

IMPROVING THE TRANSIENT FREQUENCY RESPONSE OF RICH-GENERATION ISLANDS VIA OPTIMAL CONTROL

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Abstract: This paper presents Genetic Algorithm (GA) optimization technique as a tool for tuning PID Load Frequency Control LFC. This is to ensure the sustainability of the formed islands after uncontrollable system separation. A two-area single-reheat tandem-compound thermal system is considered. It is focused on an island with excess generation to be equipped with local PID-LFC. The PID controller uses Genetic Algorithm (GA) to obtain the values of PID controller parameters. PID controller parameters are tuned off-line to minimize integral square error over a wide-range of interrupted power. The PID controller is tuned by Ziegler-Nichols method in order to demonstrate the superior efficiency of the proposed (GA) in tuning the PID controller. Therefore, the proposed technique could tune the PID controller for optimal response at any value of the interrupted power. Testing of the developed technique shows that, the proposed PID-LFC could present optimal performance and it capable of improving the transient frequency response of thermal power plants. So it contributes in improving the overall area response. Results are provided in the form of time domain simulations via MATLAB /SIMULINK.

Key words: Islanding, blackout, auxiliary governor, Load Frequency Control (LFC), PID controller, Genetic Algorithm.

1. Introduction

Modern power systems are subjected to thousands of disturbances annually. Some of these disturbances take the form of cascading natures [1]. These might cause the splitting of large interconnected power systems into

islands. Some islands suffer over frequency and others suffer under frequency. This problem is illustrated in Fig. 1 [2]. It is clear that upon system split, Area 1, the power exporting area, would suffer excess generation and frequency of Area 1 rises. In contrast, Area 2, the importing area, suffers over load and the area frequency starts to decrease [2]. In this case, the automatic generation control (AGC) is suspended [3]. Hence, each island frequency is controlled via the primary frequency controllers (speed governors) of the existing power plants. A question of (whether or not each island will reach a state of operating equilibrium) determines the frequency stability [4].

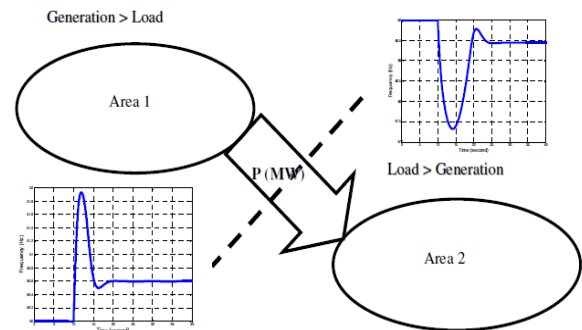


Fig. 1. Frequency problem associated with the splitting of interconnected power systems [2]

2. Proposed Power System Model

The proposed model is a simplified model based on Kundur's two-area system [3]. In this model the power system consists of two similar areas connected by a tie line as shown in Fig. 2.

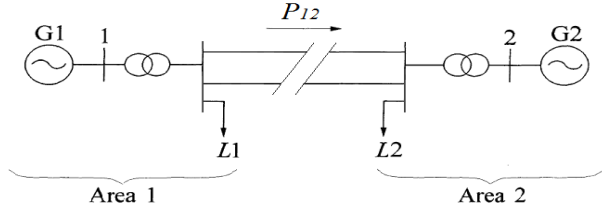


Fig. 2. A simple two-area system

Each area consists of one generating unit with 1 GW of generation at 20 kV. A generic model for the case study was built using MATLAB/SIMULINK. More details about the proposed model are presented in the following subsections.

2.1. Generator Model

Each area is represented by a single synchronous machine generating 80 % of its capacity equipped with a prime mover. The electrical part of the synchronous machine is represented by a sixth-order state-space model and the mechanical part by a second-order system. The model takes into account the dynamics of the stator, field, and damper windings. The equivalent circuit of the model is represented in the rotor reference frame (qd frame) [3, 5]. The generator parameters in per unit are as follows [3]:

$$\begin{array}{llll} X_d=1.8 & X_q=1.7 & X'_d=0.3 & X'_q=0.55 \\ X''_d=0.25 & X''_q=0.25 & X_i=0.2 & R_a=0.0025 \\ T'_{d0}=8.0s & T'_{q0}=0.4s & T''_{d0}=0.03s & T''_{q0}=0.05s \\ H=4s \end{array}$$

2.2. Transformer Model

The transformers are represented by three phase 20/500 kV transformers. Each transformer has an impedance of $j0.15$ per unit on 1000 MVA base.

