



School of Information Technology and
Engineering at the ADA University



School of Engineering and Applied Science
at the George Washington University

FREQUENCY REGULATION OF COMBINED CYCLE POWER PLANTS IN
LOCAL/AUTONOMOUS/ISOLATED GRID OPERATION MODE

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THESIS ACCEPTANCE

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ABSTRACT

The frequency of the power supply is one of the most important indicators of the quality of electrical energy. The required frequency values are maintained by automatic and operational frequency control or regulation. Frequency changes usually occur due to some imbalances between the power consumed by loads and the power generated by the power stations and in the event of an imbalance, all frequency regulation systems work to restore the power balance. These mentioned above facts work for overall power system as well as to the power systems in the isolated (islanded) grid operation mode. In the following work the frequency regulation of combined cycle power plants (CCPP) in the isolated grid operation mode has been studied. First of all, some fundamental characteristics of the primary, secondary and tertiary frequency regulation stages in the power system have been provided and then the general aspects of combined cycle power plants and their control mechanisms have been researched. In order to show the importance of CCPPs in Azerbaijan power system, necessary data regarding the installed power capacities and generated electrical energy has been provided. In order to analyze the frequency regulation in CCPP in isolated grid operation mode we have researched for existing mathematical models of these kind of systems. Finally, the Rowen model was selected and implemented in the following work. The simplified mathematical model for simulation purposes of the frequency regulation in isolated grid operation mode using CCPP was developed using MATLAB SIMULINK 2023 software. The results obtained during simulation were very much realistic and then the impact of different unit block in the CCPP system to the frequency regulation has been studied. Finally, the obtained results have been discussed and some ideas for the future work in the area of interest have been given.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
CCPP	Combined cycle power plant
CCGT	Combined cycle gas turbine
GT	Gas turbine
ST	Steam turbine
HRSG	Heat-recovery steam generator
PFR	Primary frequency regulation
NPFR	Normalized primary frequency generation
GPFR	General primary frequency regulation
HV	High voltage
RES	Renewable energy sources
TSO	Transmission system operator
ALS	Automatic load shedding
VNV	Variable nozzle vane

CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

The frequency of the power system supply is one of the most important indicators of the quality of electrical energy. The necessary frequency values are maintained by automatic and operational frequency regulation. The hierarchical structure of frequency regulation is conventionally divided into primary, secondary, and tertiary frequency regulation systems. In cases of significant power imbalances, emergency automatic systems are being activated to limit frequency increase or decrease (disturbances). Frequency changes usually occur due to imbalances between the power consumed by loads and the power generated by power stations. In the event of an imbalance, all frequency regulation systems work together to restore the power balance. Primary, secondary, and tertiary frequency regulation systems utilize generation reserves available in the power system at the time. Emergency automation acts to disconnect generation in case of frequency increase or to disconnect loads when frequency decreases. Primary reserves are activated early to prevent the development of accidents when power imbalances occur. Primary frequency regulation (PFR) is carried out using frequency correctors of power blocks. Primary frequency regulation is further divided into general (GPFR) and normalized (NPFR) frequency regulation. [1]

Among the first to raise questions about the reaction of CCPP (Combined Cycle Power Plants) to frequency deviations were well-known scientists like V. Rowen, L. Meegahapola, D. Flynn, P. Poverbeck, and D. Laylor who made the most significant contributions to the research on the CCPP 's response to frequency deviations. Also, significant research in this area was conducted by scientific groups from organizations such as CIGRE (International Council on Large Electric Systems) and IEEE (Institute of Electrical and Electronics

Engineers). The general scheme of the frequency regulation in the power system is given in Figure 1.1.

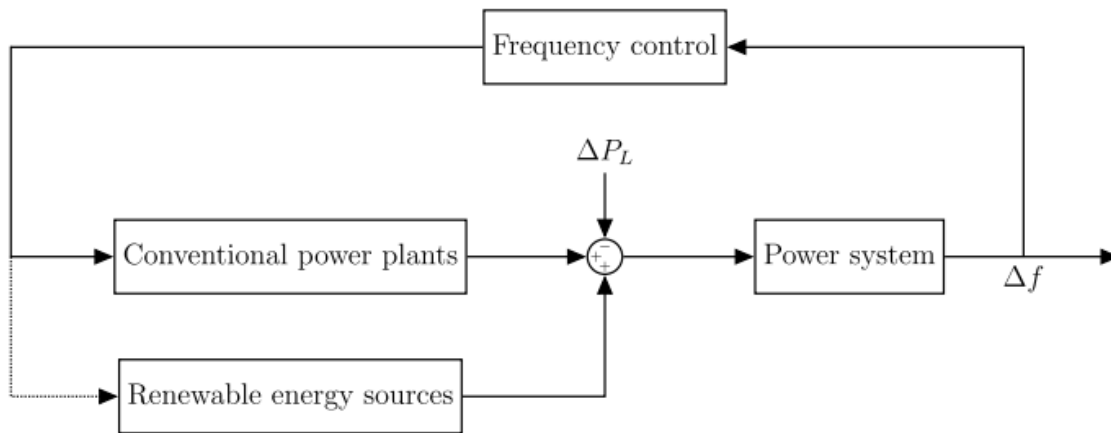


Figure 1.1: General overview of the frequency control in the power system [1].

1.2 MOTIVATION

Combined cycle power plants working on natural gas play crucial role in Azerbaijan power system. By saying so, we have to mention that around 2105 MW from total of 6454 MW (in 2020) installed power capacity of Azerbaijan accounts for CCPPs. Although, a number of new projects focused on the renewable energy sources are currently being integrated to the power system, the CCPPs will continue to play the crucial role in the system in the coming decades. Taking into account that the new generation sources integrating to the power system are mainly focused on renewable energy sources, and considering the intermittent nature of renewable energy sources we can assure that CCPPs will even become more crucial in the frequency regulation of the power system. That is why, currently, a huge attention by “AzerEnerji” OJSC is being paid to the frequency regulation issues in the power system of Azerbaijan by holding a number of research and development works in the area of interest. The installed power capacity of CCPPs is expected to grow taking into account the new reinforcement project at “Azerbaijan” PP, where it is planned to add gas turbines and heat

recovery steam generator (HRSG) units to the existing steam turbines which will also increase the current efficiency (around 39 %) of the plant to around 55-56 %

1.3 THESIS STRUCTURE

In the following work, first of all, some fundamental characteristics of the primary, secondary and tertiary frequency regulation stages in the power system have been provided and then the general aspects of combined cycle power plants and their control mechanisms have been researched. In order to show the importance of CCPPs in Azerbaijan power system, necessary data regarding the installed power capacities and generated electrical energy has been provided involving clear graphical representations of the obtained data. In order to analyze the frequency regulation in CCPP in isolated grid operation mode we have researched for existing mathematical models of these kind of systems. As a result of deep analysis of existing models, the Rowen model was selected and implemented in the following work as it best suits the frequency regulation issues in the CCPP system. The simplified mathematical model for simulation purposes of the frequency regulation in isolated grid operation mode using CCPP was developed using MATLAB SIMULINK 2023 software based on the Rowen model. The results obtained during simulation were very much realistic and then the impact of different unit block, namely gas and steam turbine, inertia of the system and governor, in the CCPP system to the frequency regulation has been studied. Finally, the obtained results have been discussed and some ideas for the future work in the area of interest have been given.

CHAPTER TWO

LITERATURE REVIEW

2.1 Frequency Regulation in Power Systems

An electric power system has two crucial parameters: voltage and frequency. Maintaining these parameters within the specified predefined limits is essential to ensure smooth operation and provide reliable energy to all connected users, preventing unexpected disruptions that could harm connected loads or even lead to the system failures. Power systems typically use a nominal frequency of 50 Hz (generally in Europe and most of Asia) or 60 Hz (like in North America). These frequency choices result from technical considerations and historical factors. Normally, when the frequency operates within the range of $f_n \pm 0.1$ Hz deviation, it's considered to be in standard conditions. However, if the frequency deviates from this range, such as falling between 47.5 to 52.5 Hz in a 50 Hz network, it's considered and referred to as an emergency or restoration condition. The mentioned thresholds can vary from country to country. Variations in frequency in a power system arise from imbalances between load and generation. When the frequency in the system approaches an emergency condition, a control scheme is triggered. Frequency control is conventionally divided into three major levels: primary, secondary, and tertiary regulation, each of them serving distinct purposes and possessing unique characteristics. When a loss-of-generation event occurs in the power system, the immediate consequence is that the system load surpasses the available generation capacity, leading to a rapid decline in frequency. The governor response mechanism then comes into play, whereby the remaining connected generators promptly supply additional power to counteract the frequency decline and bring about the stabilization of the system frequency. This automatic and self-governing control process, taking place within the initial 30 seconds of the event, is referred to as Primary Frequency Control. In contrast, actions associated with

Secondary Frequency Control, being externally directed, are deemed too slow to effectively contribute to preventing and stabilizing the frequency within the limited timeframe. The interconnected nature of these frequency control functions is depicted in Figure 2.1 and the summary of the three frequency control levels is given in Table 2.1.

