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ANALYSIS OF STAGES AND PRINCPLES OF FREQUENCY REGULATION IN ENERGY SYSTEMS

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THESIS ACCEPTANCE

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ABSTRACT

Nowadays, because of the increasing demand for electrical energy, the stability of electrical systems is reaching its critical limit. As the use of renewable energy sources increases in total

production, maintaining a stable frequency becomes more challenging. This study discusses frequency regulation by traditional and modern methods and the encountered problems. First-, second, and third-order frequency control systems play crucial roles in maintaining frequency stability. However, with the grow in both the cases and output of renewable sources, it's crucial to seek more advanced solutions, such as synthetic inertia, fast-frequency response technologies, artificial neural networks. This review emphasizes the need for developing algorithms and control strategies that meet the dynamic requirements of modern systems while ensuring reliability and stability.

The increase in renewable energy sources in our country and the high rate of trust in them creates several problems in energy systems, one of which is the problems it creates in frequency regulation. Considering that the average electricity production capacity in Azerbaijan is approximately 4500 MW, even if 480 MW of renewable energy is added to this system, many studies and regulations are needed. Although the construction of solar and wind power plants is very useful in itself, it has brought with it many negative effects that undermine the reliability of the energy system, the most significant of which is the inertia of the system and the dependence of energy on natural factors.

Traditional frequency regulation systems are a main but increasingly not effective for new power systems. Primary frequency control system manages immediate energy changings by using of generator inertia, when secondary control, often achieved through Automatic Generation Control (AGC), restores the system frequency to nominal. Tertiary control, aiming on resource optimization and economic dispatch, provides a long-term balance. However, the variability and unpredictability of renewable energy require modern solutions that complement these traditional techniques.

Advanced frequency regulation approaches, containing synthetic inertia, fast-frequency response (FFR) technologies, and adaptive systems, are very critical in controlling and stabilazing the challenges posed by renewable energy. Synthetic inertia emulates the stabilizing impact of mechanical inertia through power electronics, ensuring rapid responses to deviations. FFR technologies such as battery storage systems (BESS) and flywheel energy storage systems (FESS) provide instantaneous power controls to keep the grid under nominal parameters before slower-acting controls intervene. Furthermore, adaptive control systems like Artificial Neural Networks (ANNs) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) influence real-time and historical data to optimize responses dynamically, enhancing overall grid resilience.

The main objective of this master thesis is to investigate the effects of 3 renewable energy sources that will enter the Azerbaijan's energy system in 2025 on the stability of the system and to pay attention to maintaining the main frequency. The aim of the simulations is to see how, in parallel with the increase in the number of renewable energy sources, when any of the main frequency regulating generators of the system is shutdown, it is felt in other stations and how it is felt on the main Derbent Power Transmission line. Based on the simulation results, new proposals have been put forward, the most important of which is the installation of a new battery system and maintaining stability in the system during emergency shutdowns by remaining in standby mode. Another proposal is the reconfiguration of the AGC and PSS systems at the main Power Plants

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LIST OF ABREVIATIONS

Abbreviation	Explanation
AC	Alternating Current
AGC	Automatic Generation Control
AI	Artificial Intelligence
ANN	Artificial Neural Network
ANFIS	Adaptive Neuro-Fuzzy Inference System
BESS	Battery Energy Storage System
CAISO	California Independent System Operator
DER	Distributed Energy Resources
DFIG	Doubly Fed Induction Generator

ESS	Energy Storage Systems
FFR	Fast Frequency Response
FESS	Flywheel Energy Storage System
GB	Great Britain
GW	Gigawatt
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
LFC	Load Frequency Control
MLP	Multi-Layer Perceptron
MW	Megawatt
PID	Proportional-Integral-Derivative (Controller)
PI	Proportional-Integral (Controller)
PSS	Power System Stabilizer
PSO	Particle Swarm Optimization
PV	Photovoltaic
ROCOF	Rate of Change of Frequency
SCADA	Supervisory Control and Data Acquisition
SMES	Superconducting Magnetic Energy Storage
SO	System Operator
TSO	Transmission System Operator
SPP	Solar Power Plant
VPP	Vind Power Plant
AVR	Automatic Voltage Regulator
UFLS	Under Frequency Load Shedding
EPL	Electrical Power Line
HPP	Hydro Power Plant
SGG	Steam-Gas Generator
FSNL	Full speed No- Load