2.3. Transmission Line Model

The transmission system is a double circuit system has a nominal voltage of 500 kV. It is represented using distributed line parameters model. The line length is 100 Km for each line. The parameters of each line in per unit, based on 1000 MVA base, are [3]:

$$R = 0.0001 \text{ pu/km}, \quad X_L = 0.001 \text{ pu/km}, \quad B_C = 0.00175 \text{ pu/km}$$

2.4. Load Model

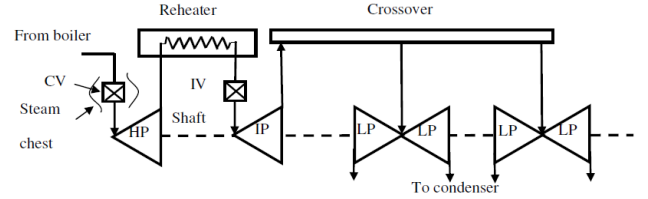
The loads are represented by a parallel combination of resistive and inductive RL elements. The power exported from area 1 to area 2 ranging between 100 to 900 MW. The load of area 1 varies from 100 to 900 MW. The load of area 2 varies from 1100 to 1900 MW. All loads at 0.8 lagging power factor.

2.5. Prime Mover and Energy Supply Systems

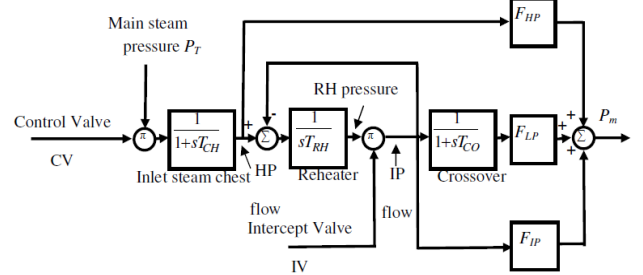
The speed control and the subsequent responses of prime mover and energy supply systems play a major role in determining the nature of the system dynamic performance [3]. Hence, for studies of frequency stability, the steam turbine and governing system are represented in detail in the following subsections.

2.5.1. Steam Turbines

A fossil-fuelled single reheat tandem-compound steam turbine is considered. The basic configuration illustrating the turbine elements that need to be considered, for purposes of modelling, is shown in Fig. 3(a) [3]. Fig. 3(b) shows the block diagram representation of the tandem-compound single reheat steam turbine. The model accounts for the effects of inlet steam chest, reheater, crossover, control valves and intercept valves [3].



(a) Turbine configuration



(b) Block diagram representation

Fig. 3. Single reheat tandem-compound steam turbine model [3]

T_{CH} = time constant of steam chest.

T_{RH} = time constant of reheater.

T_{CO} = time constant of crossover piping

P_m = mechanical turbine power in MW.

F_{HP} , F_{IP} , F_{LP} = fraction of total turbine power generated by HP, IP, LP sections, respectively.

Typical values of parameters of the model shown in Fig. 3, applicable to a tandem-compound single reheat turbine of fossil-fuelled units, are [3]:

$$\begin{array}{lll} F_{HP} = 0.3 & F_{IP} = 0.3 & F_{LP} = 0.4 \\ T_{CH} = 0.3 \text{ s} & T_{RH} = 7.0 \text{ s} & T_{CO} = 0.5 \text{ s} \end{array}$$

2.5.2. Steam Turbine Control

Mechanical Hydraulic Control (MHC) governor is considered for governing a steam turbine, see Fig. 4. The basic elements of the governing system are a speed governor, speed relays, and hydraulic servomotors [3].

