Steam Turbine Governor (STG) Controller Design Based on Particle Swarm Optimization (PSO)

Farah Ayad Abdul Majeed
Al Farahidi University / Aeronautical Technical Engineering Department, e-mail: f.ayad.majeed@gmail.com

Abstract. A reheat and non-reheat steam turbines governor is a component of the turbine control system that regulates rotational speed in response to changing load conditions. The governor output signal manipulates the position of a steam inlet valve or nozzles which in turn regulates the steam flow to the turbine. The application of PID (proportional integral derivative) controller has been widely used from small industry to high technology industry. Tuning the parameters of a PID controller is very important in PID control, Ziegler-Nichols method also used to tune the coefficients of a PID controller. The compensation has been proposed to be 4%, 6%, 8%, 10% and 15% of the actual load.

This paper evaluates the feasibility of using the Particle Swarm Optimization (PSO) method for determining the optimal PID controller parameters for steam turbine speed control. The PSO optimization technique is compared with Ziegler-Nichols method and (PID) controllers. It is validated that PSO based controller is more efficient in reducing the steady-states error, settling time, rising time, and overshooting limit in speed control of the steam turbine control. In which the maximum peak overshoot has been reduced from 44.8% in case of the original system without any controller to 3.45% for the case of PSO based controller and that for 15% load change.

1. Introduction

The principal of a Steam Turbine (ST) speed governing system is shown in figure 1. When the system frequency changes and the turbine speed changes due to the wavelength of the network load, a speed controller detects the change and automatically rotates the controller valve through the drive machine and the servo machine. Steam flow and ST mechanical power output will be modified to meet load variation requirements. The ST control system consists of the speed controller, the servo machine and the turbine. The analysis and modeling of these three components should precede the modeling of the entire control system [1].

![speed governor system](image)

Figure 1. speed governor system [1]
In the electrical system, in addition to guaranteeing the availability of electrical energy, maintaining the frequency of the electrical system is of the utmost importance. The intention is to guarantee a stabilized frequency to consumers at all times and maintain control of the charging frequency of the electricity grid. In an interconnected energy system, the energy load demand varies randomly; this affects both the frequency and the exchange of link line energy. Therefore, it is necessary to develop a methodology to make decisions synchronously and automatically by all the generating units connected to the networks.

The load frequency control together with the restricted governor mode control addresses this problem and minimizes the deviations in the frequency of the power grid and the energy exchange of the link line, which brings the steady state errors to zero and maintains the balance between demand and supply in real time.[2]

The PID controller is the most common form of feedback. It was an essential element of early governors and became the standard tool when process control emerged in the 1940s. Today, more than 95% of the control loops in processes control are of PID type [3-5]. Most loops are actually PI control. The PID control is an important ingredient of a distributed control system. The controllers are also embedded in many special purpose control systems [3].

Particle Swarm is based on the algorithm described in using modifications suggested [6-7]. Ziegler-Nichols rules for tuning PID controllers: Ziegler and Nichols proposed rules for determining values of the proportional gain Kp, integral time Ti, and derivative time Td, based on the transient response characteristics of a given plant. Such determination of the parameters of PID controllers or tuning of PID controllers can be made by engineers on-site by experiments on the plant. In this paper, the second method will be applied. Many techniques have been used for controlling steam turbine governor like, Pole Placement technique, Robust H-infinity technique, Linear Quadratic Regulator (LQR) technique, Linear Quadratic Gaussian (LQG) technique and Two Degree of Freedom Linear Quadratic Gaussian (2DOFLQG) technique.

[8] introduces a computational methodology that adopted a method of Linear Quadratic Gaussian (LQG) controller as Automatic Voltage Regulator (AVR) and Governor to control the generator terminal voltage and the turbine speed.

Another papers published by [9] and [10] with different techniques, these papers introduces a methodology to design a steam turbine governor based on pole assignment technique to control the speed of the turbine. A robust governor has been designed using $H_\infty$ techniques to replace the conventional governor of the hydro turbine of the power system to regulate the frequency of the power grid. This has been done with [11] in their paper of designing adopted Robust $H_\infty$ controller.

