# Optimisation of CCPP speed control parameters using genetic algorithm

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**Abstract:** This paper is focused on using the conventional Proportional, Integral and Derivative (PID) controllers optimised using Genetic Algorithm (GA) to control the speed of a Combined Cycle Power Plant (CCPP). The system is simulated using MATLAB/Simulink and the PID controller is implemented as a box in the simulation where the parameters KP, KI and KD have been determined using the GA. Different types of the PID controller have been tried in order to obtain the required speed response which achieves certain transient and steady state behaviour.

**Keywords:** gas turbine; steam turbine; combined cycle power plant; power system; modelling and control; PID controller; genetic algorithm; Matlab/Simulink.

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## 1 Introduction

Gas turbines are important for electric power generation, specially the Combined Cycle Power Plants (CCPP). For this electric power generation, the dynamics of the gas turbines become increasingly more important. Combined cycle gas turbines integrate the technologies of both the gas turbine and the steam turbine. The exhaust gases from the gas turbine are fed into the Heat Recovery Steam Generator (HRSG), which produces a supply of steam to drive the steam turbine (Chase, 2001; Boyce, 2002; Horlock, 2003; Walsh and Fletcher, 2004; Giampaolo, 2006).

Moreover, there has been continuous development of CCPPs due to their increased efficiency and their low emissions (Bagnasco et al., 1998; Zhang and So, 2002; Kakimoto, 2003; Kunitomi et al., 2003; Lalor et al., 2005; Mantzaris and Vournas, 2007).

During the past several years, requests have been received for simplified mathematical models of CCPP. The intent of these studies has been the investigation of power system stability, the development of dispatching strategy and contingency planning for system upsets. Rowen has presented ‘Simplified mathematical representations of heavy-duty gas turbines’ with single shaft, together with its control and fuel systems (Rowen, 1983).

The work done in this paper relies on the model developed by Kunitomi et al. (2003) which is based on the model presented by Rowen (Rowen, 1983).

The basic controllers in the CCGT model are the Inlet Guide Vane (IGV) control, the temperature control and the frequency dependency of the Gas Turbine (GT) output. This paper focuses on the speed control loop (Ferrari-Trecate et al., 2004).

## 2 CCPP control loops

Two control loops are introduced so that the combined cycle unit functions properly. The first one is the frequency control loop, which includes the speed governor. The second one is the overheat control loop.

### 2.1 *Speed control*

The first loop involves the speed governor, a speed governor is the main means of control on the gas turbine which detects frequency deviation from the nominal value and determines the fuel demand signal ($F_d$) so as to balance the difference between generation and load. Autonomous operation is assumed, so power imbalances will cause electrical frequency deviations as shown in the rotor inertia block of Figure 1.

### 2.2 *Temperature control*

The second loop is the temperature control and consists of two branches. The normal temperature control branch acts through the air supply control. When the temperature of the exhaust gases exceeds its reference value ($T_r$), this controller acts on the air valves to increase the airflow, so as to decrease exhaust gas temperature (air control loop in Figure 2). In certain situations, however, this normal temperature control is not enough to maintain safe temperatures. Thus, in cases of a severe overheat; the fuel control signal is reduced through a Low-Value-Select (LVS) function that determines the actual fuel flow into the combustion chamber (Chase, 2001; Horlock, 2003; Giampaolo, 2006).