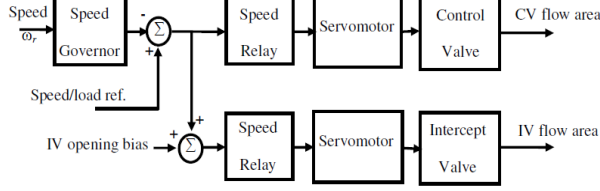


Fig. 4. Functional block diagram of MHC turbine-governing system [3]

2.5.2. Modelling Of MHC Governors

MHC governors can be modelled at different forms such as [3]:

- I. Normal speed regulation / Primary speed control.
- II. MHC Including the Overspeed Control Function.

I. Normal Speed Regulation/Primary Speed Control

The CVs control the steam flow through the turbine for load/frequency control during normal operation or small speed (frequency) deviations, see Fig. 5[3].

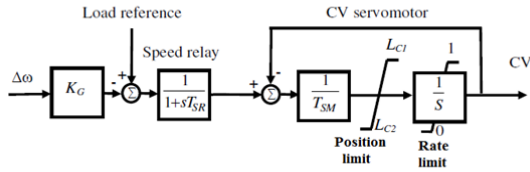


Fig. 5. Generic speed-governing system model representing normal speed/load control function [3]

Sample values of the parameters are [3]:

$$K_G = 20 \text{ (5\% droop)}$$

$$T_{SR} = 0.7 \text{ s} \quad T_{SM} = 0.23 \text{ s}$$

$$\text{Rate limits: } L_{C1} = 1.0 \text{ pu/s (opening)}$$

$$L_{C2} = -3.0 \text{ pu/s (closing)}$$

II. MHC Including the Overspeed Control Function

The speed governing systems of many large thermal generating units include auxiliary control features designed to assist in limiting unit overspeed following load rejection. These control features are introduced in the following sections.

a) Intercept valves

For the reheat type steam turbines, steam enters the HP section through a set of valves, known as the control valves CVs. The HP exhaust steam is then reheated and enters the

IP turbine section through another set of valves called intercept valves IVs Fig. 6. [3].

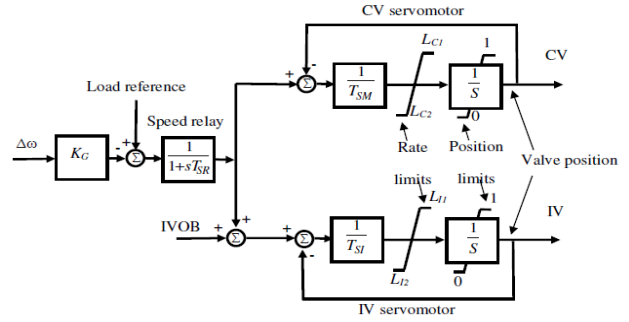


Fig. 6. Governing system with intercept valve [3]

Typical values of parameters are [3]:

$$K_G = 20 \quad T_{SR} = 0.7 \text{ s} \quad T_{SM} = 0.23 \text{ s}$$

$$T_{SI} = 0.23 \text{ s} \quad L_{C1} = 1.0 \quad L_{C2} = -3.0$$

$$L_{I1} = 1.0 \quad L_{I2} = -2.5 \quad IVOB = 1.17$$

In the event of overspeed, the rapid closure of the CVs alone would not be effective because of the large amount of stored steam in the reheater. Therefore, the intercept valve is used for rapid control of the turbine mechanical power in the event of overspeed due to load rejection. IVs are very effective in this purpose as they control the steam flow to the IP and LP turbines which generate nearly to 60 to 80% of the total turbine power [3].

b) Auxiliary governors

Auxiliary governors act in parallel with the main governors, see Fig. 7. When the overspeed exceeds the auxiliary governor setting, ranging from 1% to 3% overspeed, the action of the auxiliary governor effectively increases the gain of the speed control loop by a factor of approximately 6 and rapidly closes the governor and intercept valves [6].