In this paper a controller will be designed for a steam turbine governor based on different techniques namely PID (proportional integral derivative) control, Ziegler-Nichols method and Particle swarm optimization (PSO). A comparative study will be done for number of loading cases (4%, 6%, 8%, 10% and 15%) of the actual load on the basis of state space representation.

2. Steam Turbine Power Plants

A steam turbine converts stored energy of high pressure and high temperature steam into rotating energy, which is in turn converted into electrical energy by the generator as shown in figure. 2.

The steam turbines of different configurations are built depending on the size of the unit and the steam conditions. It usually consists of more than two turbine or cylinder sections coupled together in a chain. Each section of the turbine consists of a set of movable blades connected to the rotor and a set of fixed blades [12].

![Figure 2. Steam turbine basic representation](image-url)
2.1 Steam Turbine Modeling

Before developing the model of complete turbine system, a transfer function of the steam vessel should be derived first that is shown in figure. 3.[12]

![Figure 3. Steam vessel](image)

The vessel continuity equation can be given in equation (1) as below:

\[
\frac{dw}{dt} = \frac{V}{\partial P} \frac{dP}{dt} = Q_{in} - Q_{out}
\]  

(1)

Assuming the flow out of the vessel to be proportional to pressure in the vessel,

\[
Q_{out} = \frac{Q_o}{P_o} P
\]

(2)

With constant temperature in the vessel,

\[
\frac{dP}{dt} = \frac{dP}{\partial P}
\]

(3)

Now, from the equations (1), (2) and (3):

\[
Q_{in} - Q_{out} = V \frac{dP}{dt} = V \frac{dP}{\frac{Q_o}{P_o}} \frac{dQ_{out}}{dt} = \frac{TV}{\partial P} \frac{dQ_{out}}{dt}
\]

(4)

Where,

\[
Tv = \frac{P_o}{Q_o} V \frac{dP}{\partial P}
\]

(5)

In Laplace form, equation (3) and equation (4) may be written as:

\[
\frac{Q_{in} - Q_{out}}{Q_{in}} = TV S Q_{out}
\]

Or,

\[
\frac{Q_{out}}{Q_{in}} = \frac{1}{1+TVS}
\]

(6)

Equation (6) represents the transfer function of the steam vessel, and TV is its time constant.

2.2 Steam Turbine Governor Modeling

The block diagram below provides a configuration of the primary controls for the steam turbine unit. It consists of a turbine and a governor model. The regulator consists of a speed changer, speed regulator, speed relay, control valves and the turbine system.

The isochronous regulator (constant speed), for two or more generator units it is not recommended to be connected to the same system because of the generators must have the same design of the speed in the system.

Therefore, regulators with the characteristic of speed drop, that is, the speed decreases as the load increases, are used to stabilize the load distribution between several operating units in parallel. Figures 4 and 5 show the block diagram of the governor with its transfer function and the gain l/R [11], respectively [13].
3. Speed Droop Governor Time Response
When a load increases to the subjected generating unit, with a speed drop regulator, the time obtained response will be as shown in figure. 6. The increase in output power is accompanied by a frequency deviation ($\Delta \omega_{ss}$) due to the full characteristics of [12].

4. Steam Turbine Modeling
The configuration under consideration is a reheating type tandem compound turbine. As noted previously, control valves adjust the steam flow throughout the turbine to control load / frequency through normal operation. The reaction of the steam flow to the change in the opening of the control valve exhibits a time constant $T_{CH}$ because of the loading time of the steam chamber and the inlet piping to the HP section. This time constant is of the order of 0.2 s to 0.3 s. 