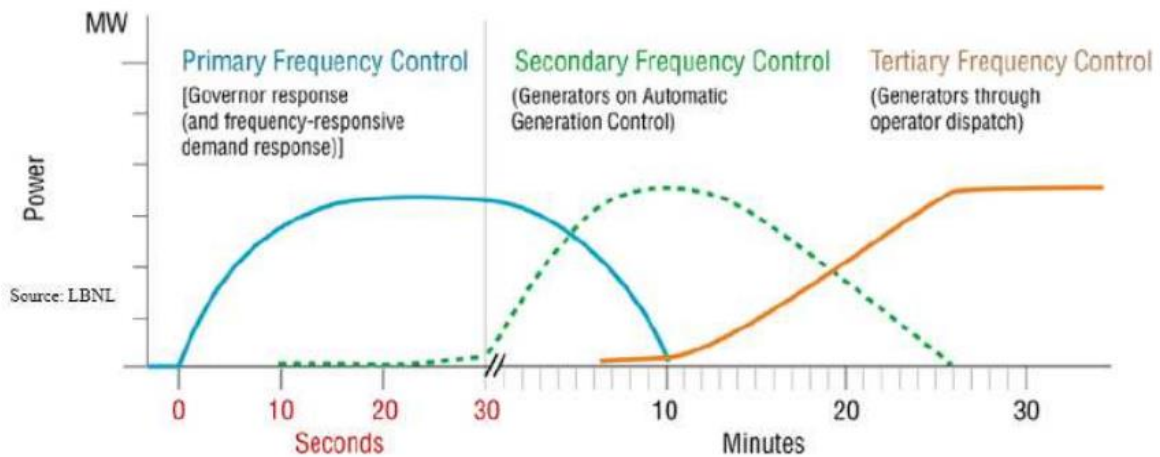


Figure 2.1: Types of frequency control by the timeframe [2].

Table 2.1: Summary of the three frequency control levels and their main characteristics

	Response time	Duration time	Operation
Primary control	15-30 seconds	15 minutes	Automatic response of the system to frequency disturbance to regulate the frequency to nominal value
Secondary control	200 seconds	120 minutes	Stabilization of the frequency to the nominal value and restoration the power reserves of the generators which have been used in the primary frequency control
Tertiary control	15 minutes	Indicated by Transmission System Operator	Restoration of the reserves of power of the generators which have been used for the secondary frequency control

2.1.1 Primary Control

The primary control, also known as frequency response control, in case of frequency deviations operates fast and automatically with a response time of just a several seconds. When an imbalance occurs between power generation and consumption, it leads to a change in the

power system's frequency. For instance, if the load suddenly increases, the generated power can't simultaneously match this change. Instead, additional energy for the increased load is sourced from the kinetic energy of the spinning generating reserves, causing a decrease in their rotational speed (referred to as inertial response). Following this, each generator's speed controller, known as the "governor," takes action to boost power generation, restoring the decreased speed and addressing the imbalance. Typically, within approximately 30 seconds, every power generation unit must be capable of producing the required additional power and sustaining it for minimum of 15 minutes (although the precise duration depends on the TSO's requirements). All power generating plants interconnected to the High Voltage (HV) power system are responsible for providing this service, except for non-scheduled Renewable Energy Sources (RES), such as wind, solar, biogas, and hydro. Due to this, every generation unit must maintain a dedicated and adequate "reserve" power to fulfill this regulation when needed. The primary objective of primary regulation is to rectify the imbalance between power generation and consumption, restoring the system to a stable state. It's mandatory for all generators designated to provide this service, and they are not compensated for it. As for non-scheduled RES, these generators must be capable of adjusting their power output based on the frequency value, following a defined $P(f)$ function. This adjustment is relatively straightforward in cases when frequency is more than nominal value, which necessitates a power reduction. Nevertheless, it can be exceedingly challenging (sometimes impossible) in situations of when frequency falls below nominal value, which would require increasing power output. This isn't always feasible, even with reserve power, as a result of inherent variability of the primary energy source itself. The ongoing expansion of RES results in a reduction in operational thermal electric plants, posing challenges for maintaining frequency regulation. Various solutions are being explored, with some already implemented in a number of power systems,

with battery energy storage standing out as one of the most perspective options. That presents a significant challenge in the widespread adoption of RES in power systems.

2.1.2 Secondary Control

This control level involves employing a central regulatory mechanism to adjust the power set points of generating sets under its purview. The primary objective is to restore power exchanges with neighboring control areas to their designated values while simultaneously returning the system frequency to its predetermined set-point value. This is achieved by modifying the operating parameters of individual generating units, ensuring the complete availability of primary control power reserves. Unlike primary control, secondary control operates at a slower pace, typically taking minutes. Its impact becomes evident approximately 30 seconds after a disturbance or event, concluding within 15 minutes. In the context of normal power system operations, where power demand experiences continuous fluctuations, secondary control functions continuously without impeding the actions of primary control. Implementing secondary control requires a central regulator, a system for measuring power interchanges in tie-lines, frequency measurement systems, and a mechanism for transmitting regulator signals to relevant generating units. During disturbances that disrupt the balance between power generation and demand in synchronous systems, variations in system frequency are observed system-wide, regardless of the disturbance's location. In such instances, a coordinated response from the primary control of all interconnected systems is expected to restore the equilibrium between generation and demand. However, the achieved frequency may deviate from its set-point value by Δf , and power interchanges on tie-lines may differ from scheduled values. Effectively implementing secondary control requires that the generating units involved possess sufficient power reserves to respond to the regulator signal by making the necessary adjustments in generated power and meeting the required rate of change. The rate of change in power output at the generator terminals is significantly influenced by the

generation technique. Typically, the rate is approximately 8% per minute for oil or gas-fired power stations, up to 2% and 5% per minute for lignite-fired and hard-coal-fired power stations, respectively, and up to 5% per minute for nuclear power stations [3]. Even in the case of reservoir power stations, the rate is about 2.5% of the rated plant output per second.

2.1.3 Tertiary Control

Tertiary control encompasses both automatic and manual adjustments to the operating points of participating generating units. This is done to either reinstate a sufficient secondary control reserve or to optimize the allocation of this reserve among the active generating units based on economic considerations. The implementation of tertiary control involves several methods, including:

- **Adjusting Set Operating Points:** This entails modifying the set operating points of thermal power plant generation sets, which are the reference points around which primary and secondary control operate.
- **Connection/Disconnection of Pump Storage Hydro Power Stations:** Tertiary control can be achieved by intervening in the operation of pump storage hydro power stations, either by connecting or disconnecting them as needed.
- **Altering Power Interchange Programs:** Tertiary control may involve changes to the power interchange program, adjusting the planned exchange of power with other control areas.
- **Load Control:** This includes centralized tele-command systems or controlled load shedding, where the power demand is managed to achieve the desired balance and control objectives.

In summary, tertiary control is a higher-level control mechanism that goes beyond primary and secondary control. It focuses on optimizing the reserve capacity and strategically managing

the allocation of this reserve among the generating units in service, taking economic considerations into account.

2.2 Combined Cycle Power Plants

2.2.1 General overview

A combined-cycle power plant (CCPP) is a configuration comprising a gas turbine (GT), a steam turbine (ST), a heat-recovery steam generator (HRSG), and an electric generator like in Figure 2.2. Various combinations are possible, involving multiple gas turbines, HRSGs, and generators arranged in different configurations. One major advantage of combined-cycle power plants lies in their enhanced overall plant efficiency. The total thermal efficiency of a CCPP surpasses that of a conventional fossil fuel plant due to the more effective utilization of the total enthalpy generated in the combustion process. This is achieved through the combination of the gas turbine Brayton cycle and the steam turbine Rankine cycle, giving rise to the term "combined-cycle." In comparison, a typical simple-cycle conventional fossil fuel plant, such as a simple cycle GT or a coal-burning ST plant, exhibits an efficiency of 30-35%, while a CCPP can achieve efficiencies exceeding 55%. The essence of the combined-cycle plant lies in the integration of two cycles—the "topping" or high-temperature cycle (GT Brayton cycle) and the "bottoming" or low-temperature cycle (ST Rankine cycle). These cycles are interconnected through a heat exchanger, which transfers the exhaust low-energy from the topping cycle to the bottoming cycle, resulting in additional work production. In the case of a combined gas-steam cycle, the heat from the gas turbine exhaust gas is recovered in an HRSG to generate steam for the bottoming steam cycle. This integration enhances the overall efficiency of the power plant. [10]

