Review of Gas Turbine Models for Power System Stability Studies

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1 Introduction

Power system stability studies require accurate models of power system components. Governor and turbine are relevant components of the generating units. A number of gas turbines, alone and within combined cycle power plants, have been incorporated to the Spanish power system. A wide variety of models have been provided by the manufacturers. This paper reviews the dynamic models of gas turbine for power system stability studies. It describes the main control loops and explains the purposes of each one as well as different ways to implement them. Simulations are carried out to show the performance of each control loop.

Key words: Stability Studies, Dynamic Models, Gas Turbines.

2 Structure of gas turbine models

The typical model of gas turbines in stability studies consists of three control loops [1]:

- Load - frequency control.
- Temperature control.
- Acceleration control.

Figure 1 shows a simplified representation of such model.

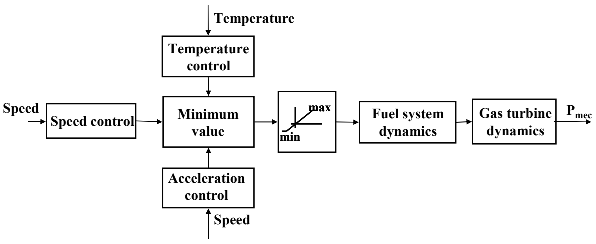

Figure 1: Simplified representation of the model proposed in [1].

The load - frequency control is the main control loop during normal operating conditions. The temperature and acceleration control are active in the case of abnormal operating conditions.

When the temperature of the exhaust gases exceeds the limit value, the temperature control takes action to reduce the output power of the gas turbine, so that the temperature comes within limits. This control loop will be further described in Section 4.

The acceleration loop takes control in the case that the generator experiences high positive acceleration. When the acceleration of the generator exceeds the acceleration limit, the control reduces the fuel signal and the output power of the gas turbine is reduced, thus limiting the acceleration. This control loop will be further described in Section 5.

The output of the three control loops are the input to a minimum value gate so that the loop which takes control is the one which output is the lowest of the three. The output of minimum value gate commands the fuel system and therefore the mechanical power delivered by the gas turbine.

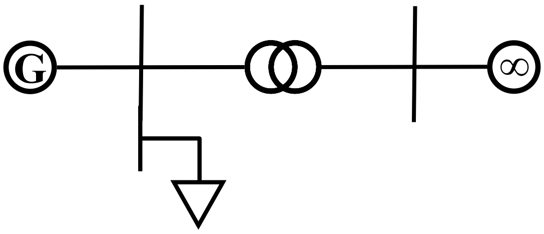

Figure 2: Single line diagram of the power system used time domain simulations.

To check the performance of the three control loops time domain simulations of several disturbances have been conducted. The power system simulated consists of a generator connected to an infinite bus through a power transformer. There is also a load connected at the generator terminals. This load represents an industrial consumption. The single line diagram is depicted in Figure 2.

3 The load - frequency control

The load - frequency control is active during normal operating conditions. The input to this control is the speed deviation. Proportional or integral action can be used depending on whether the generator is running in parallel with other generators and performing load - frequency regulation or it is isolated performing frequency regulation. In the case of load - frequency regulation, the gain of the control is the inverse of the permanent droop.

There is one additional type of load - frequency control which is the Woodward control [2]. The block diagram of this type of governor is shown in Figure 3. There are two inputs to this control which are the electrical power and the speed deviation.

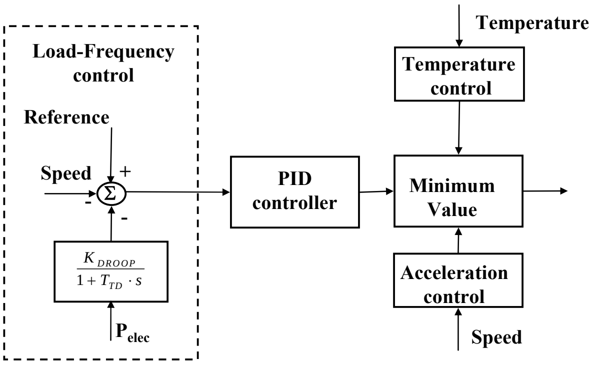

Figure 3: Block diagram of the Woodward governor.