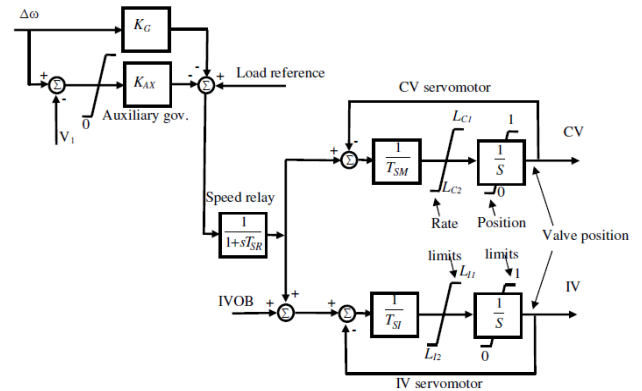


Fig. 7. Governing system with intercept valve and auxiliary governor ($K_{AX} = 149$, $V_1 = 0.02$) [3]

3. Case Studies of Severe System Upsets

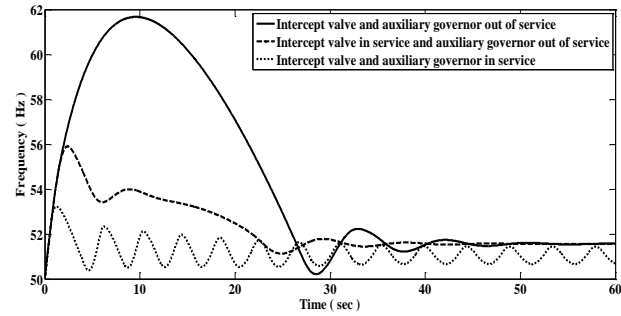
In this section consider case studies of involving an overgenerated island at different values of interrupted power. Initially, the first area exports power to the other area ranging from 10% to 90% of its generation ($P_{12} = 10\%P_{G1}, 20\%P_{G1}, 30\%P_{G1} \dots 90\%P_{G1}$). The disturbance simulated is the simultaneous opening of all ties connecting the two areas. The result being two islands, which lead to make a load rejection from 10% to 90% on area 1. This case study is intended to demonstrate the impact of turbine-generator overspeed controls on the performance of a generation-rich island at different values of load rejections.

Fig. 8 shows the Frequency responses of the first area upon disconnection from the second area as a consequence of islanding due to interrupting the power exported from the first area to the second area for the following cases:

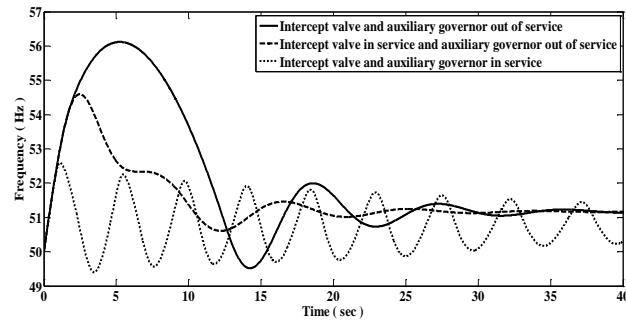
Case 1: Considering primary speed control, intercept valve and auxiliary governor out of service. Such case is modelled in Fig. 5.

Case 2: Considering overspeed control, intercept valve in service and auxiliary governor out of service. Such case is modelled in Fig. 6.

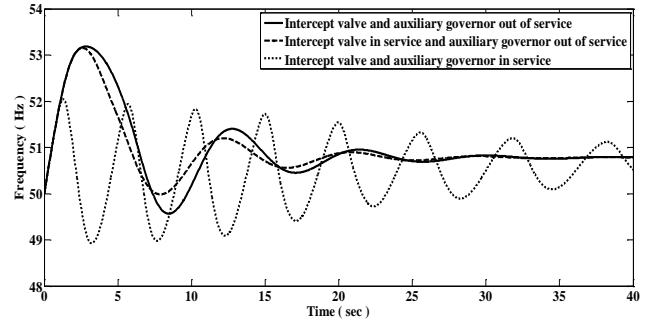
Case 3: Considering overspeed control, intercept valve and auxiliary governor in service. Such case is modelled in Fig. 7.