CHAPTER ONE

INTRODUCTION

1.1 Problem Statement

The integration of renewable energy sources into existing power systems presents significant challenges for maintaining frequency stability. In Azerbaijan, where the energy grid operates with a total capacity of approximately 4500 MW, the planned addition of a 480 MW renewable energy source raises concerns about system reliability. Renewable energy sources, such as solar and wind, are variable and intermittent, leading to fluctuations in power generation and reduced grid inertia. These factors make traditional frequency regulation methods increasingly inadequate. Without adopting advanced solutions, the grid risks frequency instability, inefficiency, and potential disruptions in energy supply.

This study addresses the critical issue of integrating renewable energy sources while maintaining system stability. By analyzing the effects of renewable energy integration and evaluating both traditional and modern frequency regulation methods, this research aims to propose actionable strategies for optimizing Azerbaijan's energy grid.

This problem is important because with the advancement of technology and the industrial enterprises increases, the demand for electricity is steadily and rapidly increasing. In this regard, energy issues are already standing as a significant problem, and worldwide actions are being taken to address them. To meet the growing demand, it is required to increase electricity production and maintain a stable power balance.

In general, the quality indicators of electricity depend on the effective organization of the generation and load consumption balance. One of the main problems of the energy system is maintaining a constant frequency, which is affected by many factors. Frequency is one of the main quality indicators of electricity. Therefore, keeping this electrical parameter stable is one of the main objectives. Frequency instability indicates that electrical equipment is not operating within its optimal parameters, causing decreased efficiency. If the frequency decreases below the required threshold values of 50 Hz and 60 Hz, it may lead to a complete shutdown of any equipment or even a power system.

Frequency control is achieved by a range of methods, from traditional to advanced techniques. The most common traditional techniques include primary, secondary, and tertiary methods. In the primary regulation method, frequency regulation is done by power generators, which are responsible for producing electricity within the specified nominal frequency conditions. In these generators, mechanical inertia is utilized to reduce frequency fluctuations and ensure stable operating conditions [4]. The operating principles of the generators involve adjusting the mechanical power input in response to frequency deviations and utilizing mechanical inertia. Mechanical inertia provides control over initial frequency fluctuations and maintains stability in the power system. Coordinating the output of multiple generators across secondary speed control regions, usually controlled by automatic generation control (AGC), returns the system frequency to its nominal value, and ensures that the system remains more stable [2]. Third-level control refers to the management of resources to ensure the long-term sustainability and security of the energy systems. Dispatchers have a significant role in this procedure, optimizing the economy and stabilizing the supply manually. Using these methods, it is also possible to maintain a balance between renewable energy sources and traditional production capacities [2].

On the other hand, the recent developments of renewable energy sources have significantly changed the energy requirements, making frequency regulation more difficult. Increasing renewable energy sources such as wind, solar and hydroelectricity is essential for sustainable development, but it also makes serious work on frequency regulation important [2]. It is known that renewable energy sources are unpredictable, altering their power generation capacity depending on the time of day due and the weather conditions. Unlike traditional generators, they do not provide the same level of inertia, leading to increased energy waste when adjusting their speed [2]. As the penetration of renewable energy sources into the grid increases, existing frequency regulation methods become less effective, making it difficult to maintain system stability. To address the problem, the development of new frequency regulation systems is required. This is one of the main problems facing modern energy systems [3].

The aim of the master's thesis is to clarify the problems arising in frequency regulation in the Azerbaijani energy system and to anticipate and consider solutions to the problems we may face after the increase in the number of renewable energy sources and the introduction of an additional 480 MW of electricity into the system in 2025. For the simulations, artificial shutdowns were conducted at Sumgait and Shimal Power Plants to examine how these openings would result in several parts of the system. New solutions have been proposed, such as the installation of a new battery system and the reconfiguration of AGC and PSS at the main power stations.