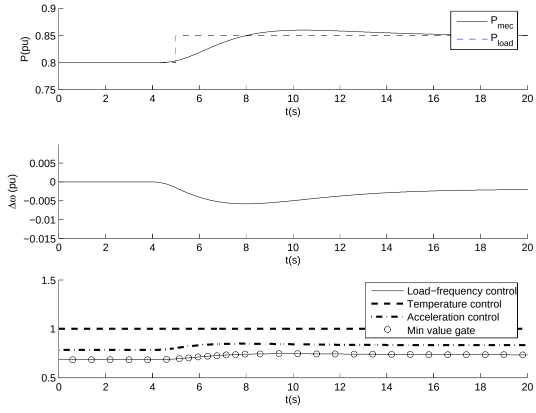

Figure 4: Mechanical power of the gas turbine (solid line) and load demand (dashed line) (above) and output of both the load - frequency control and temperature control (below) after a 0.05 pu step in load (increase) is applied.

The actual electrical power delivered by the generator is measured and scaled by the permanent droop (KDROOP). Then, the speed deviation is added to it. The sum is subtracted to a reference in order to obtain an error signal. This signal is the input to a PID controller. In steady state, the input to this control is zero due to the integral control.

Figure 4 shows the response of a gas turbine running isolated feeding a load when a load step of 0.05 pu is applied. In this condition the gas turbine is operating within limits and the control loop that commands the response of the gas turbine is the load - frequency control. The temperature control remains constant during the simulation because exhaust temperature limits are not reached. The acceleration control output corresponds to the proportional acceleration control type and its value is always higher than the load - frequency control output.

4 The role of temperature control loop

The temperature control loop takes control of the gas turbine when the exhaust temperature exceeds a fixed maximum value. If the load demanded to the turbine increases when the generator is running under normal operating conditions, the output power of the gas turbine will increase due to the action of the load - frequency control. This increase makes the exhaust temperature to rise. If this temperature is higher than the maximum rated exhaust temperature, the temperature control output will be lower than that of the load - frequency control, thus taking control of the response of the turbine.

The temperature limit depends on the ambient temperature. In the case that ambient temperature increases, the exhaust temperature will tend to increase and the action of the temperature control loop will be to reduce the amount of fuel consumption of the gas turbine. On the other hand, when ambient temperatures decreases the exhaust temperature will tend to decrease also, thus not reducing the fuel consumption, and it might occur that the load - frequency control loop becomes the active control loop. In [3] there is a representation of the relationship between exhaust temperature and ambient temperature

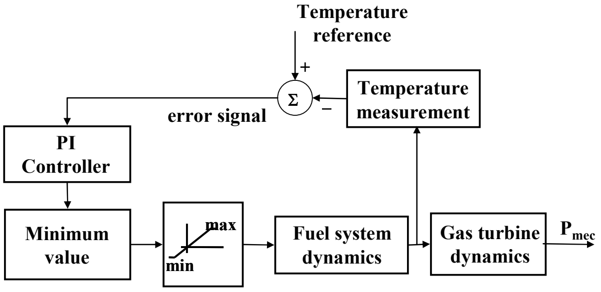

Figure 5: Basic temperature control loop.

As can be seen in Figure 5, the basic temperature control loop consists of the following components:

- Temperature measurement: this block represents the temperature measurement process.
- Comparison with a temperature reference: an error signal is obtained subtracting the output of the temperature measurement block to the temperature limit.

- PI controller: The integral part of the controller has non-windup limits. Usually the exhaust temperature is lower than the temperature limit, the error signal is positive and the trend of the integrator output would be to increase. The non-windup limits are necessary for the output of the integrator not to increase steadily.