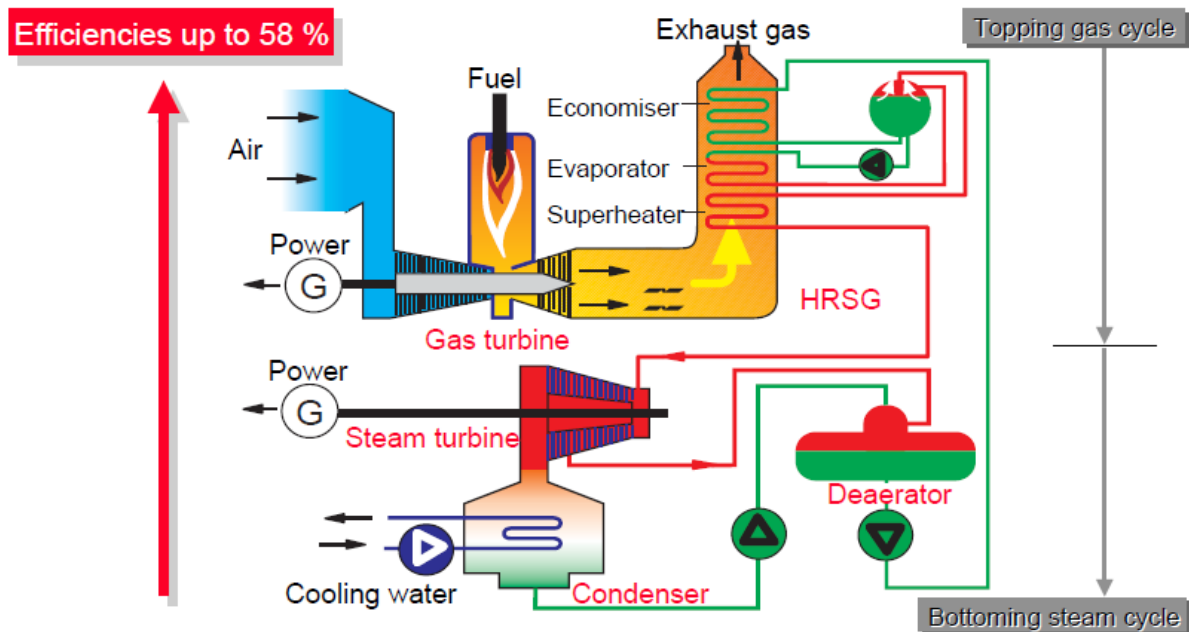


Figure 2.2: Typical combined-cycle power plant [10]

2.2.2 Configurations of Combined-Cycle Power Plants

Combined-cycle power plants offer flexibility in their configurations, falling into two main categories: single-shaft units and multi-shaft units.

Single-Shaft Units.

In single-shaft configurations, both the gas turbine (GT) and steam turbine (ST) are mounted on the same shaft, allowing them to rotate together. This integrated design simplifies the mechanical arrangement and results in a more compact layout. The advantage of a single-shaft unit lies in its ease of operation and maintenance, as the entire system is mechanically interconnected Figure 2.3.

Multi-Shaft Units:

Multi-shaft configurations involve separate shafts for the gas turbine and steam turbine. Each turbine operates independently on its own shaft. This design provides more flexibility in terms of turbine speed control and allows for optimized performance of each turbine independently. Multi-shaft units are often chosen for larger and more complex combined-cycle

power plants, where the independence of the turbines offers advantages in terms of operational control and efficiency optimization Figure 2.4.

The choice between a single-shaft and multi-shaft configuration depends on factors such as the size of the power plant, operational requirements, and the desired level of control over each turbine. Both configurations aim to maximize the overall efficiency of the combined-cycle power plant, taking advantage of the synergies among the gas turbine and steam turbine cycles.

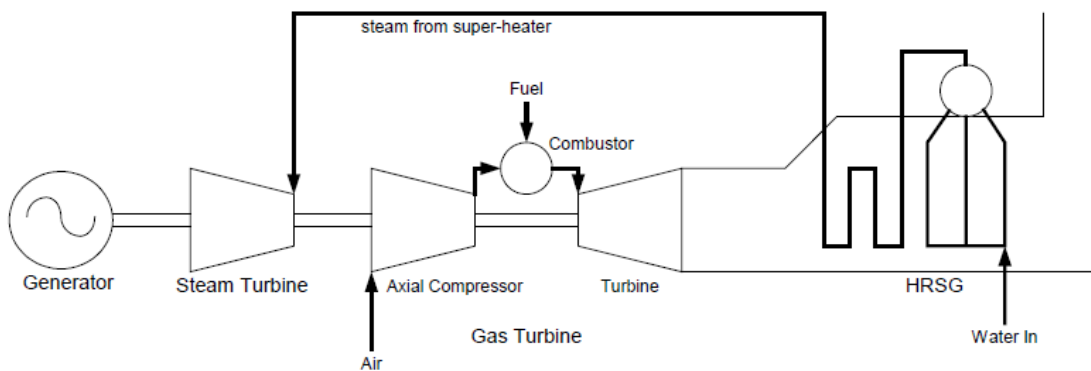


Figure 2.3: Single-shaft CCPP structure Reference [10]

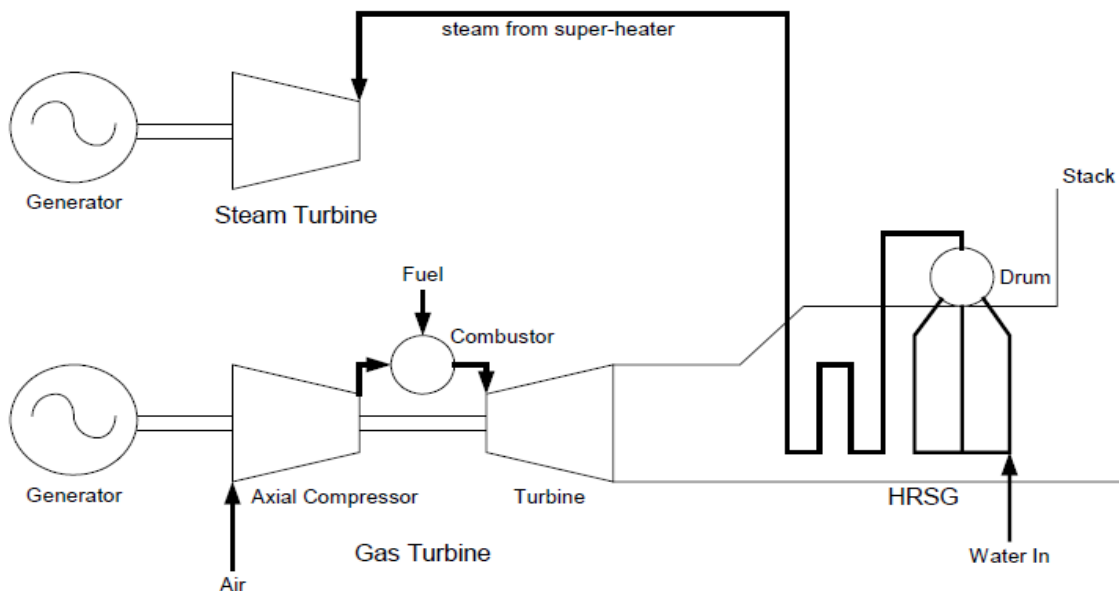


Figure 2.4: Multi-shaft CCPP structure [10]

The simplest combined-cycle power plant as it was said earlier consists of a gas turbine, a steam turbine, a heat recovery boiler, and an electrical generator. The installation can have varying numbers of gas turbines, heat recovery boilers, and generators.

The primary types of CCPP designs are [5]:

- Single-shaft, single-block (1 GT + 1 ST, turbines are on the same shaft as the generator).
- Two-shaft, single-block (1 GT + 1 ST, each turbine operates on its own generator).
- Double-block (2 GT + 1 ST, each turbine operates on its own generator).
- Triple-block (3 GT + 1 ST, each turbine operates on its own generator).