1.2 Definition of Terms

1. Frequency Stability: The ability of a power system to keep its operating frequency during specified limits under nominal and disturbed conditions.
2. Renewable Energy Sources: Naturally replenished energy sources such as hydroelectric, solar, wind, geothermal, biomass etc.
3. Grid Inertia: The resistance of a power system to impact the in-frequency changes, traditionally provided by the rotational energy of synchronous generators.
4. Synthetic Inertia: The emulation of mechanical inertia through power electronics to stabilize grid frequency in systems with high renewable penetration.
5. Fast-Frequency Response (FFR): Quick adjustments in power injection or absorption, typically from technologies like battery energy storage systems (BESS) and flywheel energy storage systems (FESS), to stabilize and control grid frequency.
6. Automatic Generation Control (AGC): A secondary frequency control system that stabilizes generator outputs to restore frequency to its nominal value.
7. Dig SILENT Power Factory: A simulation software applied for modeling, analyzing, and optimizing power systems under various operational scenarios.
8. Load Frequency Control (LFC): A subsystem of AGC that balances load demand and power generation to maintain frequency stability within a control area.
9. Tertiary Control: A long-term frequency control method focusing on economic dispatch and efficient resource allocation.
10. Primary Frequency Control: The initial automatic response of power generators to stabilize frequency deviations by adjusting their mechanical power output.
11. Secondary Frequency Control: A coordinated mechanism to restore grid frequency to its nominal value after primary control, often achieved through AGC.
12. Energy Storage Systems (ESS): Technologies such as batteries, flywheels, and compressed air systems used to store energy for later use, particularly in grid stabilization.
13. Microgrid: A small-scale, localized power grid that can operate independently or in conjunction with the main grid.
14. Power System Stability: The ability of an electrical power system to return to its steady-state operating condition following a disturbance.

15. Frequency Regulation Reserve: A reserve of generating capacity or storage that can be rapidly deployed to maintain system frequency.
16. Voltage Stability: The ability of a power system to maintain voltage levels within acceptable limits during normal and disturbed conditions.
17. Inertial Response: The immediate response of conventional generators to frequency changes, due to their rotating masses.
18. Grid Flexibility: The ability of a power system to adapt to changes in demand and generation, especially from variable renewable sources.
19. Power Flow Analysis: The study of power system behavior under different loading conditions, focusing on voltage, current, and power distributions.
20. Reserve Management: The process of scheduling spinning and non-spinning reserves to ensure system reliability during contingencies.
21. Black Start Capability: The ability of a power system or generator to restart without external power, crucial for system recovery after a blackout.
22. Dynamic Stability: The ability of a power system to maintain stable operation under changing conditions over time.
23. Intermittency: The variability in renewable energy generation due to factors like weather and time of day.
24. Curtailment: The reduction of renewable energy output to maintain system stability when supply exceeds demand.
25. Automatic Voltage Regulator: It is a special system installed in generators that immediately reacts to voltage drops in the generator or system, increases the generator's exciting currents, and thus regulates the voltage.
26. Power System Stabilizer: This system is installed on the generator, constantly monitors the generator's current, voltage, and rotor speed, and automatically intervenes if any changes in frequency occur, helping to restore the frequency to its nominal value.
27. Special Protection System: It is a protection system that accepts many parameters as input and activates when any of these parameters increases sharply or exceeds a set nominal limit. As a result, it opens the switch of any equipment or power transmission line.
28. Battery Energy Storage System: It is installed in a designated part of the power system and serves many purposes. For example, it transfers energy to the system to prevent sudden changes in frequency during large outages in the power system.

1.3 Significance of the Study

This study is significant as it addresses the challenges of integrating renewable energy into the Azerbaijani power grid, contributing to both theoretical and practical advances in the field of power system stability. Using hybrid methods that combine traditional and modern frequency regulation techniques, this study proposes a variety of solutions to enhance grid resilience and reliability.