The limit imposed by the exhaust temperature is characterized by the parameter “Temperature reference” in the block diagram. This limit is expressed as the maximum power that the gas turbine can deliver and is affected by the ambient temperature.

The model proposed in [4] includes the effect of reduction of fuel consumption when the speed of the machine decreases. This is due to the fact that exhaust temperature must be kept within limits at any time. When the turbine speed decreases the air flow through the compressor is reduced so that less fuel consumption is required by the gas turbine. If the fuel amount is kept in the same level, the exhaust temperature will increase, and the temperature control loop will tend to reduce the fuel consumption. This is shown in Figure 6 where the exponent Dm models that phenomenon.

The time constant Tm in the block diagram represents the dynamics of the temperature measurement process. Once the temperature is measured it is compared with the temperature reference and an error signal is obtained. This error signal is the input to the PI controller. The output of the PI controller is one of the inputs to the minimum value gate where it will be compared to the outputs of the speed and acceleration control loops.

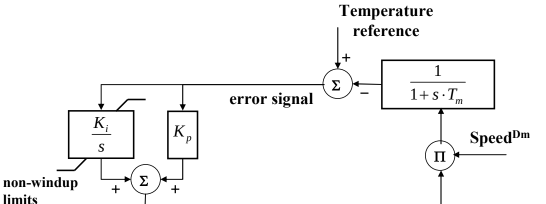

Figure 6: Temperature control loop of the gas turbine model as in [4].

Although some models ([1], [5]) do not include a representation of a non-windup limit in the integral part of the PI controller, it is important to represent it to ensure that when the temperature control loop is not acting the integrator output reaches the limit. The limit would guarantee that the output of the integrator will not steadily increase and the temperature control loop acts as soon as it is necessary. If the operation of the temperature control loop is like to be inhibited a high value of “Temperature reference” can be set.

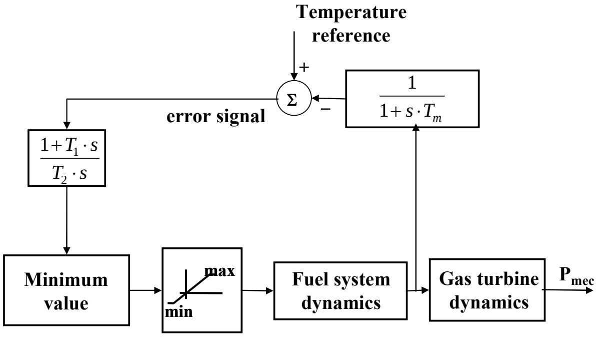

Figure 7: Temperature control loop of the gas turbine model as in [1] [5].

In [6] the temperature control loop includes the action of the inlet guide vanes (IGV). IGV are situated in the air-compressor stage of the gas turbine. The role of the latter is to regulate the mass flow of air drawn into the compressor. In the operation of open cycle gas turbines, IGV are controlled during the start-up of the gas turbine and its modelling can be neglected for simulations of the gas turbine response running under normal operating conditions [3]. Figure 8 shows the corresponding block diagram.

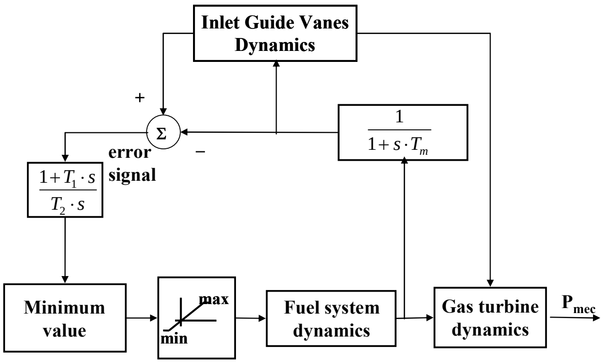

Figure 8: Simplified temperature control loop of the gas turbine model as in [6].