**Figure 1** Single-shaft combined cycle model

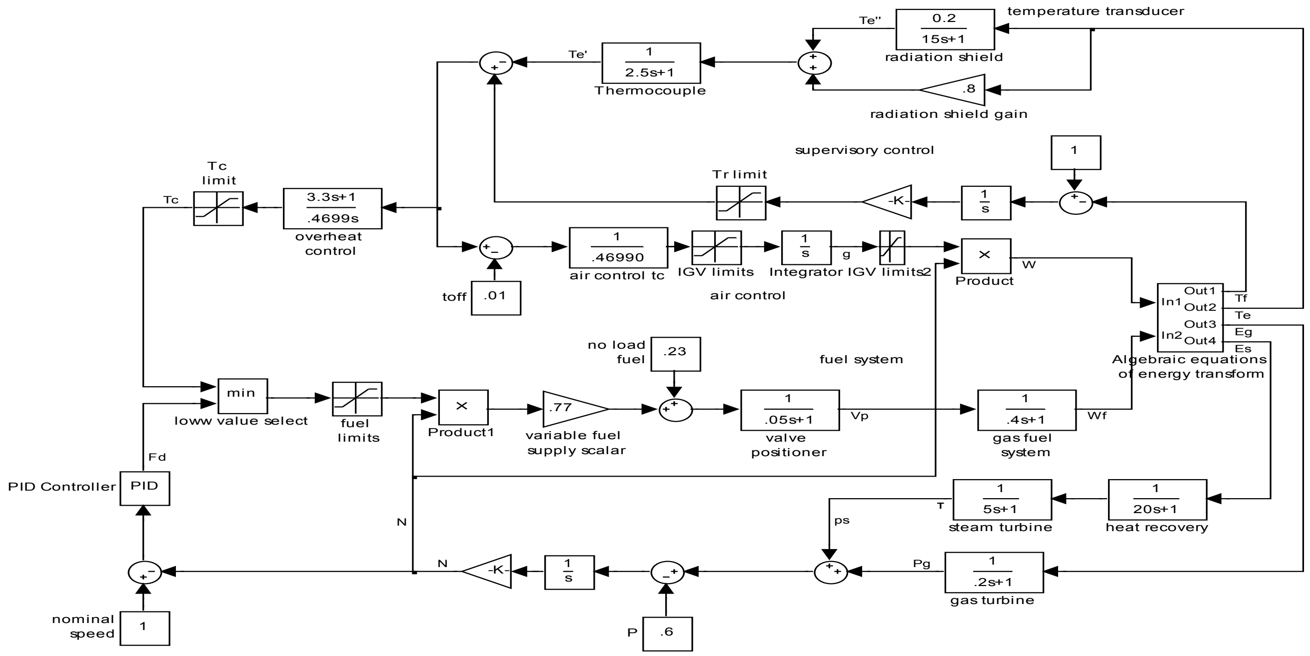
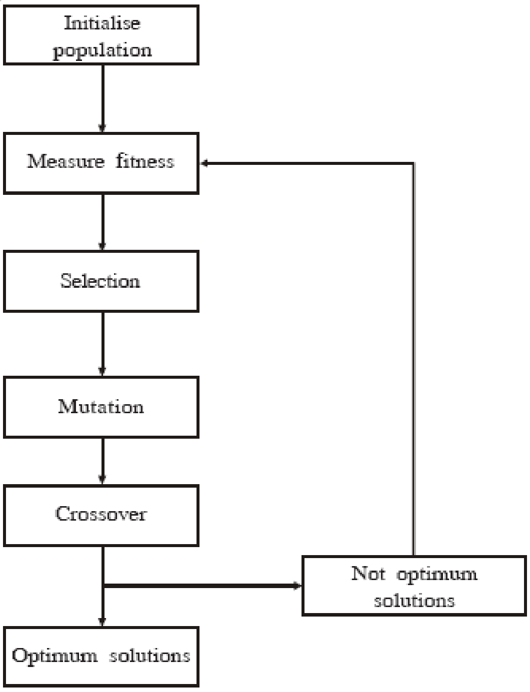


**Figure 2** Flowchart of a binary GA



## 3 The PID controller

The PID controller has been in use for over a century in various forms. PID stands for ‘proportional, integral, derivative’. These three terms describe the basic elements of a PID controller. Each of these elements performs a different task and has a different effect on the functioning of a system. In a typical PID controller these elements are driven by a combination of the system command and the feedback signal from the object that is being controlled (usually referred to as the ‘plant’). Their outputs are added together to form the system output.

Although various PID tuning techniques have been introduced in theory as well as in industry, they usually require the practitioners to possess a great deal of control system knowledge and tuning experience. The tuning procedure has been treated through many practical procedures. The application of some new techniques such as fuzzy approach, neural networks and Genetic Algorithms (GA) has been studied in the 1990s. The tuning of PID controllers is mainly concerned with the determination of the proportional gain (KP), the integration constant (TI) and the derivative constant (KD).