The steam flow to the LP sections experiences an additional time constant $T_{co}$ associated with the crossover pipe; this is of the order of 0.5 s [12]. Therefore, the steam turbine model is based on the transfer function:

$$\frac{1+sT_{FHPT}}{(1+sT_{CH})(1+sT_{TR})} \quad (7)$$

The above transfer function of Equation 7 is the relationship between turbines torque and the position of the control valve, the boiler pressure where assumed constant, the $T_{co}$ (cross time constant) is
negligible and the characteristic of the valve is linear. The time constant TRH for the reheat is an important time constant in which it controls the turbine power and steam flow. Therefore, superheat type turbines have a slower response time than non-reheat types. In vector matrix form, the speed governor system can be given as in below:

\[
\frac{d}{dt} \begin{bmatrix} \Delta P_{GV} \\ \Delta P_{SR} \end{bmatrix} = \begin{bmatrix} -1 & 0 \\ T_{SM} & T_{SM} \end{bmatrix} \begin{bmatrix} \Delta \omega_r \\ \Delta \theta_r \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 1/T_{SR} & -K_G \end{bmatrix} \begin{bmatrix} \Delta P_{GV} \\ \Delta P_{SR} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} \Delta P_{ref} 
\]

Depending on the models and derivations of the sections stated earlier, the complete model of turbine governor can be given as shown in figure 7, which shows the steam turbine system with its closed loop system configuration. In the vector-matrix form, in which the model can be given as in Equation (9):

\[
\begin{bmatrix} \Delta \omega_r \\ \Delta P_{Kr} \\ \Delta P_{Co} \\ \Delta P_{co} \end{bmatrix} = \begin{bmatrix} \frac{-K_G}{T_{SR}} & 0 & 0 & F_{sp} \\ \frac{-K_G}{T_{SR}} & 0 & 0 & 0 \\ \frac{-1}{T_{SM}} & 0 & 0 & F_{sp} \\ \frac{-1}{T_{SM}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \frac{1}{T_{CO}} & 0 & 0 & 0 \\ 0 & \frac{1}{T_{CO}} & 0 & 0 \\ 0 & 0 & \frac{1}{T_{CO}} & 0 \\ 0 & 0 & 0 & \end{bmatrix} \begin{bmatrix} \Delta \omega_r \\ \Delta P_{Kr} \\ \Delta P_{Co} \\ \Delta P_{co} \end{bmatrix} + \begin{bmatrix} \frac{2H}{1} \\ \frac{2H}{1} \\ \frac{2H}{1} \\ \frac{2H}{1} \end{bmatrix} \begin{bmatrix} \Delta \theta_r \\ \Delta P_{CO} \end{bmatrix} + \begin{bmatrix} \Delta P_{ref} \\ \Delta P_{ref} \end{bmatrix}
\]

\[\begin{align*}
\end{align*}\]

\[\begin{align*}
\end{align*}\]

5. Proposed System Step Response

The step response to a given initial state consists in the temporal evolution of its outputs when the control inputs are stepped in the Heaviside functions. In control theory, a step response is the temporal behavior of the overall output of the system when its input changes from zero to one in a very short time. The concept can be extended to include the abstract mathematical concept of a dynamical system using the parameter of evolution.

Instead of frequency response, system performance can be determined in terms of the parameter that describes the response time dependency. The step response can be described in the following quantities related to its behavior in time,
6. Results and Discussions

This section provides the means of processing the models designed in the previous sections in order to evaluate these software models and to get the required results. In the beginning a SIMULINK model for steam turbine with/without a reheat will be implemented to show the response of three scope positions to make a comparison between reheat and non-reheat type.

6.1 Reheat & Non-Reheat Steam Turbine Response

In comparing the reheat steam turbine type and the non-reheated type steam turbine, which is made by analyzing the position of the input regulator and that of the mechanical power output and speed deviation output curves. This is done with a chosen percentage value of 10% staggered to the input load for the two linear systems. The results are shown in figure 8, in which the boiler pressure is assumed to be constant. The steam turbines responses for tend to be slower than the results of the theoretical analysis. It can be concluded that although the steady-state deviation of the speed remains the same, there will be a notable variation in its transient responses. From the results of figure 8, it can be concluded that the superheat type system is highly efficient than that of the non-reheat system.