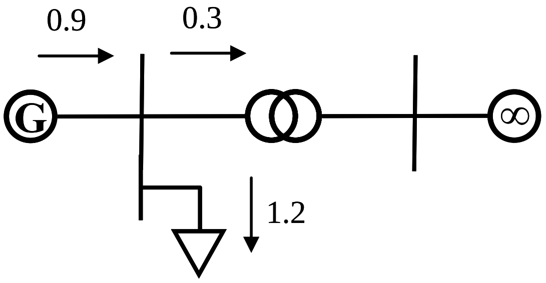

Figure 9: Single-line diagram of the scenario used in simulations to show the performance of the temperature control loop. Power flows are in pu of gas turbine rated power.

The performance of the temperature control is checked simulating a large step of load. The operating point of the test system previous to the disturbance is depicted in the single-line diagram of Figure 9 where the power flows are represented. The consumption of the industrial plant is fed mostly by the infinite network. This scenario represents a peak demand scenario of the industrial plant. The disturbance considered is the disconnection of the generator and the industrial plant from the infinite bus. Then the generator will have to supply the whole industrial plant. As the infinite bus was supplying most of the power consumed by the load before the disturbance, the generator will experience an increasing step in load.

The gas turbine was generating 0.9 pu on rated power base. When the gas turbine is disconnected from the network, the load of 1.2 pu has to be supplied by the gas turbine. Thus, an increasing step of 0.3 pu on rated power base is experienced by the gas turbine. Since the maximum output power that can be delivered by the gas turbine is 1 pu, a damping factor of the load has been considered (D = 3 pu) to reduce the load consumption and eventually and to facilitate a new steady state operating condition. For the sake of clarity only the first 15 seconds of the transient have been shown, during which the steady state is not reached.

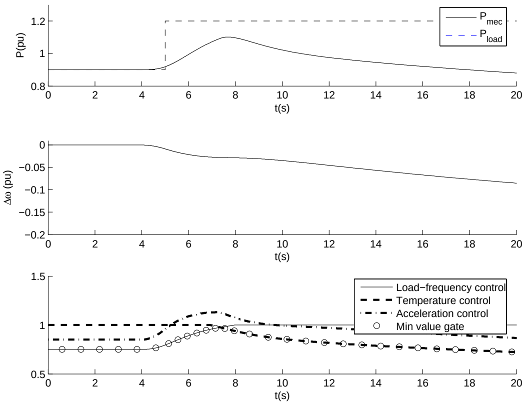

Figure 10: Mechanical power of the gas turbine (solid line) and load demand (dashed line) (above) , speed deviation (middle) and output of the load - frequency control, temperature control and acceleration control (below) after a step in load (increase) is applied.

The simulation results obtained are shown in Figure 10. The disturbance is applied in t = 4 s. The mechanical power of the gas turbine, the total load and the outputs of the load - frequency control loop, the temperature control loop and the minimum value gate of the gas turbine are presented. As it can be seen in the figure, during the first 8 seconds, the response of the gas turbine is commanded by the load - frequency control. After an increase in the load demand in t = 4 s, the output of the turbine rises until the output of the load - frequency control becomes higher than the output of the temperature control. From that moment the temperature control loop commands the output of the gas turbine, reducing its output power.

5 The role of acceleration control loop

The acceleration control loop is designed to take control of the fuel system when the generator experiences an acceleration which exceeds a limit. This condition can occur during startup and load rejection processes. The acceleration control would prevent an over-speed of the gas turbine that could damage the shaft.

The input signal to the acceleration control is the gas turbine speed. It goes through a differential block to obtain the acceleration of the turbine. Then, the acceleration is compared to an acceleration limit, and an error signal is obtained. The error signal is the input to a control block whose output goes to the minimum value gate.

Several implementations of this control block have been found:

- Integral control ([1], [5] and [7]).
- Proportional control [4].
- Proportional and integral control [8].