The equation describing a PID controller is:

$$u(t) = \mathrm{KP}e(t) + \mathrm{KI}\int e(t)\mathrm{d}t + \mathrm{KD}\frac{\mathrm{d}e(t)}{\mathrm{d}t} \tag{1}$$

where $e$ = error, KP is the proportional gain, KI is the integral gain and KD is the derivative gain (Dorf and Bishop, 1997; Liu and Daley, 2001; Ferrari-Trecate et al., 2004; Gundogdu, 2005; Kim and Park, 2005; Sadasivarao and Chidambaram, 2006).

The system response may be judged through some error estimation criterion given as (Dorf and Bishop, 1997).

$$J_n(\theta) = \int_0^\infty t^n [e(\theta,t)]^2 \,\mathrm{d}t \tag{2}$$

where θ is a vector containing [KP KI KD], $t$ is the time, and

$n = 0$ for Integral Square Error (ISE) criteria

$n = 2$ for Integral Square Error Time (ISTE) criteria

$n = 3$ for Integral Square Error-Square Time ($\mathrm{IST^2E}$) criteria.

## 4 Genetic algorithm

The genetic algorithm is an optimisation and search technique based on the principles of genetics and natural selection. A GA allows a population composed of many individuals to evolve under specified selection rules to a state that maximises the ‘fitness’ (i.e., minimises the cost function). The GA begins, like any other optimisation algorithm, by defining the optimisation variables, the cost function and the cost. It ends like other optimisation algorithms too, by testing for convergence. In between, however, this algorithm is quite different (Dorf and Bishop, 1997; Banzhaf et al., 1998; Dorf and Bishop, 2001; Fleming and Purshouse, 2002; Haupt and Haupt, 2004). A path through the components of the GA is shown in Figure 2.

### *4.1 Reproduction*

During the reproduction phase the fitness value of each chromosome is assessed. This value is used in the selection process to provide bias towards fitter individuals. Just like in natural evolution, a fit chromosome has a higher probability of being selected for reproduction. The probability of an individual being selected is, thus, related to its fitness, ensuring that fitter individuals are more likely to leave offspring.

### *4.2 Crossover*

Once the selection process is complete, the crossover algorithm is initiated. The crossover operations swap certain parts of the two selected strings in a bid to capture the good parts of old chromosomes and create better new ones. The crossover probability indicates how often crossover is performed.

### *4.3 Mutation*

Mutation is the occasional random alteration of a value of a string position. It is considered a background operator in the GA. The probability of mutation is normally low because a high mutation rate would destroy fit strings and degenerate the GA into a random search. Once a string is selected for mutation, a randomly chosen element of the string is changed or ‘mutated’.

## 5 GA based tuning of the controller

The optimal value of the PID controller parameters KP, KI and KD is to be found using GA. All possible sets of controller parameter values are particles whose values are adjusted to minimise the objective function, which in this case is the error criterion, and it is discussed in detail. For the PID controller design, it is ensured that the controller settings estimated results in a stable closed-loop system.

### 5.1 *Initialisation of parameters*

To start with GA, certain parameters need to be defined. These include population size, bit length of chromosome, number of iterations, selection, crossover and mutation types, etc. Selection of these parameters decides, to a great extent, the ability of the designed controller (Kunitomi et al., 2003; Kim and Park, 2005). The range of the tuning parameters is considered between 0 and 10.

Initialising the values of the parameters for this paper is as follows:

- Population size = 10
- Maximum generation = 40
- Number of bits of each variable = 16
- Probability of crossover = 0.8
- Probability of mutation = 0.1
- Lower bounds of each variable are zeros
- Upper bounds of each variable = 20

### 5.2 *Objective function for the GA*

The objective functions considered are based on the error criterion. A number of such criteria are available. In this paper controller's performance is evaluated in terms of ISE criteria. The error criterion is given as a measure of performance index.