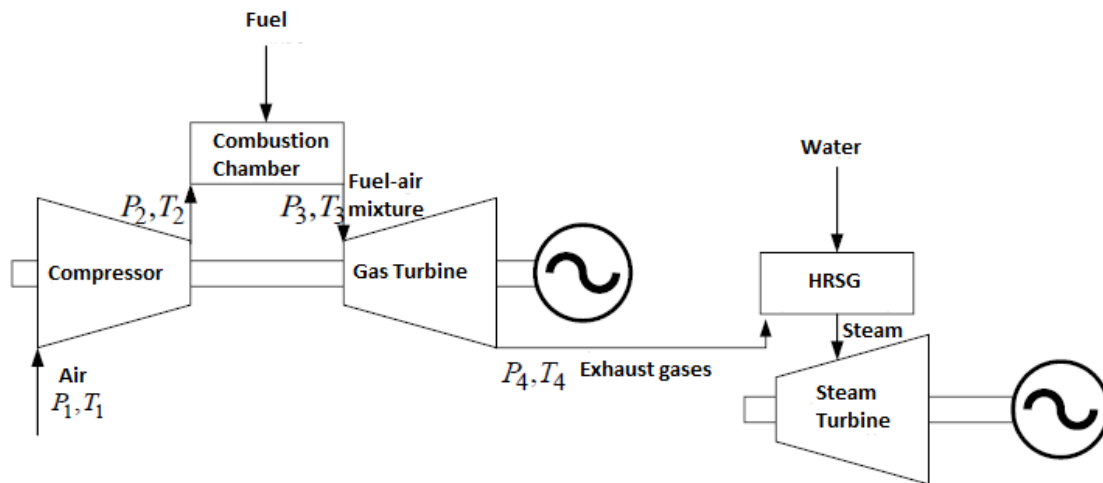


Figure 2.5: The general operational scheme of CCPP [5]

As already noted, the primary advantage of Combined-Cycle Power Plants (CCPP) is their high efficiency, which is significantly greater than the efficiency of steam turbine power plants. This high level of efficiency is achieved through the increased utilization of the enthalpy produced during the combustion process by combining the Brayton cycle in the gas turbine (GT) with the Rankine cycle in the steam turbine (ST). While single-cycle gas turbine power plants typically have efficiencies of 30-35%, CCPPs have efficiencies exceeding 55%. Thus, Combined-Cycle Power Plants (CCPP) represent an integration of two cycles: the high-temperature cycle (Brayton cycle) and the low-temperature cycle (Rankine cycle). These two

cycles are connected through the transfer of energy from the high-temperature cycle to the low-temperature cycle, and this transfer is accomplished through the heat recovery steam generator (HRSG).

2.2.3 Description of Control Systems of CCPPs

The main control systems that influence the power of Combined-Cycle Power Plants (CCPP) are the frequency controller and the temperature regulator.

Frequency Controller

The operation principle of the CCPP frequency controller is not significantly different from that of a conventional steam turbine power plant regulator. The frequency controller sets a reference value for fuel delivery based on the deviation of the frequency from its nominal value. When operating in parallel with the power grid, generating units typically function in a static control mode. The static control coefficients determine the distribution of imbalances among the generating units.

Temperature Regulator

The primary objective of the temperature regulator is to maintain the gas temperature at the inlet and outlet of the turbine at a specified level. This is achieved by measuring the gas temperature at the turbine outlet (T4 in Figure 2.5) and comparing this value to an acceptable set point. Monitoring the temperature of the exhaust gases is necessary because it is significantly lower than the temperature of the gases at the turbine inlet, making it easier to install a thermocouple at the turbine outlet. Thus, the temperature at the turbine inlet is controlled through equations that relate the temperatures of the gases at the inlet and outlet of the turbine. Under normal conditions, the temperature of the exhaust gases is maintained at the nominal level to ensure the highest efficiency of the heat recovery boiler. The combustion chamber temperature depends on the ratio of air and fuel supply. Increasing fuel supply raises

the temperature, and vice versa. Increasing air supply lowers the temperature, and vice versa. Therefore, temperature can be regulated by either adjusting fuel delivery or air supply. Priority is given to modifying air supply because changing fuel delivery affects the power output of the plant. Therefore, the signal for adjusting fuel delivery is generated with a considerably longer time delay than the signal for adjusting air supply. Adjusting the air supply is achieved by changing the position of the variable nozzle vanes (VNA). The position of these vanes is controlled by a proportional-integral controller, which responds to deviations from the set temperature. Modern gas turbines may have up to three sets of VNA, which allow reducing the load on the gas turbine by up to 40% without decreasing the temperature. If the load decreases below 40%, the gas temperature also drops, as there is no possibility to reduce air supply further.

2.2.4 Requirements for the Participation of Combined-Cycle Power Plants (CCPP) in Frequency Regulation

CCPPs are highly maneuverable installations, which means they can make a significant contribution to frequency regulation. However, due to the specific characteristics of their design, there are several points to consider when involving CCPPs in frequency regulation. For instance, when the frequency increases, the installation must reduce its power output. The most efficient way to achieve this is by closing the control valve of the steam turbine (ST), as it results in a rapid reduction in power by decreasing steam supply. Reducing fuel supply to the gas turbine (GT) is a more time-consuming process.

When the frequency decreases, the control process should work in the opposite direction. In this case, the ST cannot rapidly increase its power output because it operates under sliding parameters, and its power output depends entirely on the energy from the gases coming from the GT into the heat recovery boiler. On the other hand, in the conditions being considered, the power output of the GT can be increased fairly quickly. Thus, in the initial moments of a frequency decrease, the GT provides all the necessary primary power, and then it reduces its

output as the ST power output increases. It's worth noting that increasing the power output of the ST takes several minutes due to its significant inertia.

2.3 Combined Cycle Power Plants in Azerbaijan

As the natural gas is the main source of electricity generation in Azerbaijan, combined cycle power plants working on natural gas play crucial role in the power system of the country. By saying so, we have to mention that around 2105 MW from total of 6454 MW (in 2020) installed power capacity of Azerbaijan power sectors accounts for CCPPs. Although, a number of new projects are currently being integrated to the power system, the CCPPs will continue to play crucial role in the system in the near future. Taking into account that the new generation sources integrating to the power system are mainly focused on renewable energy sources, and considering the intermittent nature of renewable energy sources we can assure that CCPPs will even become more crucial in the frequency regulation of the power system. That is why, currently, a huge attention by “AzerEnerji” OJSC is being paid to the frequency regulation issues in the power system of Azerbaijan by holding a number of research and development works in the area of interest. The installed power capacity of CCPPs is expected to grow taking into account the new reinforcement project at “Azerbaijan” PP, where it is planned to add gas turbines and heat recovery steam generators HRSGs to the existing steam turbines which will also increase the current efficiency (around 39 %) of the plant to the around 55-56 %.

From Table 2.2 below and Figure 2.6, it is clear that CCPPs in Azerbaijan were responsible for nearly 55-56 % of total generated electric power in 2020 and this trend have continued in the following years. Only 4-5 % of the total generated electric power came from the renewable sources of energy as a result of fall in the level of water resources at hydropower plants reservoirs.

Table 2.2: Power plants in Azerbaijan owned by “AzerEnerji” OJSC (2020)

Power Plant	Type	Installed power (MW)	Generated electric power in 2020 (bil. kW/hr)
Azerbaijan PP	Thermal	2400	5,92
Cenub PP (South)	Combined Cycle Power Plant (CCPP)	780	5,185
Shimal PP (North)	Combined Cycle Power Plant (CCPP)	800	5,486
Sumgayit PP	Combined Cycle Power Plant (CCPP)	525	2,33
Sangacal PP	Internal combustion engine	300	1,074
Baku PP	Internal combustion engine	104	0,482
Shahdag PP	Internal combustion engine	104	0,3
Astara PP	Internal combustion engine	87	0,291
Sheki PP	Internal combustion engine	87	0,336
Khachmaz PP	Internal combustion engine	87	0,396
Lerik PP	Internal combustion engine	17	0,048
Mingechevir HPP	Hydropower plant	424	0,195
Shamkir HPP	Hydropower plant	380	0,4
Other		360	0,591
Total		6454	23,034