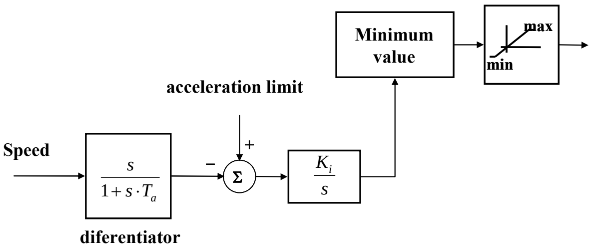

Figure 11: Integral acceleration control as in [1], [5] and [7].

The integral control type is shown in Figure 11. Although no limits are represented in the integrator block of Figure 11 the implementation of the acceleration control would require them, so that the output of the integrator does not steadily increase in the case that the acceleration control loop is not acting. This limits are shown in the model used in [7].

One point of interest is the value that the high limit should have. A proper value of this limit should be higher than the actual output of the two other control loops otherwise the acceleration control would take control of the gas turbine independently on the acceleration that is experiencing. If the limit is equal to the maximum fuel limit which is after the minimum value gate (see Figure 1), the acceleration control might not work properly in the case that the gas turbine is generating less power than the maximum. In that case, when the speed of the gas turbine starts to increase at a rate higher than the acceleration limit, the output of the integrator will start to decrease from its initial value which is the maximum output power. Since the gas turbine is delivering less power, it will take time to the acceleration control output to reach a value lower than the output of the load - frequency control. Moreover, it has to be noted that if the acceleration is high and a high over-speed is being experienced by the gas turbine, the load - frequency control output will tend also to reduce its output. The result would be that the command signal would tend to reduce the consumption of fuel, but by means of the load - frequency control instead of the acceleration control. That is why the integrator limit should have a value slightly higher than the actual power delivered by the gas turbine. This can be achieved by means of the block diagram depicted in Figure 12.

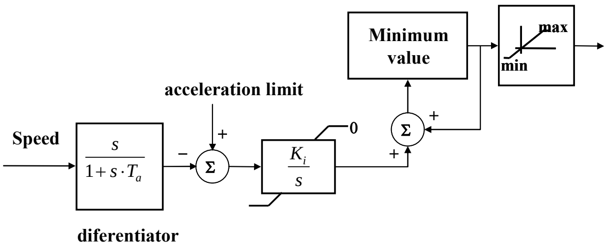

Figure 12: Modified integral acceleration control.

When the integrator starts to integrate its output will be subtracted to the minimum value gate output, which in normal operating conditions will be the output of the load - frequency control loop, thus a value lower than the load - frequency control will be obtained, and the acceleration control will command the response of the gas turbine.

The proportional acceleration control is shown in Figure 11.

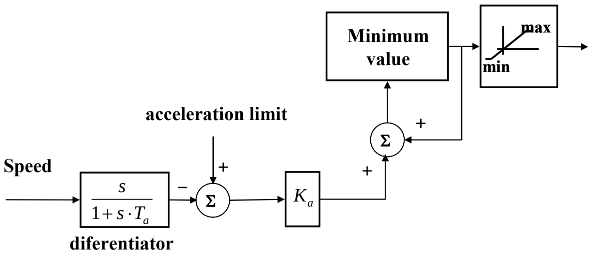

Figure 13 Proportional acceleration control as in [4].

The input signal to this control is the turbine speed which goes through a derivative block and is compared to the acceleration limit. The error signal obtained is scaled by the gain Ka and this value is summed to the actual value of the min value gate output. When the acceleration of the gas turbine is higher than the limit, the error signal will become negative, and the output of the acceleration control loop will be lower than the output of the minimum value gate and the acceleration control loop will command the response of the gas turbine.

The block diagram of the PI acceleration control is shown in Figure 14. This design presents the same problem of the integral control.