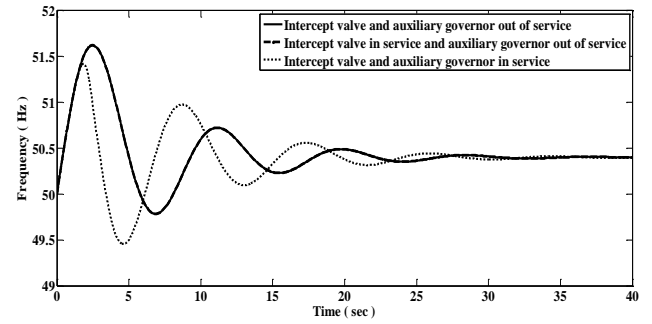
(a) interrupted power $P_{12} = 80\%P_{G1}$



(b) interrupted power $P_{12} = 60\%P_{G1}$



(c) interrupted power $P_{12} = 40\%P_{G1}$

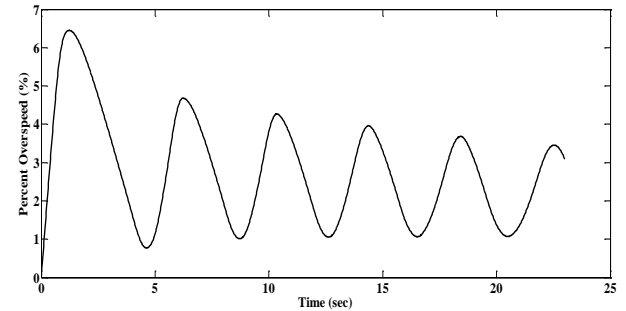


(d) interrupted power $P_{12} = 20\%P_{G1}$

Fig. 8. Frequency responses of the first area upon disconnection from the second area

As shown in Fig. 8, the frequency response shows a stable response and reaches another steady state value. But the frequency first overshoot declines in case of the system with both intercept valve and auxiliary governor in service particularly for more power interruption. But as shown, during islanding conditions the auxiliary governors introduce high gain that can lead to frequency oscillations and when the interrupted power increased, the oscillations will appear in power plant response.

The continued oscillations of speed are due to the action of the auxiliary governors, see Fig. 9.



(a) Speed deviation.

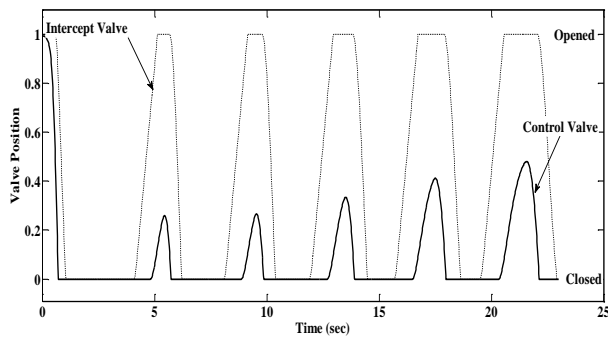


Fig. 9. Transient response with auxiliary governor
($P_{12}=80\% P_{G1}$)

When the increase in speed exceeds 2%, the auxiliary governors close the valves bringing the mechanical power of the generating units to zero. The deficit in generated power reduces the speed rapidly and the valves open again. The resultant increase in mechanical power is such that the speed exceeds the auxiliary governor setting, which causes the valves to close again. The cycle repeats itself with the valves alternately closing and opening which can lead to frequency oscillations.

The frequency maximum overshoot at different values of the load rejections for the whole cases is shown in Fig. 10.

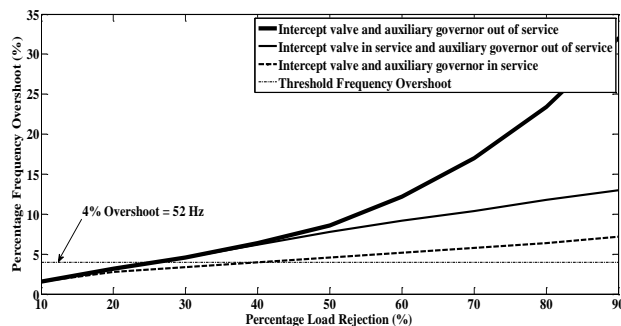


Fig. 10. Percent frequency overshoot with different values of load rejections

Fig. 10 shows that, the frequency response of the power plant equipped with intercept valve and auxiliary governor, upon disconnection between two areas, will be more effective than other cases. In this case the load rejection of about 40% does not lead the frequency to exceed the overspeed trip level (4% overshoot=52 Hz). But the frequency response still unfavourable due to the defect of the auxiliary governor of not only bringing the continued oscillations of speed, but the frequency also reaches

another steady state value that mean there is a steady state error. So introducing a local Load Frequency Control (LFC) at the rich-generation island is needed to improve the transient frequency response.