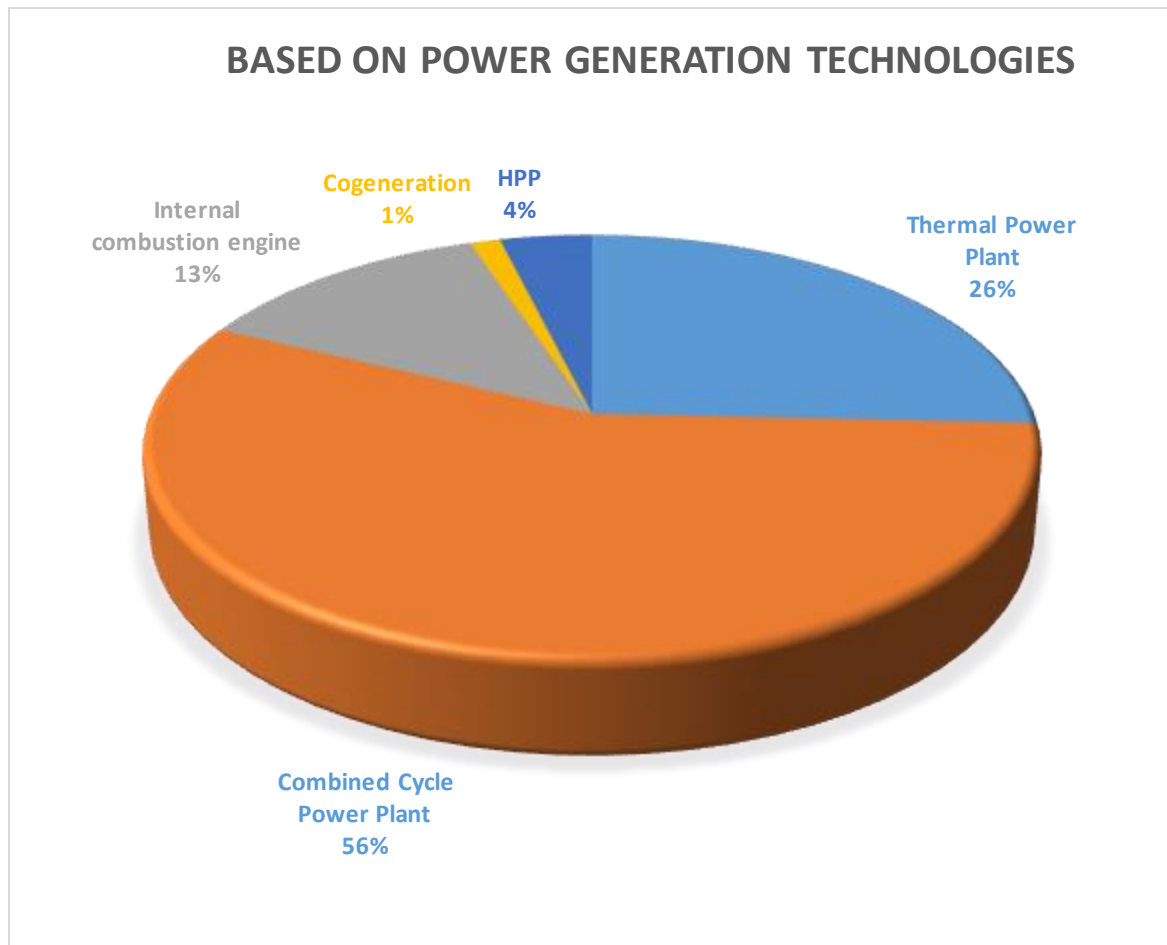


Figure 2.6: Electrical power generated in Azerbaijan in 2020 based on generation technologies

2.4 Conclusions on Chapter two

The installed capacity and the percentage of generated power by CCPPs in Azerbaijan are becoming increasingly significant. Accordingly, these installations exert a growing influence on the operation of the power system. Specifically, when addressing frequency regulation issues, it is necessary to accurately consider the response of CCPPs, as it is quite likely that these facilities will make a substantial contribution to the power balance due to their large installed capacity. Typically, significant expectations are placed on CCPPs in terms of frequency regulation due to the high maneuverability of these installations. When the frequency decreases, all the power should be taken over by gas turbines (GTs), as the steam turbines (STs) operate on sliding parameters, and changes in their power follow changes in GT power, albeit with significant inertia.

The power of CCPPs is influenced not only by the power regulator with frequency correction but also by the regulator of the temperature of the outgoing gases. Generally, gas turbines (GTs) in CCPPs have a configuration where the compressor, power turbine, and the rotor of the turbogenerator are located on a single shaft. Thus, a change in the generator's rotation frequency leads to a change in the compressor's rotation frequency, which, in turn, affects the air supply to the combustion chamber. The result of this process is a change in temperature and the initiation of the temperature regulator's action. In connection with this fact, a decrease in frequency can lead to the frequency correction regulator being blocked by the temperature regulator, subsequently reducing the power of the installation.

The problem of changing the power of CCPPs when the frequency deviates is widely discussed in foreign literature and normative-technical documentation. However, there are few suggestions for preventing accidents related to this problem. In domestic literature, this issue is practically not addressed. Thus, the discussed problem is currently relevant, and the search for new ways and the development of existing methods to solve it are promising research directions.

CHAPTER THREE

METHODOLOGY

Currently, mathematical modeling is widely used for the analysis of various operating modes of equipment, as this method of research is the least costly from an economic point of view. In order to analyze processes related to frequency changes when separating an energy region from a combined heat and power plant for isolated operation, this study employed mathematical modeling in the MATLAB Simulink software. At present, there is a wide range of gas turbine (GT) models that can be applied to investigate various processes in the power system. This chapter provides a brief overview of GT models used to study processes related to frequency changes. The GT Rowen model, which was used for the computational experiments presented in the study, is discussed in more detail. Additionally, an automatic voltage regulator loop was also modeled in order to get more precise results.

3.1 Review of Gas Turbine Models

To analyze processes related to a significant decrease in frequency, full-scale tests are the most suitable. Conducting real tests with a substantial frequency deviation is a complex and hazardous task. Therefore, simulation of such deviations is often performed, which significantly distorts the picture since it does not accurately reflect the real change in turbine shaft speed. Overall, this leads to distorted results for any installations, but for gas turbines, it is particularly significant because the change in the turbine shaft speed is coupled with a change in the compressor speed, potentially resulting in additional power variations.

Therefore, at present, mathematical modeling has become widely prevalent as the primary tool for research. Recent advancements in computer technologies have allowed for the development of sophisticated models that can simulate the behavior of equipment under continuously changing conditions in the power system.

The main objective of this research was to study the behavior of a CCPP during deep frequency reductions with the aim of proposing various approaches to prevent the development of emergency situations. Consequently, significant attention was devoted to modeling of CCPP. Currently, there exists a wide variety of gas turbine (GT) models. Boiler-utilizer and power transformer models receive less attention since, essentially, they correspond to models of conventional steam power plants.

The most common models for system studies are the Rowen model [12] and the IEEE model. They also serve as the foundation for other models, where additional blocks are added depending on the type of models and the modeling objectives. The IEEE model is constructed based on thermodynamic equations, allowing for detailed modeling of processes occurring in a CCPP. One notable feature of this model is that it assumes a fixed compression ratio for the compressor, valid only for relatively constant rotor speed. Therefore, the IEEE model does not consider investigations into deep frequency reductions [6].

The Rowen model, on the other hand, is built on the approximation of thermodynamic equations. It can be used for studies with frequency deviations ranging from 95% to 107% of the nominal value. Several articles have compared these models [5] but they do not provide a definitive answer on which model is better to use. These models yield similar results, and the choice between them depends on the available equipment data. The Rowen model is more commonly used for research, and accordingly, more detailed literature is available on it.

3.2 Rowen Model

This model was first introduced by Rowen in 1983 in the article and was among the earliest gas turbine models presented in the literature.

work focuses on a steam-gas system incorporating two turbines (steam and gas) and one generator unit. The model is established using simplified mathematical transfer functions for the turbines, as well as their control and regulatory systems. The control system is structured in the following manner:

The initial loop encompasses the speed governor, essential for load frequency control, ensuring system stability. This component detects deviations in frequency and adjusts the fuel request signal accordingly. Fuel control in the combined cycle gas turbine (CCGT) plant is directly tied to the rotor speed. The rotor speed, along with the frequency, exerts a direct impact on both air and fuel consumption. As the rotor speed changes, the fuel control system responds accordingly, affecting the overall combustion process and, consequently, the power output of the gas turbine. This relationship underscores the interconnected dynamics between the mechanical aspects of the turbine and the corresponding control mechanisms regulating fuel flow to maintain system stability and efficiency. The temperature control loop plays a crucial role in the operational system of the power plant. Its primary function is to make adjustments to fuel flow (W_f) and airflow (W) by utilizing measurements of the exhaust temperature. Specifically, it adjusts fuel demand in response to frequency decreases and the subsequent reduction in output power. This dynamic control mechanism ensures that the temperature remains within the desired range, contributing to the overall stability and efficiency of the power plant.

3.2.2 Verification

The Rowen model has been verified using real measurement data presented in numerous works [5] [12] [14]. Therefore, there is no particular need for additional verification.

3.3 Load response to the Frequency Deviation

Power grid blackouts are often a result of imbalances in frequency regulation requirements. The decrease in system frequency has various impacts on Combined Cycle Gas Turbine (CCGT) plants. One significant effect is observed in the inertia response, which, along with the load response, plays a crucial role in the power system by damping the initial frequency decline. Another consequence of a drooping frequency is a reduction in compressor speed, leading to a decrease in pressure and airflow. This, in turn, results in heightened fuel consumption and an increase in temperature. During this period, the temperature controller responds by reducing fuel demand, causing a subsequent decline in the output power of the gas turbine. Since the frequency system is directly proportional to the speed of the generator, frequency regulation becomes achievable through the regulation of the speed of the rotating part of the generator. This task is undertaken by the speed governing control system, which is installed modification the output power and regulation both speed and frequency deviation. Depending on the sign of the frequency imbalance, the frequency control action is designed to initiate automatically, promptly adjusting the active power output either upward or downward to provide necessary power support. The frequency imbalance in the system is regulated by generator speed variations which in turn leads to a change in the power output. The dependency of the frequency (speed) on the load is usually expressed like below:

$$\Delta P_e = \Delta P_L + D * \Delta w_r [3]$$

Where:

ΔP_L is the load change

Δw_r is the speed deviation

D is the load damping constant

Damping constant is usually expressed as a percentage change in load for each one percent of change in the frequency.