The main result of the research of this master thesis was to observe how the frequency changes in the perspective project of 2025 by performing openings at Sumgait and Shimal Power Plants, two important power plants of the Azerbaijani energy system, and to determine the activation of the Special Protection System and the opening of the Derbent Power Transmission Line. All these observations have been carried out by using Dig SILENT Power Factory simulation program. With these simulations, a short circuit was created in the output switch of the 2nd Block of the Shimal Power Plant and how it affected the system. The 1st block of the Shimal Power Plant, the Sumgait Power Plant and the Derbent power lines were determined as simulation points. In the second case, the shutdown of the 2nd block of the Sumgait Power Plant and the Steam Turbine Generators due to a problem in the technological process was taken, and simulations were conducted at the 1st Block of the Sumgait Power Plant and the Derbent power Transmission Line. In addition, simulations were conducted to determine how the rotor angle changes in the 1st block of the Azerbaijan Power Plant for both cases. In both incidents, the SPS was observed to operate and as a result, the Derbent Power Transmission Line was opened. In addition, the AGC and PSS systems were observed to operate and compensate for the lost load at other Power Plants.

The findings are expected to benefit investors, grid operators, and researchers. For investors, the study provides insights into the need for regulatory frameworks that support advanced and new technologies. For grid operators, it outlines strategies to mitigate the impacts of renewable energy variability. For researchers, it adds to the body of knowledge on frequency regulation and renewable energy integration, offering a basis for further research.

1.4 Limitations of the Study

When conducting simulations, there are several factors that cannot be included as input parameters in the simulation. These include the need for more extensive research, the lack of available resources, and the limitations of the simulation software. The most important of these limitations are listed below.:

1. **Scope of Simulation**: Simulations are limited to very specific scenarios and assumptions, such as average load profiles and weather conditions, which do not fully reflect real-world climate changes.
2. **Technological Focus**: The study primarily examines the basic and modern technologies currently available for frequency regulation, excluding emerging but undeveloped methods.
3. **Regional Focus**: The research focuses on Azerbaijan's energy grid, and the findings may not be directly applicable to systems with significantly different operational characteristics.
4. **Economic Analysis**: While examining technical feasibility, the study does not report on the effectiveness or financial implications of implementing advanced frequency regulation technologies.

CHAPTER TWO

REVIEW OF THE LITERATURE

The main three methods of traditional frequency regulation are primary regulation, secondary frequency regulation and third frequency regulation control systems. Especially after the integration of increasing renewable energy sources into the energy system, it is very important to investigate these methods.

The main purpose of the primary frequency control system is to adjust the frequency during sudden frequency changes by automatically adjusting the generators' main power inputs. For example, in thermal power plants, the mechanical power acting on the turbine is influenced to keep the frequency speed within a given limit. It is increased or decreased [6].

Secondary frequency regulator or by another name it can be called automatic frequency regulator, which returns the frequency to the nominal parameter of the system by connecting the outputs of several generators working in parallel. An example is AGC systems used in interconnected power grids designed to balance production and consumption [2].

The third method of frequency regulation is a method that mainly involves the long-term and efficient use of resources. This method is performed by humans with manual intervention by dispatch services. As an example, we can show the maximum use of the possible reserves of renewable energy sources depending on the time of day and weather conditions and reduce the cost of energy [2].

2.1 Primary Frequency control

Primary frequency control, also known as primary regulation or deviation control, is the first line of defense against frequency variations. The system is an automatic, decentralized intervention system powered by generators to withstand changes in frequency. These interventions are primarily achieved through control systems that adjust the mechanical power input to generators based on real-time frequency measurements [6].

Governor system: Governors are mechanical devices that regulate the speed of the rotor of the generators and, consequently, regulate and stabilize the output frequency of the generator. When a frequency fluctuation happens, sensors or relays automatically detect these changes and adjust the fuel supply to the turbine, thereby interfering with the generator power to stabilize the frequency. The effectiveness of control systems in primary frequency control is very crucial to keep the frequency under control immediately after a sudden change in the Power system [6]. The governor frequency control's one-line schematic diagram is shown in Figure 2.1 [16].