In this paper we consider the limits for the equation from time, *t* = 0 to *t* = Ts, where Ts is the settling of the system to reach steady state condition for a unit step input (Liu and Daley, 2001; Mantzaris and Vournas, 2007).

### 5.3 *Termination criteria*

Termination of optimisation algorithm can take place either when the maximum number of iterations gets over or with the attainment of satisfactory fitness value. Fitness value, in this case is nothing but reciprocal of the magnitude of the objective function, since we consider for a minimisation of the objective function. Here the termination criterion is considered to be the attainment of satisfactory fitness value, which occurs with the maximum number of iterations as 100.

## 6 Application results

The error signal *e*(*t*) defined in equation (1) is given as the difference between the working speed (*N*) and the set point of speed as shown in Figure 1. Types of controllers used are as follows.

### 6.1 *Conventional PI controller*

The parameters of the PI controller (KP and KI) have been optimised using GA. The performances of turbine speed *N* (normalised), total generated power of the steam and gas turbines, and exhaust temperature $T_e$ when different loads are applied (P = 0.4, 0.7 and 0.9 pu) are delineated in Figures 3–5.

**Figure 3** System response at KP = 19.176, KI = 5.155 and P = 0.4 (see online version for colours)

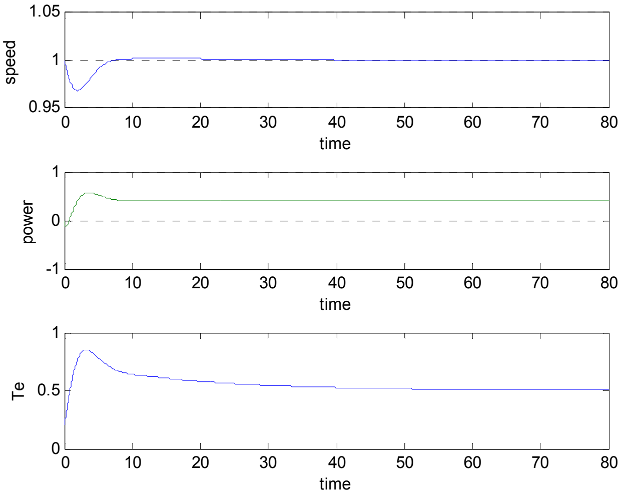


**Figure 4** System response at KP = 19.176, KI = 5.15 and P = 0.7 (see online version for colours)

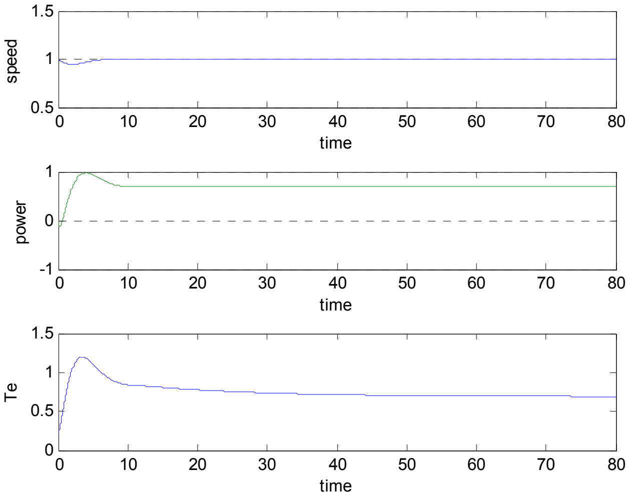
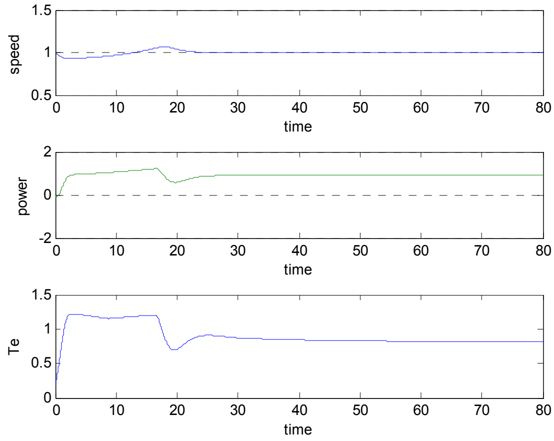


**Figure 5** System response at KP = 19.175708, KI = 5.155413 and P = 0.9 (see online version for colours)



## 6.2 *Conventional PID controller*

The performances of turbine speed *N* (normalised), total generated power of the steam and gas turbines, exhaust temperature $T_e$ when different loads are applied (P = 0.4, 0.7, 0.9 and 1 pu) are delineated in Figures 6–9.

