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Regular paper

Application of Genetic Algorithm in Optimal PID Gain Tuning for Heavy Duty Gas Turbine Plant

Gas turbine generators are commonly used in isolated operation. These generators may become unstable under severe load fluctuations. To maintain system stability an effective design and control is required. Ziegler-Nichols' method (ZN) and performance index method have been used to design PID controller. Genetic algorithm (GA) is used for finding out the optimal gain values of PID controller. The results show that GA tuned PID controller provides optimal time domain performance of the system.

Keywords: Gas turbine, PID controller, Genetic Algorithm

1. Introduction

In small networks and in isolated operations like oil fields in desert area, offshore installations and bio-gas plants, gas turbine generators are commonly used. Under severe load disturbance, such systems tend to become unstable causing an inevitable plant shut down. Therefore, an effective design and control is required to maintain system stability.

Rowen has developed the transfer function block diagram of heavy duty gas turbine plant [1], designed, calculated and verified the system gains, coefficients and time constant by test and actual field experience accumulated from numerous installations in many different applications. In dynamic analysis of combined cycle plants [2], twin shaft gas turbine model [3], combustion turbine model [4], biomass-based gas turbine plant [5] [6] and even in micro turbine power generation [7] this transfer function model has been used. Basically Rowen's model has speed, temperature and acceleration controllers. The speed controller by governor control is found to be an essential controller for the effective operation of gas turbine plant [8]. The droop governor rather than the isochronous one is found to be the appropriate governor for gas turbine plants [9], the droop setting being optimized [10]. The optimized droop governor does not settle the system speed to the reference value and therefore there is a need for an effective secondary controller to make the steady state error zero.

This paper discusses and illustrates the tuning of PID controller using Ziegler – Nichols' method, Performance Index method and Genetic Algorithm for zero steady state error. GA tuned PID controller is found to yield optimum response.

2. Mathematical Model for Gas Turbine Plant

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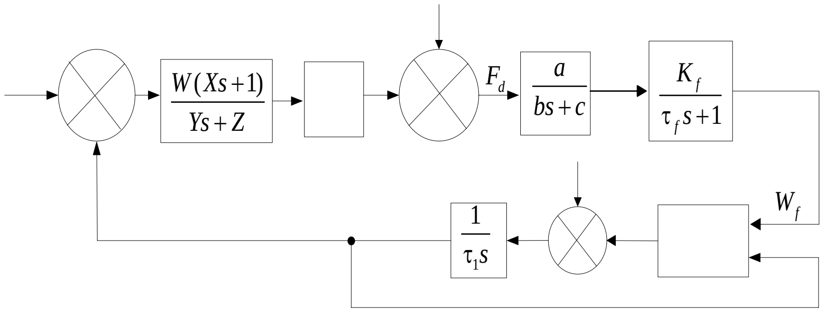

Figure 1. Transfer function model of gas turbine plant.

The transfer function model of gas turbine together with its control and fuel system is shown in Figure 1. The speed governor is the primary means of gas turbine control. The droop governor, found to be the appropriate one is a straight proportional controller which operates on the speed error. The gas turbine plant requires 23% of rated fuel to support self sustaining no load conditions [1].

The fuel system consists of two time constants in which one is associated with the gas valve positioning system.

$$e_1 = \frac{a}{bs+c} F_d \tag{1}$$

The second is the volumetric time constant associated with the downstream piping and fuel gas distribution manifold.

$$W_f = \frac{K_f}{\tau_f s+1} e_1 \tag{2}$$

The torque characteristics of gas turbine are essentially linear with respect to fuel flow and turbine speed.

$$f_1 = 1.3(W_f - 0.23) + 0.5(1 - N) \tag{3}$$

The rotor time constant is defined as the time necessary for the rotor to double its speed if the initial rate of speed change is maintained after removal of rated load torque. The rotor speed is compared with the reference speed and the error is given to the speed governor.

3. PID Controller

PID Controller is predominantly used for industrial control due to its ease of operation[11]. The standard form of the controller is expressed by the governing function

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{de(t)}{dt} \tag{4}$$

Where u(t) is the summation of three dynamic functions of the error e(t) from a specified reference output.