3.4 Dynamic Response of CCGT

The gas turbine aspect closely resembles the dynamic response of open cycle gas turbine (OCGT). OCGT and CCGT share a maximum allowable temperature determined by turbine's blade materials. Fluctuations in exhaust gas temperature entering the HRSG affect its efficiency and, consequently, the steam turbine efficiency. Maintaining the exhaust gas temperature at the maximum allowable level is crucial for optimal CCGT efficiency. The optimal exhaust temperature is upheld by regulating air and fuel flows. Variable inlet guide vanes (IGVs) at the compressor entrance manage incoming airflow. During the gas turbine startup, IGVs ensure a smooth air compressor run-up until full speed. Subsequently, IGVs adjust to maintain the programmed target exhaust gas temperature with the introduction of fuel. To sustain a constant outlet temperature, airflow must adapt to changes in fuel flow. However, as the gas turbine approaches base load, IGVs reach full openness, limiting further airflow increase. CCGTs are known for their rapid response. The speed controller reacts swiftly to declining system frequency by injecting more fuel into the combustor. However, excessive fuel flow increments may challenge IGVs in maintaining the correct air-fuel ratio. Units with fast-acting actuators on IGVs enhance responsiveness to frequency events, mitigating anticipated increases in outlet temperature by adjusting airflow. Understanding CCGT dynamic behavior during frequency disturbances involves recognizing the effects of changing system frequency. CCGTs contribute an inertial response proportional to the magnitude and rate of frequency change, aiding in system security. As system frequency falls, compressor speed decreases, reducing pressure ratio, airflow, and power output. At partial load, IGVs can offset reduced airflow, but at base load, IGVs' full openness limits further adjustment, causing an increase in fuel-to-air ratio, exhaust temperature, and subsequent power reduction. Gas turbine power output also relies on ambient atmospheric conditions. Variations in ambient temperature can significantly impact maximum power output. CCGTs are designed for maximum efficiency at

base load, and operating below this reduces efficiency, increasing per-unit fuel costs. Deviations from optimal conditions impact compressor and turbine efficiency. Compressor surge risks increase at partial loads, particularly if system frequency decreases. In sliding pressure mode, the steam turbine's power output directly correlates with gas turbine exhaust gas flow. Steam turbine response depends entirely on the gas turbine, with a notable delay before changes in gas turbine fuel flow affect steam turbine power output, making it reasonable to neglect steam turbine dynamics for short time periods. [3] [9]

3.5 Conclusions on Chapter three

For system studies, it is not necessary to model all processes occurring within the CCPP in detail. However, the main loops influencing the output power of the installation must be modeled. Despite the numerous gas turbine (GT) models available, they can generally be categorized into two main types: the Rowen model and the IEEE model. In this study, the Rowen model was chosen. Inertial links are mainly used for modeling the waste heat boiler and the power transformer. For the task of studying frequency changes, this is sufficient because the power transformer operates with sliding parameters and, concerning power increase, follows the gas turbine with the corresponding inertia.

When the system frequency decreases, it induces various effects on the Combined Cycle Gas Turbine (CCGT) unit. One outcome is the generation of an inertial response, the magnitude of which is influenced by both the rate and extent of the frequency decline. This response plays a crucial role in mitigating the initial frequency drop, complementing the load response on the system. Another impact of the decreasing system frequency on CCGT units is a reduction in the compressor speed. This leads to a lowering of the output pressure and a decrease in airflow from the compressor. The diminished output pressure across the gas turbine results in a lower power output, as the pressure ratio decreases. The reduced airflow into the combustor raises the fuel-to-air ratio, causing an increase in temperature. However, operational

constraints on the machine impose a limit on the maximum temperature at which the turbine can function. Although this limit can be exceeded briefly, it may affect the machine's lifespan. In such instances, the temperature controller intervenes, reducing the fuel flow accordingly. Consequently, the maximum power output of the gas turbine component in the CCGT is clearly restricted by temperature control during low-frequency events, leading to a further decline in power output. Unlike the beneficial inertial response of the CCGT to a falling frequency, this reduction in power output during declining frequency is undesirable. Additionally, CCGTs may experience compressor surge during a frequency transient, negatively impacting power output.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Simulation model

For the analysis and evaluation of the frequency regulation characteristics of the CCPPs in islanded operation mode we have developed simplified mathematical model (Figure 4.2) of single-shaft CCPP on MATLAB SIMULINK, having generator at the one end and driven by both the gas turbine and steam turbine from the same side (the construction similar to that of “Shimal 1” 400 MWt Power Plant IN Azerbaijan). The model consists of two generic loops: load frequency control and voltage control. The objective of frequency control loop is to maintain relatively uniform frequency which is given as reference frequency (50 Hz). The loop consists of the Governor, Gas Turbine, Steam Turbine, Inertia and Load, two speed regulators and two speed integrators. All these components are represented as mathematical models with gain and time constants which are defined for each specific type of equipment. The constants used and the source values were taken from the general sources for CCPPs simulation [3] [5] [12] and also provided in the Figure 4.1 and Table 4.1 and Table 4.2. The main purpose of the simulation of frequency control loop was to find out the response of the developed system (single shaft CCPP) to the sudden change in the demand in our islanded grid. For this purpose, we have supposed that the demand (or the load) have changed to some degree, expressed that change in per unit values and applied it to the Inertia and Load block of the simulation chain, and then we have examined the response of the CCPP model to that change in order to know how fast the system will restore the grid’s reference frequency of 50 Hz. On the contrary the voltage regulation loop consists of the following mathematically modelled blocks: Amplifier, Exciter, Generator field, Sensor and PID controller. Again the gain and time constants for the block are provided in Table 4.1 and Table 4.2.

Controlling the generator rotor speed allows for the regulation of the frequency network, as it is directly proportional to the generator speed. This function is undertaken by the speed governing control system, which is implemented to fine-tune the output power and oversee the adjustment of speed and frequency deviation [3] [13]. The automatic initiation of frequency control action occurs promptly based on the direction of the frequency deviation. It promptly and automatically adjusts the active power output, either increasing or decreasing it, to provide immediate power support.

Symbol	Description	Value
t_i	Compressor inlet temperature	30 °C
t_{d0}	Compressor discharge temperature	390 °C
t_{f0}	Gas turbine inlet temperature	1085 °C
t_{e0}	Gas turbine exhaust temperature	535 °C
P_{r0}	Compressor pressure ratio	11.5
γ	Ratio of specific heat	1.4
η_c	Compressor efficiency	0.85
η_t	Turbine efficiency	0.85
R	Speed Regulation	0.04
T_t	Temperature control integration rate	0.469

Symbol	Description	Value
$T_c \text{ max}$	Temperature control upper limit	1.1
$T_c \text{ min}$	Temperature control lower limit	0
$F_d \text{ max}$	Fuel control upper limit	1.5
$F_d \text{ min}$	Fuel control lower limit	0
T_v	Valve positioner time constant	0.05
T_{fu}	Fuel system time constant	0.4
T_w	Air control time constant	0.4669
T_{cd}	Compressor volume time constant	0.2
K_0	Gas turbine output coefficient	0.0033
K_1	Steam turbine output coefficient	0.00043
T_g	Governor time constant	0.05
K_4	Gain of radiation shield (instantaneous)	0.8
K_5	Gain of radiation shield	0.2
T_3	Radiation shield time constant	15
T_4	Thermocouple time constant	2.5
T_5	Temperature control time constant	3.3
K_3	Ratio of fuel adjustment	0.77
K_6	Fuel valve lower limit	0.23
T_m	Time constant heat capacitance of waste heat recovery boiler	5
T_b	Boiler storage time constant	20
T_i	Turbine rotor time constant	18.5

Figure 4.1: List of constants used in the study [3]

Table 4.1: Constants used in simulation frequency control loop [5]

	Gain Constant	Time Constant
	K	T
Governor	1	0.2
Gas Turbine	1	0.5
Steam Turbine	0.01	1
Amplifier	10	0.1
Exciter	1	0.4
Generator field	1.4	1
Sensor	1	0.05

Table 4.2: Constant used in simulation of voltage regulation loop [3]

Speed Regulator 1	K_s	20
K integrator	K_i	6
Inertia	H	5
Regulation	R	0.05
Duty	D	0.8
Synchronizing coefficient	P_s	1.5
Voltage integrator (K_6)	K_6	0.5
Coupling Constants	K_2	0.2
	K_1	1.4
	K_5	-0.1
PID Controller	P	1
	I	0.25
	D	0.3