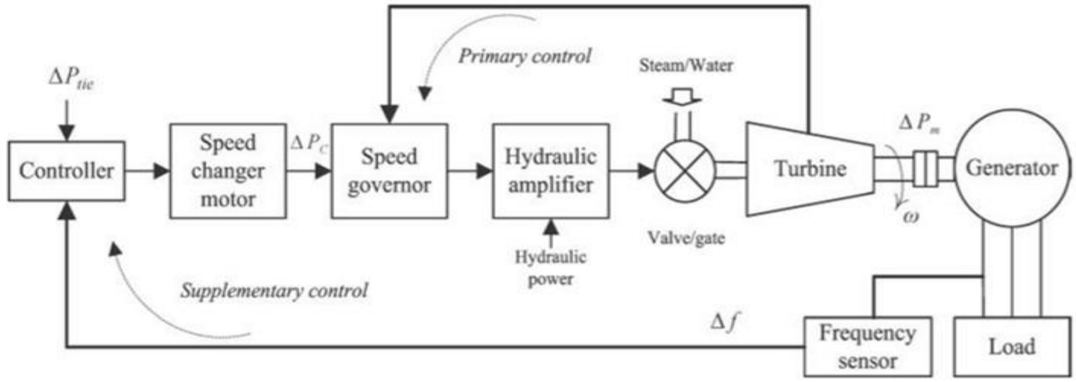


Figure 2.1**:** Governor-frequency control system's diagram.

Inertia Response: In conventional generators, the natural inertia of rotating masses initially prevents frequency deviations. This inertial response not only slows down potential frequency changes but also provides time for other control mechanisms to take effect and perform their functions. In systems with a high penetration of renewable energy sources, the synthetic inertia method provided by modern power electronics has become more important today [6]. Synthetic inertia refers to a system that can substitute the effect of conventional mechanical inertia and allows grid stabilization during periods of high renewable energy production [4]. For instance, the unplanned outage of a large generator can create a significant gap in the power system. Synthetic inertia can manage the changes associated with frequency fluctuations that may occur in such situations [4].

2.1.2 Secondary Frequency Control

Secondary frequency control, also known as automatic generation control (AGC), is crucial to return the system frequency to its nominal value after the primary frequency regulation. Maintaining the frequency balance of the system is not possible without this system. By installing this control mechanism in different parts of the system, the balance between production and consumption in systems where multiple generators work as a single entity is controlled. These systems function as relays [2].

Automatic Generation Control (AGC): The main purpose of AGC systems is to adjust the frequency output of the selected generators. This is accomplished by continuously monitoring the system frequency and analysis of real-time control signals from setpoint adjustments and relays located at various locations. AGC is very important for controlling long-term frequency changes to ensure that changes do not persist. An AGC system typically operates in two modes: cross-tilt control and flat frequency control [15]. In cross-tilt control, the AGC adjusts the output to maintain the scheduled exchange power flow between control areas. In flat frequency control, AGC manages the power produced in the system to prevent the system frequency from deviating from its nominal value [4]. Figure 2.2 shows us a schematic diagram of automatic generation control system. [17]