The proportional control is used for increasing the loop gain to make the system less sensitive to load disturbance. The integral control is used to eliminate steady state errors. The derivative control is used to improve closed loop system stability. The parameters of PID controller have to be chosen properly, in order to achieve the desired performance.

In this paper Ziegler-Nichols' method (ZN), Performance Index method and Genetic Algorithm have been used for the PID tuning.

3.1 PID Tuning by ZN Method

The PID tuning proposed by Ziegler and Nichols [12] is a standard method developed empirically through the simulation of a large number of process systems to provide a simple rule. In this method, the process is kept under closed loop Proportional (P) control, the gain of the P controller at which the loop oscillates with constant amplitude being referred as the ultimate gain (K_{cu}). The ultimate gain is the gain at which the loop is at the threshold of instability. Ultimate period (T_u) is the period of these sustained oscillations. The higher the ultimate gain, it is easier to control the process loop. PID controller is tuned using the parameters K_{cu} and T_u.

3.2 PID Tuning by Performance Index

The PID controller is designed to make the system speed to settle at rated value. The tuning by performance index is based upon the criterion that the overall performance in terms of certain measurable quantities should be a minimum one. The design procedure will become logical and straight forward if a single performance index (J) could be established, on the basis of which, the goodness of the system response is derived. Extreme value of this index (J) obtained at the point of minimum slope then corresponds to the optimum value.
The following are the list of performance indices used for PID tuning,

- The integral of the square of the error criterion (ISE).
- The integral of the time multiplied absolute value of the error criterion (ITAE).
- The integral of the time multiplied square of the error criterion (ITSE).

In order to reduce the weighting of the large initial error and to penalize the small errors occurring later in the response more heavily, the above indices are proposed.

ISE of the system is measured fixing the value of k_i and k_d to zero but varying k_p. The optimum value of k_p is determined at the point of minimum slope from the graph drawn between ISE (J) and k_p. Keeping the optimum k_p value and considering k_d to be zero, k_i is varied and a plot of J Vs k_i is drawn. The point of minimum slope of J Vs k_i yields the optimum value of k_i. Finally, the optimal values of k_p and k_i are fixed and k_d is varied to determine the optimal k_d value.

The procedure adopted as above for obtaining optimal values of k_p, k_i and k_d using ISE is repeated for ITAE and ITSE.

3.3 PID Tuning by Genetic Algorithm

The Genetic Algorithm (GA) can be seen as a search algorithm based on the concept of natural selection and genetic inheritance [13]. It searches an optimal solution to the problems by manipulating a population of string that represents different potential solutions.

A string structure in GA represents each parameter. This is similar to the chromosome structure in natural genes. The population is a group of strings. After mutation and crossover between strings in a given population, a new generation of strings evolves. For each generation, all the populations are evaluated based on their fitness. An individual with larger fitness has a higher chance of evolving into the next generation.

The features of GA are different from other search techniques in several aspects. The algorithm works with a population of strings. By searching many peaks simultaneously, GA reduces the possibilities of trapping into a local minimum. Coding of parameters is used instead of using the parameters themselves which is useful to evolve the next state with minimum computations. Finally, fitness of each string is evaluated to guide its search. There is no need for computations of derivatives or other auxiliary knowledge. The framework of Genetic Algorithm is shown in Figure 2.

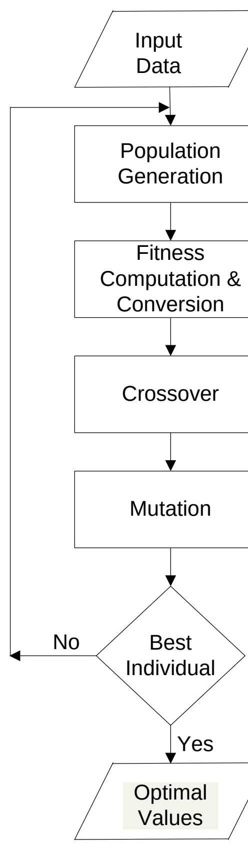

Figure 2. Framework of genetic algorithm.

a. Population Generation:

A random number generator is used to generate individual. The chromosome length of an individual is equal to the number of parameter to be optimized. For the enhancement of GA, these parameters are first concentrated into strings. Binary coding is then applied to encode concentrated parameter string. In the current study, population size is 10 with a string length of 30 bits. Number of variables to be optimized is 3 and therefore 10 bits are used for each variable. An initial population is randomly created considering the population size and the number of variables.

b. Fitness computation:

Different fitness functions are used in this study. They are

- The integral of the square of the error criterion (ISE).
- The integral of the time multiplied absolute value of the error criterion (ITAE).
- The integral of the time multiplied square of the error criterion (ITSE).

c. Parent Selection:

This process is similar to spin of roulette wheel. The roulette selection algorithm is implemented based on the computed fitness of individuals. A new population pool can be formed by several spins of roulette wheel. Since the slot size is made proportional to the individual fitness, most selected individuals come with higher fitness in the new population pool. The averaged fitness of the new pool was higher than that of the original pool. A pair of parents is then selected from this new pool, ready for a further genetic operation.

d. Crossover:

A crossover point along the chromosome is randomly selected. Part of the genes on the side of this point is given to the child. The rest of the child’s genes come from the other side of the other parent. The crossover is performed with a probability of 0.7.

e. Mutation:

A mutation operator, which arbitrarily alters one or more components of a selected structure, provides the means for producing new information into the population. The presence of mutation ensures that the probability of reaching any point in the search space is not zero. The mutation is randomly applied with low probability, typically in this study it is taken as 0.05.

f. Scenario Decision:

The number of generated individuals in the population pool and the number of generations are experimentally decided. All the individuals in each generation must be evaluated. If the errors are improved, genes of this individual can be decoded as optimal values.

4. Simulation Results

The transfer function model of the gas turbine explained in Section 2 is simulated using MATLAB/Simulink [14] for unit step load disturbance. The response is shown in Figure 3. The response shows the occurrence of the steady state error.

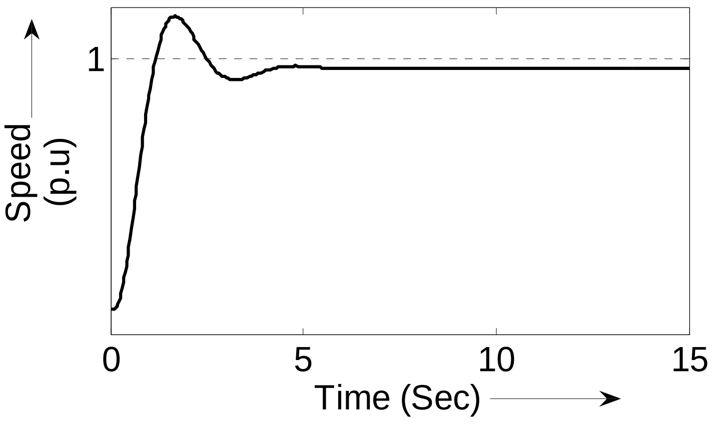

Figure 3. Response of gas turbine plant without secondary controller

The optimal values of PID controller using ZN method is shown in Table 1.

Table 1. Tuned PID values using ZN Method

Method	**k_p**	**k_i**	**k_d**
ZN Method	3.33990	5.2917	0.5267

The gas turbine plant with the above mentioned PID controller is simulated over a suitable time following an applied step in load at t=0. The response in Figure 4 shows that ZN tuned PID controller removes the steady state error.

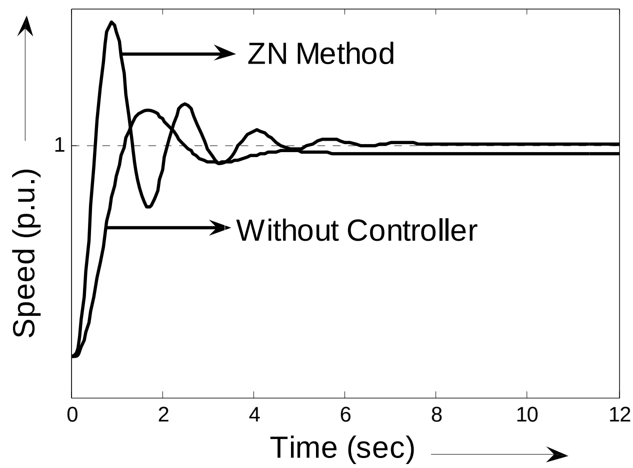

Figure 4. Response of gas turbine plant without controller and with PID controller tuning using ZN method – A Comparison.