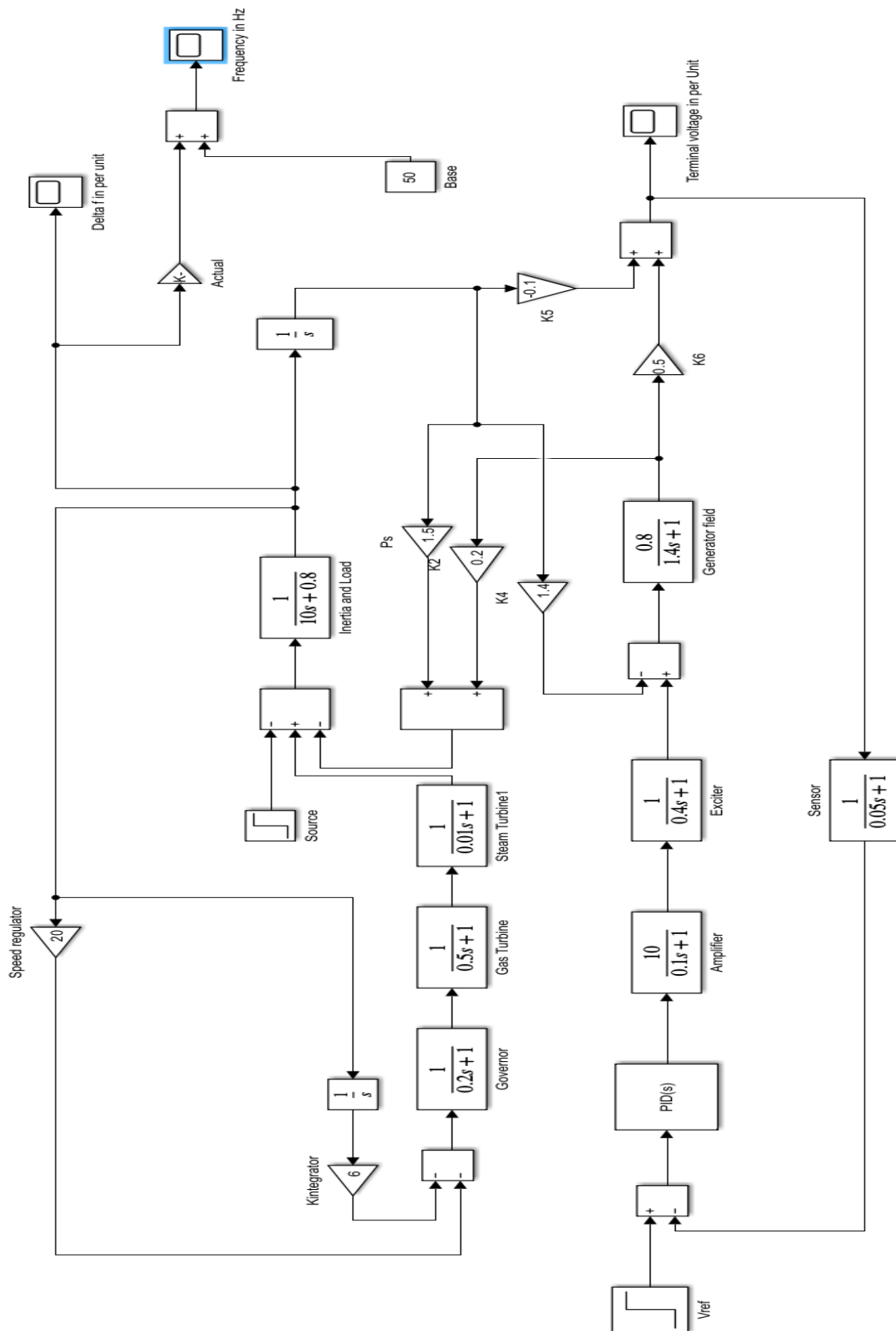


Figure 4.2: Simplified mathematical model of frequency regulation at the single-shaft CCPP

4.2 Results

The results obtained from the simulation under given constants provided in Table 4.1 and Table 4.2 and Figure 4.1 are represented on Figures 4.3 and Figure 4.4 for frequency regulation and voltage regulation respectively. From Figures 4.3 we can extract the settling time of frequency deviation to nominal 50 Hz which is around 14 seconds and falls in the range of primary frequency regulation timeframe. At the same time the maximum overshoot (0.4 Hz) after initial frequency deviation caused by the increase in the load is relatively small and is in the tolerable borders.

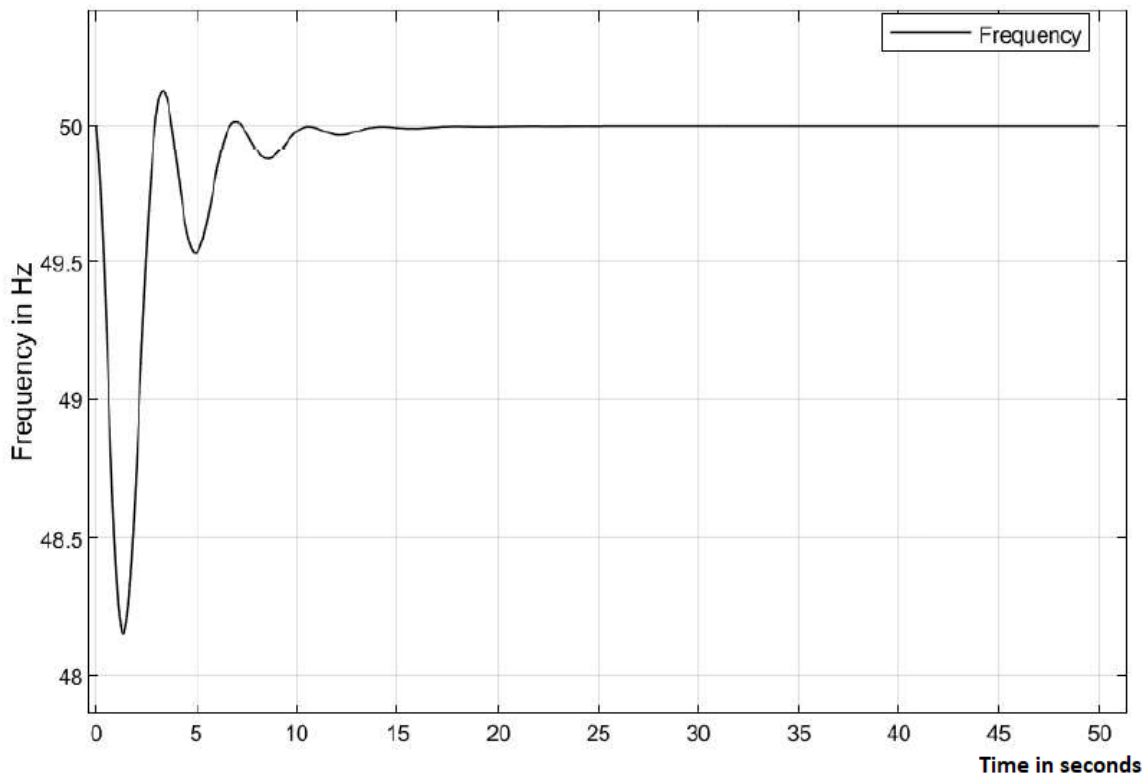


Figure 4.3: Frequency regulation (generated on MATLAB SIMULINK)

In terms of the automatic voltage regulation loop the obtained results from the basic simulation are provided in the Figure 4.4. We can see the settling time of voltage to its nominal p.u. value is 13 seconds.

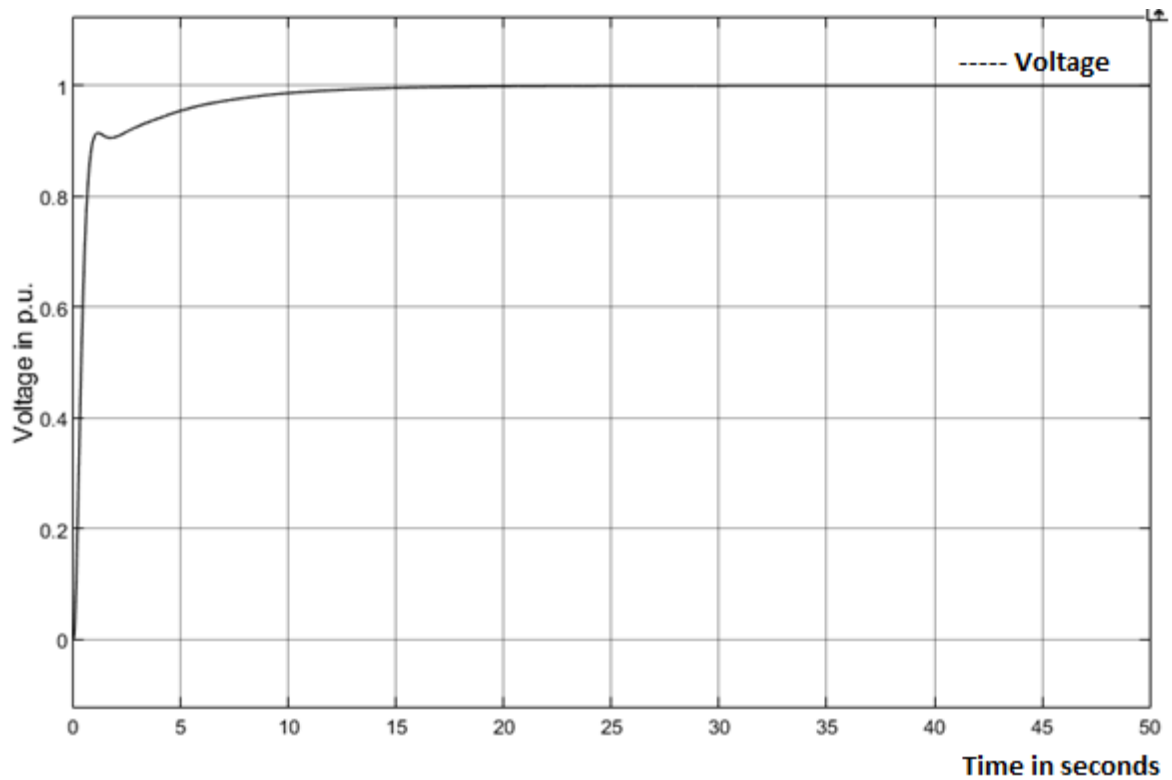


Figure 4.4: Voltage regulation (generated on MATLAB SIMULINK)

After the completion of the base simulation we have tested how the different types of gas and steam turbines time constants, the speed controller's governor time constant and the overall CCGT's inertia time constant affects the settling time and peak deviation of the frequency in the system after the 20 % change in the applied load. The results obtained during the simulation are provided in the Tables 4.3-4.6. The outcomes of the simulations are discussed in the following chapter.