6.2 Steam Turbine with Closed Loop Feedback Response

The complete turbine governor system which was derived and set previously, Particularly in figure 7 which represent a simulation model in order to have the ability to apply the compensation methods on it. Simulation model has been created for this system. Five cases for load changes ($\Delta$PL) have been made; which are chosen to be:
- 4% change in load
- 6% change in load
- 8% change in load
- 10% change in load
- 15% change in load

Figure 9 shows the step response configurations for the above percentages of the load change.

![Figure 9. Responses of different load changes](image)

The time response characteristics for these five responses will be given in table 1. From the results of table 1, it can be noticed that:

- The maximum peak overshoot value is high. This significant value makes a big noise in the system response, which is a bad factor. The value of the max peak for each response is determined from the level when the specified system settles, not from the level of general unity line.
- The system takes a long time before it settles because of the big value of. The settling time is high (9 seconds).
- The rise time is big

Therefore, compensation by the specified three methods will be applied for this system in order to improve the response of the systems.

### Table 1. Time response parameters for different Loads

| ∆PL % | Rise time | Settling Time | Peak Amplitude | Peak Time | Mp % | Steady State Final Value |
|-------|-----------|---------------|----------------|-----------|------|------------------------|
| 4%    | 1.15      | 9             | 0.406          | 3.32      | 44.8 | 0.28                   |
| 6%    | 1.15      | 9             | 0.608          | 3.32      | 44.8 | 0.42                   |
| 8%    | 1.15      | 9             | 0.811          | 3.32      | 44.8 | 0.56                   |
| 10%   | 1.15      | 9             | 1.01           | 3.32      | 44.8 | 0.7                    |
| 15%   | 1.15      | 9             | 1.45           | 3.32      | 44.8 | 1                      |

6.3 Compensation Response using Ziegler-Nichols Method

The Ziegler-Nichols tool provides a plot for Nyquist and hence calculating Kc and Pu values and plot the improved step response with the required parameters for PID. Therefore this procedure will be applied on the other four systems where their corresponding results and parameters are listed in table 2. From the results of table 2, it can be shown that the settling time and rise time have been reduced compared with the conventional.

### Table 2. The parameters of the improved systems using Ziegler-Nichols

| ∆PL % | Ts    | Tr    | Peak Amplitude | Mp % | Kp    | Ki    | Kd    |
|-------|-------|-------|----------------|------|-------|-------|-------|
| 4%    | 7.53  | 0.665 | 1.31           | 31.5 | 6.7721| 4.9747| 2.2124|
| 6%    | 7.52  | 0.665 | 1.31           | 31.5 | 4.4834| 3.2937| 1.4647|
| 8%    | 7.53  | 0.665 | 1.31           | 31.5 | 3.3613| 2.4690| 1.0981|
| 10%   | 7.53  | 0.665 | 1.31           | 31.5 | 2.6887| 1.9749| 0.8783|
| 15%   | 7.52  | 0.665 | 1.31           | 31.5 | 1.8827| 1.3830| 0.6150|
6.4 Compensation Response using PID tuning

In this paper, a PID TUNER tool will be used for the compensation. The tool can be imported by typing PIDTUNER from Matlab programming in the command prompt. The screen of the PID tuner will be as shown in figure 11.

Then, the five different load changes will be simulated in order to make the compensation on them. For the first system which is 4% change in load, figure 12 gives a better understanding, then a compromise sliding behavior is made using these two slides to give the improved response shown in figure 13.

For this response, the parameters of the time response characteristics and PID Parameters (Kp, Ki and Kd) are shown in the next figure which is figure 14. It can be shown that a good compensation have been made for this system. The same procedure that have applied for the compensation of 4% load change system will be applied for the other four systems (6%, 8%, 10% and 15%) by the PID TUNER tool as shown sub figures of figure 15.

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![Figure 11. PID tuner tool](image1.png)

![Figure 12. 4% change system imported in PID tuner tool](image2.png)

![Figure 13. The improved response of 4% system with a PID tuner](image3.png)
Figure 14. The parameters of the improved response

(a) 6% change in load  (b) 8% change in load

(c) 10% change in load  (d) 15% change in load

Figure 15. The improved responses of 6% 8% 10% and 15% with a PID tuner

Therefore, the corresponding parameters of time response characteristics and PID parameters for all systems are presented in Table 3 for all systems. It can be noticed that the main parameters (Ts, Tr and Mp %) have been reduced (improved) in a good way.