The performance index ISE, ITAE and ITSE for the heavy duty gas turbine plant are shown in Figure 5, 6 and 7 respectively. From these figures, the optimal value of k_p, k_i and k_d for various performance indices are obtained and tabulated in Table 2.

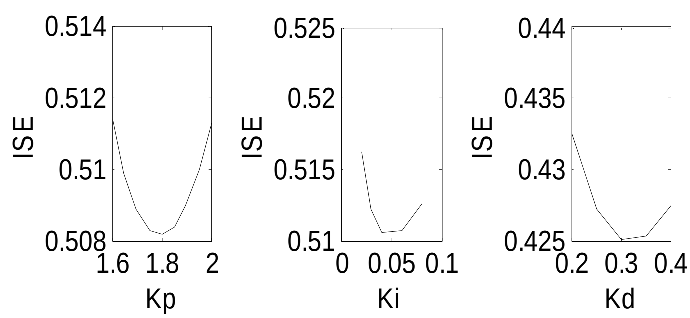

Figure 5. Performance index ISE of gas turbine plant

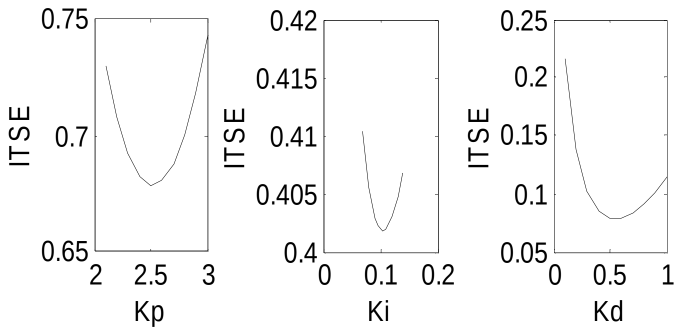

Figure 6. Performance index ITAE of gas turbine plant

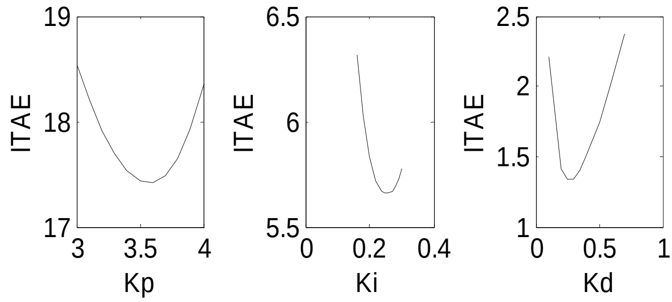

Figure 7. Performance index ITSE of gas turbine plant

Table 2. Tuned PID values using performance index methods

Performance Index (J)	k_p	k_i	k_d
ISE	1.8	0.04	0.3
ITSE	2.5	0.04	0.3
ITAE	3.6	0.25	0.25

The response of heavy duty gas turbine with these tuned values is shown in Figure 8. The response shows that, there is a steady state error in ISE tuning. The ITAE tuning is having more oscillations. ITSE tuned PID controller settles the speed exactly at rated value with less oscillation and at a faster rate. The response is tabulated in Table 3. Though ITSE is not comfortable computationally, less sensitive, it gives better design of PID controller.

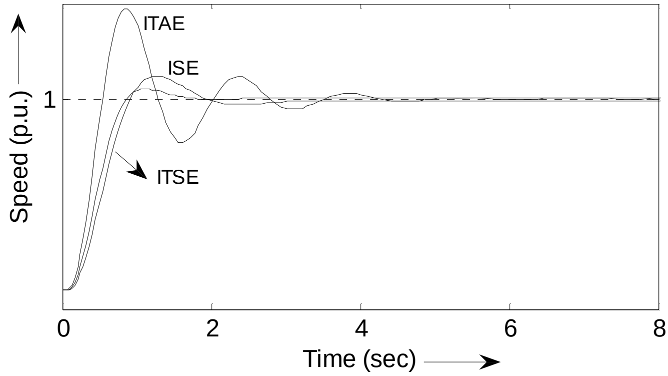

Figure 8. Comparison of gas turbine plant response with PID controller, tuned using ISE, ITAE and ITSE.