Table 4.3: The impact of the gas turbine time constant to the frequency regulation

Gas turbine Time constant	Settling time seconds	Peak deviatoin
0.5	14	0.4
0.1	13	1.3
0.01	13	1.2
1	33	0.8

Table 4.4: The impact of the steam turbine time constant to the frequency regulation

Steam turbine Time constant	Settling time seconds	Peak deviatoin
0.01	14	0.4
0.1	22	0.4
0.5	diverges	

Table 4.5: The impact of the inertia time constant to the frequency regulation

Inertia	Settling time seconds	Peak deviatoin
5	14	0.4
6	12.5	0.1
7	12	0.25
1	diverges	
2	50	0.9
3	21	0.8

Table 4.6: The impact of the governor time constant to the frequency regulation

Governor Time constant	Settling time seconds	Peak deviatoin
0.2	14	0.4
0.5	45	0.8
1	diverges	
0.1	13	1.7

4.3 Discussion

We have developed the simplified mathematical model of single-shaft CCGT on the MATLAB SIMULINK software in order to analyze the frequency regulation in the isolated grid operation of combined cycle power plant. First of all, we run the base simulation model in order to see if our model works properly and if yes what would be the settling time and peak frequency deviation in the system after applied 20 % change in the load. The simulation was successful and it took around 14 seconds for the system to restore the nominal frequency of the system to the desired 50 Hz value. The maximum deviation in frequency during the settling time settling time was 0.4 Hz maximum overshoot, in other words 49.6 Hz which is tolerable for the power system.

After that in order to analyze the effects of different segments of the system to the frequency regulation procedure we have completed simulations for different types of gas and steam turbines time constants, the speed controller's governor time constant and the overall CCGT's inertia time constant affects the settling time and peak deviation of the frequency in the system after the 20 % change in the applied load. From the Table 4.3 for gas turbine time constant simulations we can conclude that with the decrease of the GT's time constant the settling time of the frequency decreases as well but at the same time it negatively affects the maximum overshoot in the frequency which increases rapidly.

For different types of steam turbines, the results obtained in Table 4.4 shows more or less the same trend as it was in the case of gas turbine. However, there is one necessary point to be mentioned, from the results we can see that the impact to the frequency regulation of steam turbine in comparison with the impact of gas turbine is less as it comes after the gas turbine in the system and plays secondary role.

In terms of the inertia characteristics of the system the primary point to be mentioned is the nature of the inertia. The inertia of the system represents the stored energy within sizable

rotating generators and certain industrial motors imparts a natural inclination for them to sustain their rotational motion. So the inertia constant increases with the increase in the generating capabilities of the power system, in our case, as the islanded power system consists of the one CCPP, the inertia constant represents the generating capabilities of the CCPP. To summarize, power plants with big generating capacities have higher inertia constant. From our simulation results provided in Table 4.5 we can prove that the CCPPs with higher installed power capacity and subsequently with higher inertia time constant tend to have lesser settling time and smaller maximum overshoot in the frequency deviation.

The last part of the simulation was dedicated to the study of the governor block to the frequency regulation in the CCGT system. From the results given in Table 4.6 we can understand that the governor time constant represents the sensitivity of the frequency regulation in the CCGT system. As the time constant of the governor increases it results in a higher peak deviation in the frequency and the system also needs more time to return to the nominal frequency.

CHAPTER FIVE

CONCLUSION AND FUTURE WORK

The paper in general discusses the dynamic responses of the CCGT system to changes in load and damping, manifested through alterations in frequency. The speed governor control, influenced by the characteristics of speed deviation and the sensitivity of frequency to load changes, plays a crucial role in achieving a steady-state frequency. During this process, the output of the Combined Cycle Gas Turbine (CCGT) remains close to its rated value until the system frequency returns to its nominal level. Given that frequency is tied to the output power, maintaining a nearly constant frequency is essential to keep the generator speed at its rated value. Therefore, the reliability and effectiveness of the frequency control system are paramount for ensuring the stability of power system generation. This underscores the significance of a robust frequency control mechanism in sustaining the overall stability and efficiency of the power system.

A decrease in frequency results in a reduction of the compressor rotation speed, leading to an increase in the temperature of the outgoing gases. This process may trigger the temperature regulator to reduce fuel supply, causing a decrease in the power of the installation. If there are insufficient power reserves in the power region, this can lead to an increase in imbalance and an avalanche-like process.

Further development of the provided simulation model, namely, adding fuel and temperature control loops in order to obtain more accurate results is suggested.

Testing installations for their suitability in frequency regulation is done by inputting a signal into the frequency corrector that simulates a change in frequency. These conditions do not provide information about the change in compressor rotation speed, and therefore, the tests will not reveal a possible decrease in power. Instead of the expected increase in power after testing, the actual power of the combined cycle power plant (CCPP) may, on the contrary,

decrease. To account for this, two solutions can be considered. The first is conducting real-world tests, but tests with deep frequency deviations are costly and risky. The second approach involves creating equipment models and conducting tests using mathematical modeling as it was done in the following work.

If CCPPs predominate in a separated region, in the event of an emergency situation with a significant frequency change, the volume of load disconnected by automatic load shedding (ALS) will be noticeably higher than expected. Thus, it is necessary to consider the potential decrease in CCPP power during frequency reduction and take this into account when calculating the maximum imbalance to determine the capacity of ALS.

To prevent unacceptable frequency reduction resulting from the action of the temperature regulator in CCPPs, it is proposed to utilize power augmentation during deep frequency decreases. [5] [16]

To prevent the occurrence of an avalanche process in a power region with CCPPs during deep frequency decreases, the use of power augmentation is proposed [5] and the graphical representation is given in the Figure 5.1. It has been demonstrated that a rapid increase in the active power output of CCPPs in the initial moments of an emergency situation can help support the frequency and, consequently, sustain the power output of the CCPP.

Experiments conducted with CCPPs operating in a separated power region alongside conventional steam power plants have shown that if there are sufficient power reserves in other installations, the avalanche process occurs with a higher power imbalance. However, this process can also be mitigated using the proposed CCPP power augmentation algorithm.

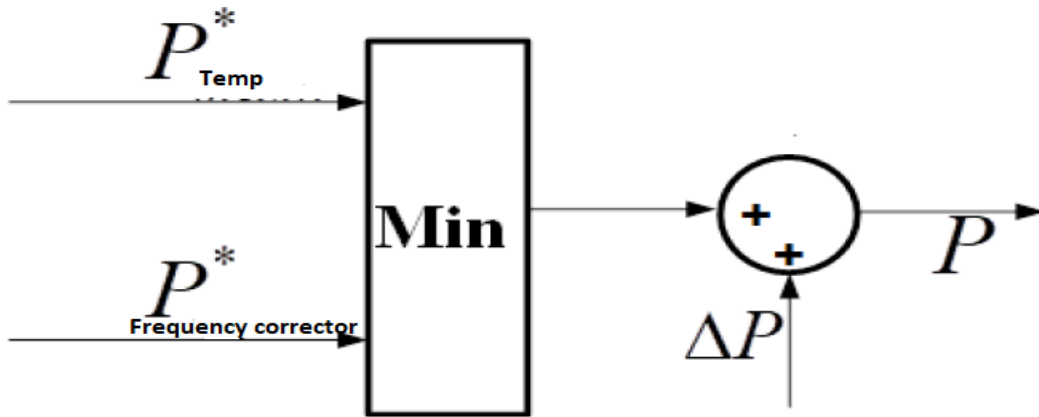


Figure 5.1. Realization scheme of power augmentation [5]

As an additional and extreme measure to prevent the avalanche process, load shedding through voltage regulation may also be considered. By adjusting the AVR (Automatic Voltage Regulator) set point, it is possible to reduce the imbalance if the active power of the load is voltage-dependent.

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