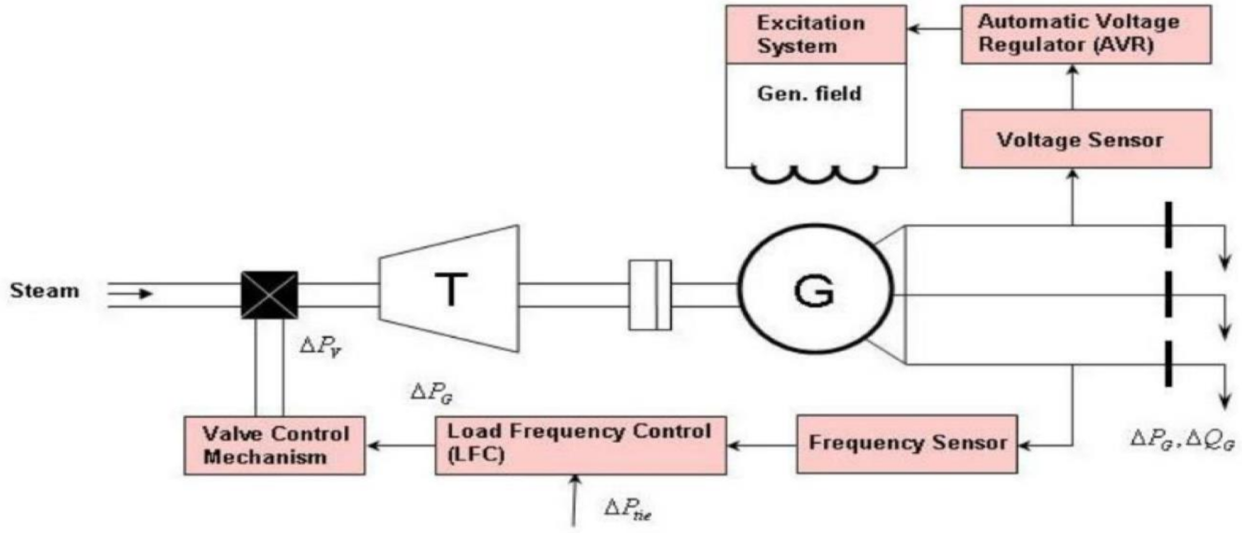


Figure 2.2 Automatic Generation Control

Load Frequency Control (LFC) LFC, is a crucial part of AGC, which balances load and generation in the controlled zone. This system continuously measures the load demand and adjusts the output of grouped generators to eliminate any load imbalance that may occur. Efficient LFC maintains the overall stability of the power system by preventing sudden frequency fluctuations. LFC systems use 2 basic controllers to minimize frequency error and maintain power balance. These are proportional-integral (PI) or proportional-integral derivative (PID) controllers [4] [13].

Secondary control helps maintain the integrity and reliability of the power grid by ensuring immediate restoration to its rated value [2].

2.1.3 Tertiary Frequency Control

The third frequency control system pertains to the long-term frequency control mechanism. This approach is often viewed more as economic frequency regulation rather than technical. Its working principle emphasizes the efficient use of reserves by effective management. Unlike the others, this method is planned by the dispatcher service instead of automatically [4].

Economic dispatcher: This strategy is used for controlling the frequency stability of the system and for the useful management of energy resources in the determined modes. It is a strategy that integrates the operating costs of energy resources, their location, useful work coefficients and other parameters. In addition, it considers environmental impacts caused by energy sources, making the strategy significant. The primary objective is to minimize the total cost of energy while operating the system under given conditions [4] [12].

Reserve Management: Spinning and non-spinning stock management is crucial for maintaining system stability. Rotating resources are online generators that can ramp up production quickly, while non-rotating resources are offline resources available for use as needed. Effective reserve management is useful for preventing unexpected events and accidents caused by regime disruptions.

This strategy is appropriate for organizing the joint efforts of quick-acting and late-acting energy sources during emergencies. The coordination of these resources helps to maintain frequency stability during major disturbances, ensuring it stays within the nominal 50 or 60 Hz limit [4].

The tertiary control mechanism ensures the power system remains active and adapts to power balance changes promptly. Maintaining a balance that supports both operational stability and economic efficiency [4].

2.2. Principles of Frequency Regulation in Renewable Energy Systems

2.2.1 Impact of Renewable Energy Integration

The integration of renewable energy sources into the system and the change depending on the conditions create great problems in the regulation of the frequency in the energy system. Wind and solar power generation is dependent on weather conditions and time of day, and if not managed effectively, it often leads to frequent fluctuations in energy demand [3].

Variability and Intermittency: Renewable energy sources cannot be easily adjusted according to the demand of energy users and need additional frequency regulation mechanisms and systems to keep the frequency at the required standard value. Another disadvantage is that it minimizes the possibilities of variability because it is difficult to predict energy [1] [8].

Grid Inertia: The rapid integration of renewable energy sources into the power sector reduces the inertia of the electric grid and makes the system more sensitive to possible frequency fluctuations. An example of synthetic inertia created with the help of power electronics can be given as a solution to such problems in modern energy [2]. As mentioned, as the integration of renewable energy sources into energy systems increases, it creates problems in these regulations, which makes it important to find new modern solutions [3].