Table 3. The parameters of the improved systems using PID tuning

| ΔPL % | Ts  | Tr  | Peak Amplitude | Mp % | Kp   | Ki   | Kd   |
|-------|-----|-----|----------------|------|------|------|------|
| 4%    | 7.85| 0.673| 1.15           | 14.9 | 6.5065| 3.6645| 2.8882|
| 6%    | 8.07| 0.677| 1.14           | 13.5 | 4.3003| 2.3612| 1.958 |
| 8%    | 8.65| 0.853| 1.12           | 11.7 | 2.4842| 1.5549| 0.9921|
| 10%   | 8.60| 0.738| 1.10           | 10.1 | 2.3406| 1.2737| 1.0753|
| 15%   | 8.60| 0.738| 1.10           | 10.1 | 1.6384| 0.8915| 0.7526|
6.5 Compensation Response using PSO Algorithm
The particle swarm optimization technique starts by creating the primary particles, and assigning those primary velocities, in which:

- The objective function will be evaluated at each particle location, and determines the best location and the best (lowest) function value.
- It chooses new velocities, based on the particles individual best locations, current velocity, and the best locations of their neighbors.
- It then iteratively updates the particle locations (the new location is the old one plus the velocity, modified to keep particles within bounds), velocities, and neighbors. Iterations continue until the technique reaches a stopping criterion.

Now For the software implementation, two script files are employed for the PSO compensation. The response results for the five changes (4%, 6%, 8%, 10% and 15%) respectively, as shown in figure 16.

Finally, the time response parameters which shown in the figure in addition to PID parameters tabulated in table 4. From the results in the mentioned table, it can be shown that this method gives a very good improvement for all the parameters.

(a) Response for 4% change
(b) response for 6% change
(c) Response for 8% change
(d) Response for 10% change
(e) Response for 15% change

Figure 16. Governor Compensation using PSO under different load changes
6.6 Compensation between proposed compensation methods

Finally, after implementing the proposed control methods in this paper, a full comparison chart will be included to have an overall overview of the work done to decide on the best controlling method. From the data in tables 5 - 9, it can be concluded that from three methods based on PID (Ziegler-Nichols Method, PID Tuning and PSO Optimization); the best controller from them definitely the PSO optimizer which give a fast system in its rising with best settling time and the overshoot is very small.

Table 4. The parameters of the improved systems using pso algorithm

| ∆PL% | Ts   | Tr   | Peak Amplitude | Mp% | Kp   | Ki   | Kd   |
|------|------|------|----------------|-----|------|------|------|
| 4%   | 2.92 | 0.395| 1.08           | 8.3 | 4.2346| 5.8447| 5.3128|
| 6%   | 3.79 | 0.529| 1.00           | 0.0135| 2.8464| 4.0019| 4.0084|
| 8%   | 6.65 | 0.39 | 1.05           | 5.47 | 2.0502| 2.3517| 2.7376|
| 10%  | 3.37 | 0.515| 1.01           | 1.03 | 1.5227| 2.3651| 2.3694|
| 15%  | 7.85 | 0.468| 1.03           | 3.45 | 1.0000| 2.0969| 1.5599|

Table 5. Comparative study between methods for 4% load change

| Control Method          | Ts   | Tr   | Peak Amplitude | Mp% | Kp   | Ki   | Kd   |
|-------------------------|------|------|----------------|-----|------|------|------|
| Original system         | 9    | 1.15 | 0.406          | 44.8| -    | -    | -    |
| Ziegler Nichols         | 7.53 | 0.665| 1.31           | 31.5| 6.772| 4.9747| 2.2124|
| PID Tuning              | 7.85 | 0.673| 1.15           | 14.9| 6.5065| 4.0019| 2.8882|
| PSO Optimization        | 2.92 | 0.395| 1.08           | 8.3 | 4.2346| 5.8447| 5.3128|