4. Local Load Frequency Control (LFC)

Several controllers have been introduced for LFC to achieve a better dynamic performance. Some examples for these controllers are proportional integral derivative (PID) control [7], state feedback control [8], and output feedback control [9]. Recently, intelligent control techniques such as fuzzy logic control and neural network control are applied to LFC problem. Most of the above controllers depend on fixed gain control parameters, like PID controller shown in Fig. 11.

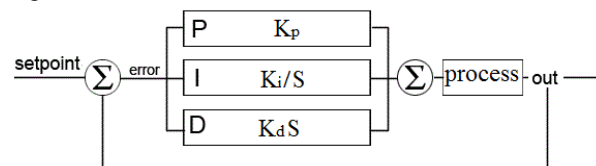


Fig. 11. Schematic diagram of the PID Controller

The PID controller has the following structure:

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \quad (1)$$

Where: K_p is proportional gain, K_i and K_d are integral and derivative time constants, respectively.

The aim of LFC is to maintain a real power balance in the power system through controlling the system frequency. Whenever the real power demand changes, a frequency change occurs. This frequency error is amplified, mixed and changed to a command signal which is sent to turbine governor. The governor works to restore the balance between the input and output by changing the turbine output [10].

5. Implementation of PID-LFC

The rich generation island in the proposed model is equipped with PID controller, see Fig.12.

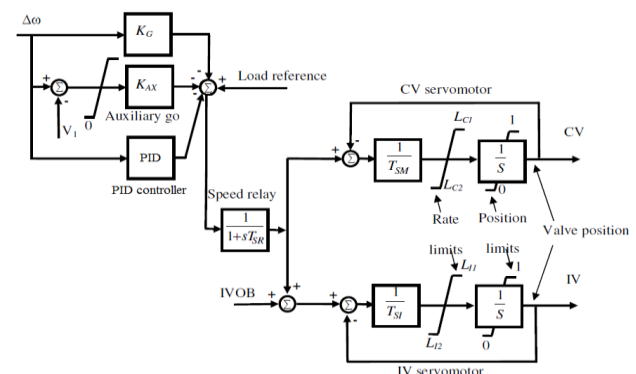


Fig. 12. Rich-generation island with PID controller

There are several methods used for PID tuning to get the optimum values of control parameters (K_p , K_i and K_d). In this paper the PID use Genetic Algorithm (GA) to obtain the values of PID controller parameters for optimal response of PID-LFC at different values of interrupted power. The PID controller is tuned also by Ziegler-Nichols method in order to demonstrate the superior efficiency of the proposed (GA) in tuning PID controller.

6. Genetic algorithms

Genetic algorithms (GAs) are biologically inspired techniques used for optimization. These algorithms encode a potential solution to a specific problem on a simple chromosome like data structure and apply recombination operators to these structures so as to preserve critical information. The GA begins by defining the optimization variables and the fitness function and ends by testing for convergence [10].

The general steps implemented when using GAs are [10]:

1. Generate a random initial population of solutions.
2. Evaluate fitness of each solution.
3. Selection of individual solutions.
4. Apply the mutation operator to each string in the new population.
5. Replace the old population with the newly created population.
6. Copy the best-fitted individuals to the newly created population to warrant evolution.
7. If the number of iterations is less than the maximum go to step three, else stop OR If the fitness of the best result does not get better over certain number of iteration, then stop.

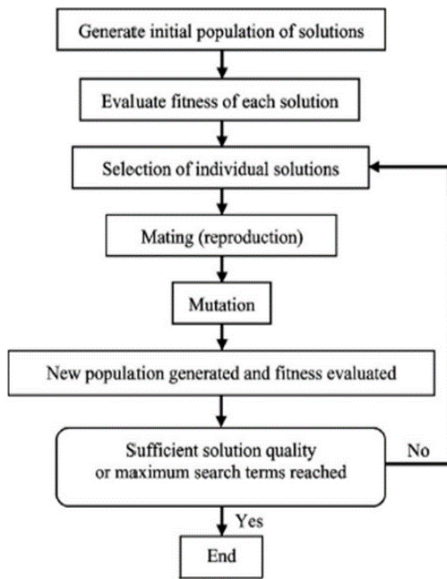


Fig. 13. Genetic Algorithm Process Flow chart

7. Implementation of GAs in the optimization problem

In this simulation, the objective is to minimize the fitness function. For this reason the fitness function is chosen as the Integral Square Error (ISE). The (ISE) squares the error to remove negative error components.

$$ISE = \int_0^t (e(t))^2 dt \quad (2)$$

Where $e(t)$ is the error signal in time domain.