Table 3. Tabulated response of gas turbine plant with performance index tuned PID values

Performance Index (J)	**Peak Over Shoot (p.u.)**	**Settling Time (sec)**	**Steady State Error (p.u.)**
ISE	1.12	3.75	0.01
ITSE	1.055	2.5	0.0
ITAE	1.475	7.5	0.0

The main disadvantage in the performance index method is that the various gain values are obtained separately, not simultaneously. This will not give the global optimum. But while using GA, all the gain values are searched simultaneously.

The optimal values of PID controller are obtained using GA with various fitness functions like ISE, ITAE and ITSE and the values are furnished in Table 4.

Table 4. Tuned PID values using GA

Method	$\mathbf{k_p}$	$\mathbf{k_i}$	$\mathbf{k_d}$
ISE	15.5478	0.2633	3.127
ITSE	12.1771	0.1588	2.5541
ITAE	6.1999	0.1281	1.4147

The response of the gas turbine plant with the above mentioned PID controllers is simulated with a step load disturbance. The responses are shown in Figure 9 for comparison. The response is tabulated in Table 5. The comparison indicates that the time domain response of PID controller using ITAE is well damped one than ISE and ITSE.

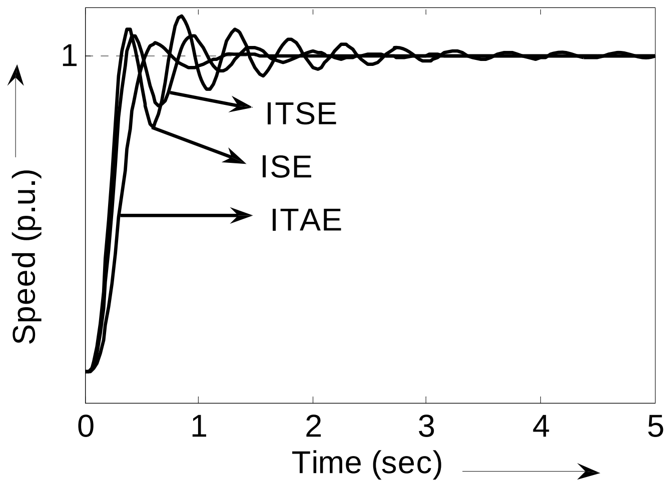

Figure 9. Comparison of gas turbine plant response with various PID controllers tuned using various fitness functions in GA.

Table 5. Tabulated response of gas turbine plant with GA tuned PID values

Performance Index (J)	Peak Over Shoot (p.u.)	Settling Time (sec)	Steady State Error (p.u.)
ISE	1.085	>5.0	0.0
ITSE	1.062	2.75	0.0
ITAE	1.04	1.75	0.0

5. Conclusion

Using ZN, Performance index and GA, PID controller has been designed for heavy duty gas turbine plant. The ZN tuned PID controller makes the steady state error zero with more peak over shoot. Performance index method reduces the peak over shoot. In Genetic Algorithm tuned PID controller, ITAE penalizes long duration transients, and it is much more selective than ISE and ITSE. The Genetic Algorithm tuned PID controller developed in this paper provides well damped and fast time domain response.

Appendix

f_1 = Turbine torque
W_f = Per unit fuel flow
K_f = Fuel System gain constant = 1
τ_f = Fuel system time constant = 0.4
N = per unit turbine rotor speed
s = Laplace operator
e_1 = Valve position
F_d = Per unit fuel demand signal
a,b,c = Fuel system transfer function coefficients
a=1; b=0.05; c=1

W,X,Y,Z = Governor transfer function coefficients
W=K_d; X=0; Y=0.05; Z=1
K_d = Droop gain = 2 t0 10%
τ_1 = Rotor time constant = 12.2
k_p, k_i, k_d = PID parameters
t = time
u(t) = control signal
e(t) = error signal

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