Table 6. Comparative study between methods for 6% load change

| Control Method          | Ts   | Tr   | Peak Amplitude | Mp% | Kp   | Ki   | Kd   |
|-------------------------|------|------|----------------|-----|------|------|------|
| Original system         | 9    | 1.15 | 0.608          | 44.8| -    | -    | -    |
| Ziegler Nichols         | 7.52 | 0.665| 1.31           | 31.5| 4.4834| 3.2937| 1.4647|
| PID Tuning              | 8.07 | 0.677| 1.14           | 13.5| 4.3003| 2.3612| 1.958 |
| PSO Optimization        | 3.79 | 0.529| 1.00           | 0.01| 2.8464| 4.0019| 4.0084|

Table 7. Comparative study between methods for 8% load change

| Control Method          | Ts   | Tr   | Peak Amplitude | Mp% | Kp   | Ki   | Kd   |
|-------------------------|------|------|----------------|-----|------|------|------|
| Original system         | 9    | 1.15 | 0.811          | 44.8| -    | -    | -    |
| Ziegler Nichols         | 7.53 | 0.665| 1.31           | 31.5| 3.3613| 2.4690| 1.0981|
| PID Tuning              | 8.65 | 0.853| 1.12           | 11.7| 2.4842| 1.5549| 0.9921|
| PSO Optimization        | 6.65 | 0.39 | 1.05           | 5.47| 2.0502| 2.3517| 2.7376|

Table 8. Comparative study between methods for 10% load change

| Control Method          | Ts   | Tr   | Peak Amplitude | Mp% | Kp   | Ki   | Kd   |
|-------------------------|------|------|----------------|-----|------|------|------|
| Original system         | 9    | 1.15 | 1.01           | 44.8| -    | -    | -    |
| Ziegler Nichols         | 7.53 | 0.665| 1.31           | 31.5| 2.6887| 1.9749| 0.8783|
| PID Tuning              | 8.60 | 0.738| 1.10           | 10.1| 2.3406| 1.2737| 1.0753|
| PSO Optimization        | 3.37 | 0.515| 1.01           | 1.03| 1.5227| 2.3651| 2.3694|

Table 9. Comparative study between methods for 15% load change

| Control Method          | Ts   | Tr   | Peak Amplitude | Mp% | Kp   | Ki   | Kd   |
|-------------------------|------|------|----------------|-----|------|------|------|
| Original system         | 9    | 1.15 | 1.45           | 44.8| -    | -    | -    |
| Ziegler Nichols         | 7.52 | 0.665| 1.31           | 31.5| 1.8827| 1.3830| 0.6150|
| PID Tuning              | 8.60 | 0.738| 1.10           | 10.1| 1.6384| 0.8915| 0.7526|
| PSO Optimization        | 7.85 | 0.468| 1.03           | 3.45| 1.0000| 2.0969| 1.5599|
7. Conclusion
In this paper, the proposed system with different cases of change in load are considered in order to simulate with the controller and hence make the desired controller. MatLab has been used for the software simulation; SIMULINK part has been implemented for showing and understanding the operation of governor position, mechanical power and speed deviation; while the simulation part has been used particularly to set the proper and valid model as a script file and then the compensation mechanism have been applied.
From this work which are summarized in tables given in section 6, it can be concluded from the three methods based on PID (Ziegler-Nichols Method, PID Tuning and PSO Optimization), the best controller response regarding the system parameters ($T_s, T_r & M_p$) is the PSO optimizer which gives a fast system for all load changes as shown in tables 5 - 9, and that because of creating the proper initial particles and assuming initial velocities.

**NOMENCLATURE**

$v = \text{volume of vessel, m}^3$

$Q = \text{steam mass flow rate, kg/s}$

$t = \text{time, sec}$

$P = \text{pressure of steam inside the vessel, kPa}$

$P_0 = \text{rated pressure, dimensionless}$

$Q_0 = \text{rated flow out of vessel, dimensionless}$

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