive, exactly, to a zero-state error. This is due to the imbedded system nonlinearities and the absence of integral controller. One more thing, the increase of the time delay will result in unstable system.

Conclusion

In this paper, two classes of controllers have been applied to a single area LFC. The system under study has three sources of nonlinearities, the GRC, GBD, and time delay. The first controller is the classical PID controller while the second is the VP-PID controller. The parameters of these two controllers have been optimally evaluated using the Cuckoo Search Algorithm. Results show that the second controller behaves better than the first one. Furthermore, the effect of dealing with the three embedded nonlinearities, the GRC, GBD, and time delay, have been investigated but more detailed research is recommended.

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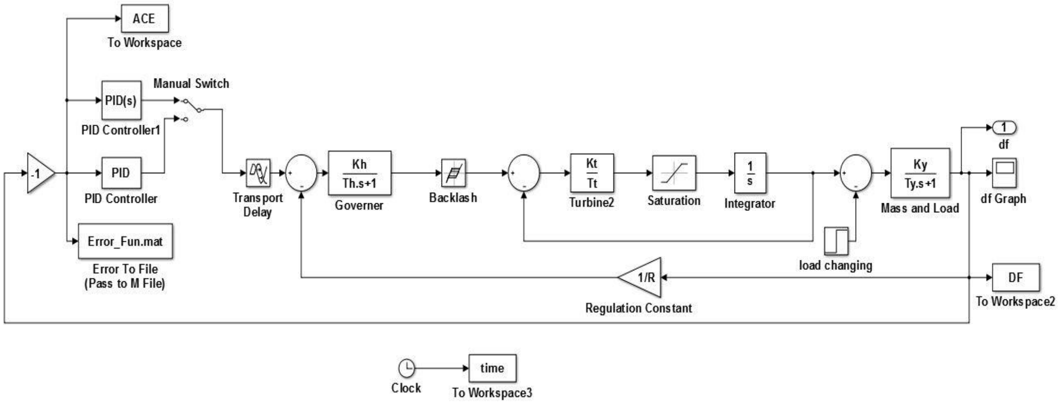

Fig. 1: Diagram of the LFC under investigation using Classical and VP-PID controllers

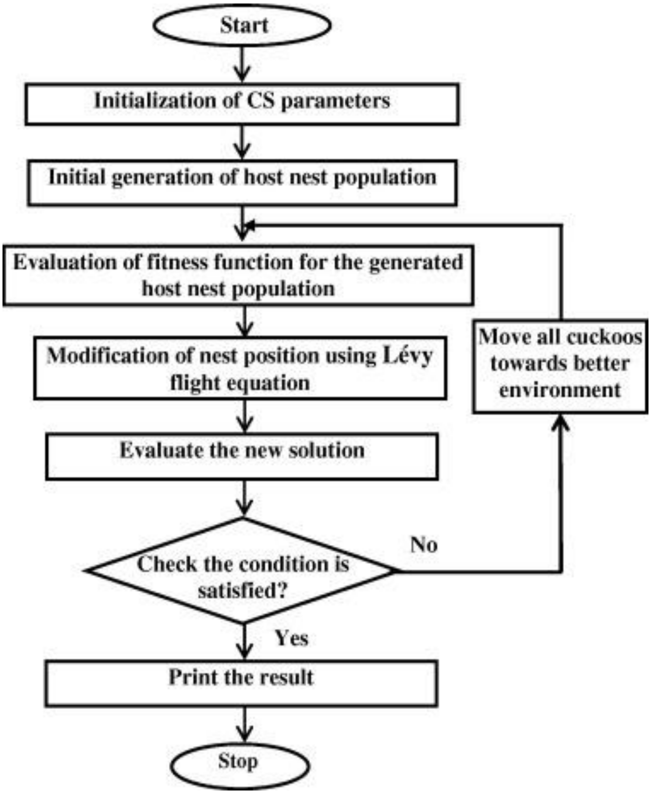

Fig. 2: The flow chart of the Cuckoo Search (CS) Algorithm [13]

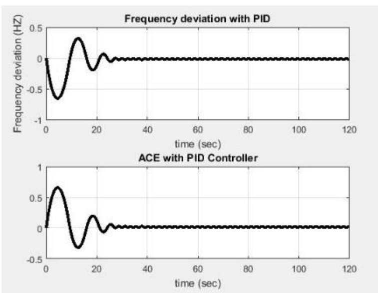

Fig. 3: Results of the PID controller (1.5 seconds time delay)

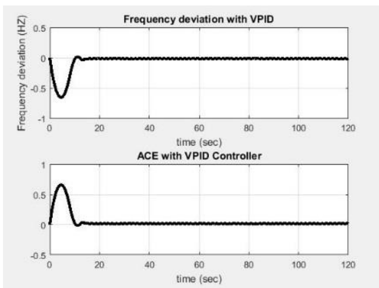

Fig. 4: Results of the VP-PID controller (1.5 seconds time delay) (VPID=VP-PID)

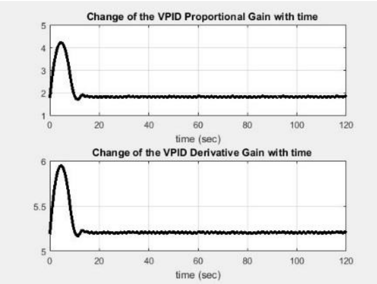

Fig. 5: Variation of VP-PID controller gains (1.5 seconds time delay)

(VPID=VP-PID)

Table 2. Results of the two proposed controllers

Controller	Parameters					
PID Controller	K_p	K_d	K_i	-	-	-
	2.4491	1.8840	0	-	-	-
ISE	12.2269					
	C_1	C_2	C_3	C_4	C_5	C_6
VP-PID controller	1.7509	3.7527	5.1860	1.1559	0	0
ISE	9.4966					