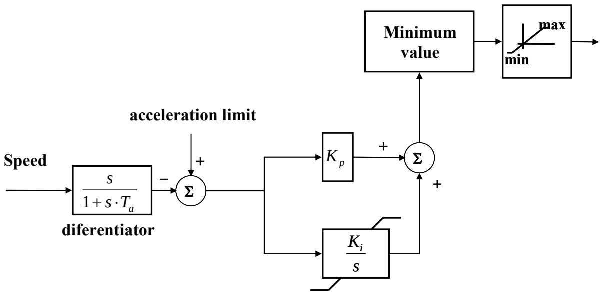

Figure 14: Proportional and integral acceleration control as in [8].

The performance of the acceleration control is checked simulating a large step of load. The state of the system previous to the disturbance is depicted in the single-line diagram of Figure 15 where the power flows are represented. The consumption of the industrial plant is supplied by the gas turbine which delivers also power to the network.

The disturbance considered is the disconnection of the generator and the industrial plant from the infinite bus due to the actuation of the transformer protection relays. In that moment, the generator will supply the load of the industrial plant, and no power will be delivered to the network. Since before the disturbance the gas turbine was delivering power to the network, the gas turbine will experience a decreasing step in load as its actual output power is higher than the load consumption. A proportional acceleration control has been used in the simulations.

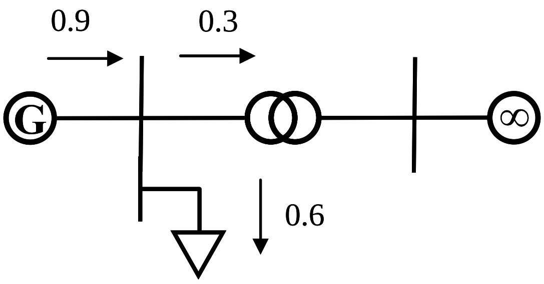

Figure 15: Single-line diagram of the scenario used in simulations to show the performance of the acceleration control loop. Power flows are in pu of gas turbine rated power

The gas turbine was generating 0.9 pu on rated power base. When the gas turbine is disconnected from the network, only the load of 0.6 pu has to be supplied by the gas turbine. Thus, a decreasing step of 0.3 pu on rated power base is experienced by the gas turbine.

The results obtained for the simulation are shown in Figure 16. The disturbance is applied in t = 4 s. The mechanical power of the gas turbine, the total load demand and the output of the load - frequency control loop, the acceleration control loop and the minimum value gate are presented. As it can be seen, during the first 5 seconds the load - frequency control commands the response of the gas turbine. After the step in load is applied in t = 4 s, the turbine accelerates until the acceleration loop takes control of the response, reducing its output power faster than the load - frequency control loop.

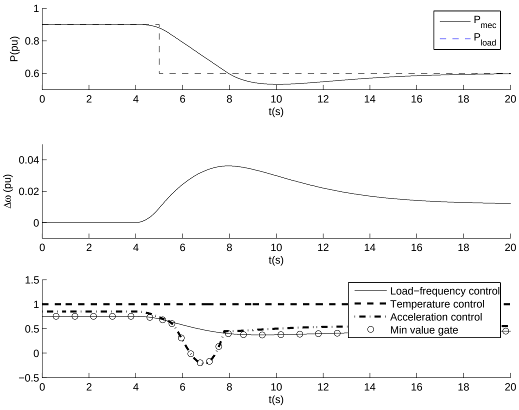

Figure 16: Mechanical power of the gas turbine (solid line) and load demand (dashed line) (above) and outputs of the load - frequency control and acceleration control (below) after a step in load (increase) is applied.

6 Conclusions

This paper has reviewed gas turbine models for power system stability studies. The main control loops of the typical models of gas turbines used in stability studies are described. The temperature and the acceleration control loops are described in detail and different ways to implement them are shown.

Some aspects that should be taken into account when modelling the temperature and acceleration control loops are also described.

Simulations show the performance of the temperature and acceleration control loops when the gas turbine experiences increasing and decreasing steps in load.

7 References

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