**Figure 6** System response at KP = 19.721, KI = 14.891, KD = 17.277 and P = 0.4 (see online version for colours)

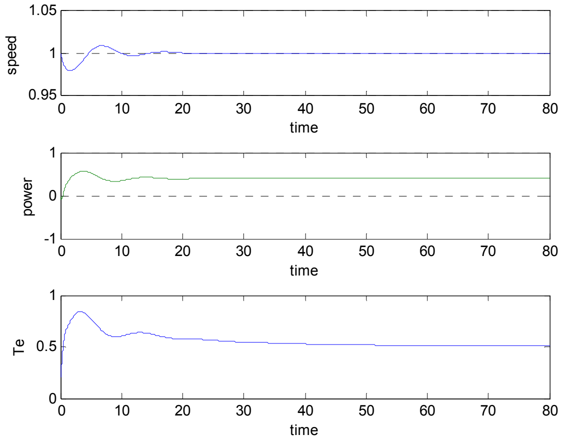


**Figure 7** System response at KP = 19.721, KI = 14.891, KD = 17.277 and P = 0.7 (see online version for colours)

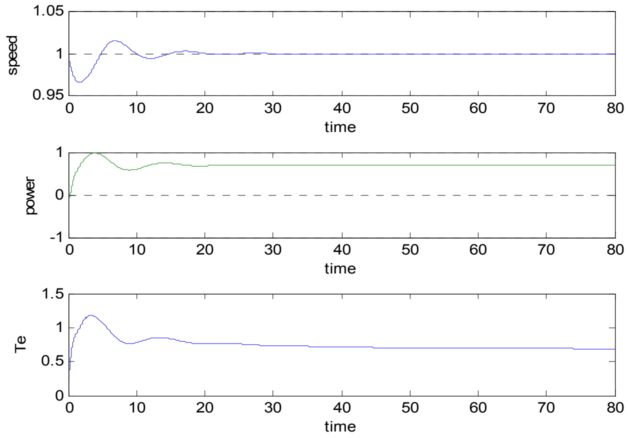


**Figure 8** System response at KP = 19.721, KI = 14.891, KD = 17.277 and P = 0.9 (see online version for colours)

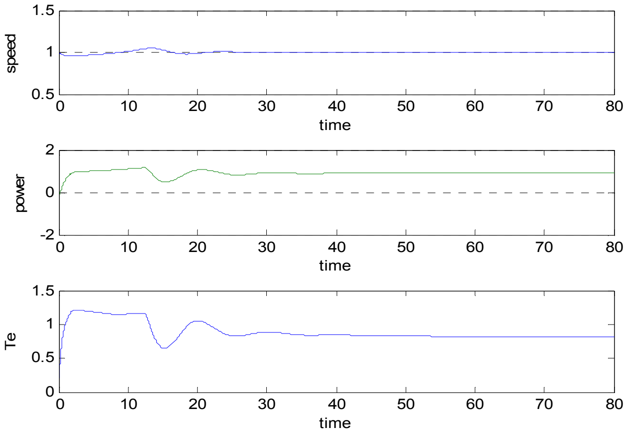
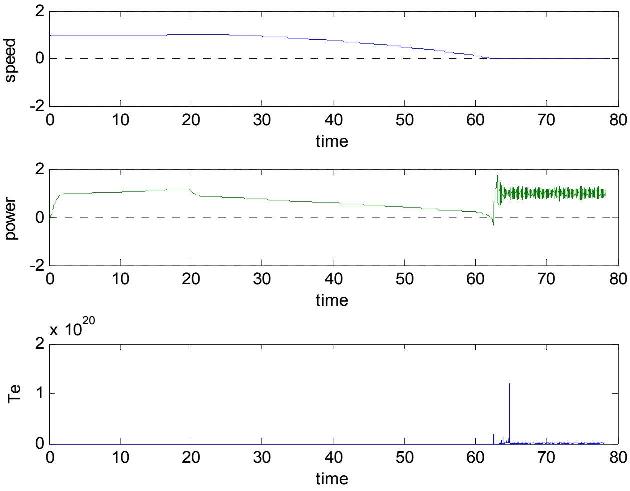