PID controller parameters will be optimized by applying GA. Here use Matlab Genetic Algorithm Toolbox [11] to simulate it. The convergence criterion of a genetic algorithm is a user-specified condition for example the maximum number of generations or when the string fitness value exceeds a certain threshold. In this paper the no of variables is three (K_p , K_i and K_d). The population type is double vector. The population size is 20. The initial range of variable is [0–100]. For the reproduction, the elite count is 2 and the crossover friction is 0.8. The mutation function is constraint dependent. The crossover function is scattered. The stopping rules is the no of generation is 150.

Table (1) gives the values of the controller parameters (K_p , K_i and K_d), tuned using GA, at different values of interrupted powers (load rejections).

Table 1 Values of PID controller parameters (K_p , K_i and K_d) at different values of load rejection

| Load1 (MW) | P ₁₂ (MW) | Load2 (MW) | Load Rejection (%) | K_p | K_i | K_d |
|------------|----------------------|------------|--------------------|--------|--------|--------|
| 900 | 100 | 1100 | 10.0% | 40.828 | 11.322 | 43.891 |
| 800 | 200 | 1200 | 20.0% | 37.329 | 12.070 | 44.380 |
| 700 | 300 | 1300 | 30.0% | 36.615 | 8.9920 | 45.010 |
| 600 | 400 | 1400 | 40.0% | 47.076 | 18.728 | 36.297 |
| 500 | 500 | 1500 | 50.0% | 45.556 | 25.758 | 27.738 |
| 400 | 600 | 1600 | 60.0% | 43.819 | 38.785 | 42.696 |
| 300 | 700 | 1700 | 70.0% | 37.034 | 33.781 | 48.295 |
| 200 | 800 | 1800 | 80.0% | 32.314 | 23.660 | 46.126 |
| 100 | 900 | 1900 | 90.0% | 40.447 | 12.668 | 41.651 |

The load frequency control is applied on the proposed model for the following cases, see Fig. 14:

Case 1: System equipped with auxiliary governor only.

Case 2: System equipped with PID controller, based Ziegler-Nichols method, rather than auxiliary governor.

Case 3: System equipped with PID controller, based Ziegler-Nichols method, and auxiliary governor.

Case 4: System equipped with PID controller, based GA, rather than auxiliary governor.

Case 5: System equipped with PID controller, based GA, and auxiliary governor.

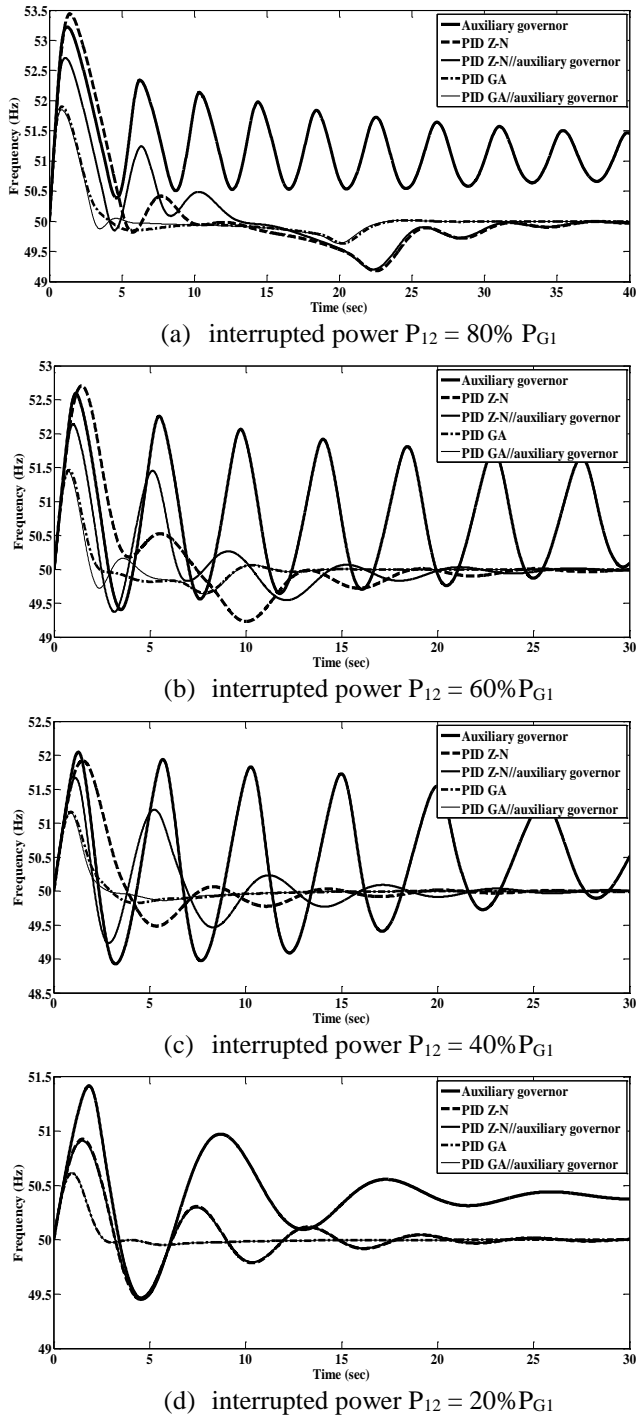


Fig. 14. Frequency response of first area with PID load frequency controller

It is clear from Fig. 14 that, the introducing of PID controller rather than auxiliary governor gives a good performance. The standard performance measures such as:

percent frequency overshoot, settling time, peak time and the frequency oscillations are reduced at different values of load rejections. In addition the steady state error is eliminated due to the integral action. The PID controller which tuned by genetic algorithm gives a better performance than the PID controller that tuned by Ziegler-Nichols method. In case of system equipped with PID controller, based GA, and auxiliary governor, the effect of auxiliary governor of limiting the overspeed will disappear because the tuning of PID using GA based on minimizing the integral square error (ISE) so limiting the overspeed too. So it is not needed to install the auxiliary governor with PID controller. Fig. 15 shows the frequency overshoot at different values of the load rejections for the whole cases.

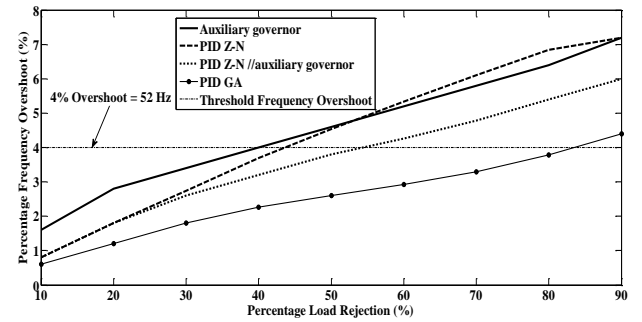


Fig. 15. Percent frequency overshoot with different values of load rejections

From Fig. 15, the frequency response of the area equipped with PID controller tuned by Genetic Algorithm (GA) will be more effective than the other cases. In this case the load rejection of more than 80% does not lead the frequency to exceed the overspeed trip level (4% overshoot=52 Hz).

8. Conclusion

Many large thermal generating units include auxiliary control features designed to assist in limiting unit overspeed following load rejection. These controls could adversely affect the performance of the units under system disturbance conditions. So introducing a local Load Frequency Control (LFC) is needed to improve the transient frequency response. A local load frequency control is introduced using (PID) controller, which can be tuned using the genetic algorithm. The frequency response in such case is compared with (PID) controller tuned using Ziegler-Nichols method. The simulations demonstrate the superior efficiency of the proposed (GA) in tuning (PID) controller where the proposed local optimal controller assists in damping the first frequency overshoot. Not only the first overshoot is damped but the steady state error is also removed. So it contributes in improving the overall area response.

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