**Figure 9** System response at KP = 19.721, KI = 14.891, KD = 17.277 and P = 1 (see online version for colours)



## 7 Conclusion

The use of GA provides optimal PID settings. Hence, the accuracy and efficiency of the system performance can be maintained. The ease of implementation further adds to its attraction. The present paper successfully discussed the designing of GA controller for a CCPP model.

The outcomes of this work can be summarised as follows:

- For the conventional PI, the optimised parameters used in the CCGT model gave good response. The settling time decreases as the power demand increase and overshoot percentage increases as the power increases. But the response is satisfactory till the power reached 0.9 pu.
- For conventional PID controller, the settling time is less than the conventional PI controller but the overshoot increases. The settling time and overshoot increases as the power increases. The system is stable till power reaches 0.9 pu.

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## Appendix System parameters

As an example, we consider a 1100 class single-shaft combined cycle plant. Its rated power output is 160 MW (gas turbine 106.7 MW, steam turbine 53.3 MW). The model parameters are shown in the following table (Zhang and So, 2002; Mantzaris and Vournas, 2007).

**Table A1** Model parameters

| Variable | Description | Value |
|---|---|---|
| $t_{i_\circ}$ | Ambient temperature (K) | 303 |
| $t_{d_\circ}$ | Nominal compressors discharge temperature (C) | 390 |
| $t_{f_\circ}$ | Nominal gas turbine inlet temperature (c) | 1085 |
| $t_{e_\circ}$ | Nominal exhaust temperature (C) | 532 |
| $p_{r\circ}$ | Nominal compressor pressure ratio | 11.5 |
| $\gamma$ | Ratio of specific heat (Cp/Cv) | 1.4 |
| $\eta_c$ | Compressor efficiency | 0.85 |
| $\eta_t$ | Turbine efficiency | 0.85 |
| $K_\circ$ | Gas turbine output coefficient (1/K) | 0.00303 |
| $K_1$ | Steam turbine output coefficient (1/K) | 0.000428 |
| $R$ | Speed governor regulation | 0.04 |
| $T_g$ | Governor time constant (s) | 0.05 |
| $K_4$ | Gain of radiation shield (instantaneous) | 0.8 |
| $K_5$ | Gain of radiation shield | 0.2 |
| $T_3$ | Time constant of radiation shield (s) | 15 |
| $T_4$ | Time constant of thermocouple (s) | 2.5 |
| $T_5$ | Time constant of temperature control (overheat) (s) | 3.3 |
| $T_t$ | Temperature control (overheat) integration rate (s) | 0.4699 |
| $T_c$ max | Temperature control upper limit | 1.1 |
| $T_c$ min | Temperature control lower limit | 0 |
| $F_d$ max | Fuel control upper limit | 1.5 |
| $F_d$ min | Fuel control lower limit | 0 |
| $K_3$ | Ratio of fuel adjustment | 0.77 |
| $K_6$ | Fuel valve lower limit | 0.23 |
| $T_v$ | Valve positioner time constant (s) | 0.05 |
| $T_f$ | Fuel system time constant (s) | 0.4 |
| $T_6$ | Time constant of fuel system control(s) | 60 |
| $g_{\max}$ | Air valve upper limit | 1.001 |
| $g_{\min}$ | Air valve lower limit | 0.73 |
| $T_w$ | Time constant of air control (s) | 0.4699 |
| $T_{cd}$ | Gas turbine time constant (s) | 0.2 |