2.2.2 Synthetic Inertia

Power electronics are used to reproduce the inertial reactions of conventional generators in the system. This system is designed for grid stabilization in systems where renewable energy sources are used more often [4].

Power Electronics in Synthetic Inertia: Advanced and modern power electronics systems react instantly to frequency changes and adjust the output by mimicking the inertial capabilities of the rotating part. This method helps to stabilize frequency deviations [4].

Case Studies: The use of synthetic inertia in systems where renewable energy sources are used more often demonstrates its effectiveness in frequency regulation and highlights its benefits [3]. The main function of the synthetic inertia system is to immediately respond to frequency deviations, prevent large frequency errors and maintain the stability of the power grid. Such systems are usually important in systems where there are inertial sources and where renewable energy sources have more penetration [4].

2.2.3 Fast Frequency Response (FFR)

Fast frequency response (FFR) technologies, such as battery energy storage systems (BESS) and flywheel energy storage system (FESS) provide rapid frequency support by injecting or absorbing power within milliseconds of a frequency deviation [1] [9].

Battery Energy Storage Systems (BESS): The main advantage of BESS is that it provides short-term support by charging and discharging energy and is an effective way to fill the gap and prevent frequency deviations until slower-acting resources take over [1].

Flywheel injected Storage Systems (FESS): FESS store energy as rotational kinetic energy and rapidly injects power into the grid. They are effective for short-term frequency regulation, improving stability in high renewable penetration grids [1].

The role of FFR technology in keeping the frequency stable in energy systems where renewable energy sources are used is a replacement. These technologies can immediately react to changes in the frequency of energy obtained from renewable energy sources [1]. Figure 2.3 explains characteristics of dynamic and static fast frequency response (FFR) services in Great Britain (GB) [31]

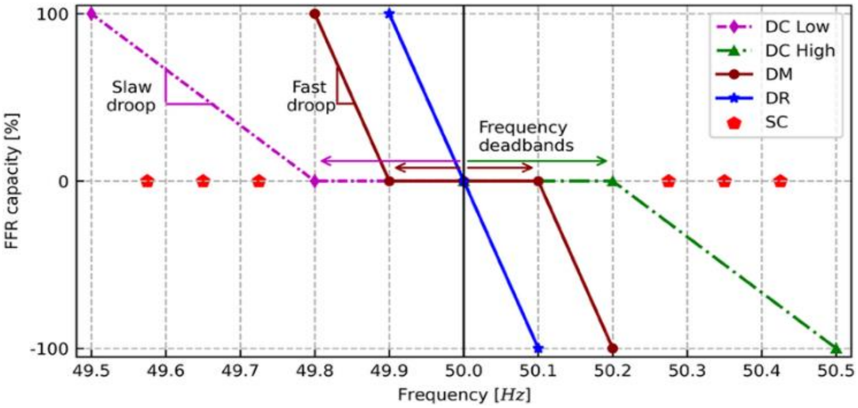


Figure 2.3: Working principles of dynamic and static fast frequency response (FFR) services in Great Britain (GB)

2.3. Advanced Techniques for Frequency Control

2.3.1 Artificial Neural Networks (ANN)

Artificial Neural Networks (ANN), one of the advanced systems, make predictions in complex energy systems, model and collect old data to extract and optimize new control strategies [2] ANN

Architecture: ANNs are composed of interconnected neurons used to receive input data, process information from historical sources, and obtain output data [2].
Applications in Frequency Control: Mary et al demonstrate successful applications of ANNs in frequency regulation by predicting load changes and adjusting generator output parameters, allowing for improved response and accuracy. ANNs show considerable potential in enhancing frequency regulation effectiveness by offering accurate predictions and optimized control actions based on real-time data [2]. For instance, ANNs can learn new methods in the energy cycle, specifically in energy production and consumption. This allows for better control of cost and frequency. An ANN was utilized in one application to forecast a microgrid's short-term demand fluctuations. The artificial neural network (ANN) could reduce frequency variations brought on by abrupt changes in load by evaluating past load data and current circumstances and adjusting generator outputs in real-time to fit demand [2] [10].

2.3.2 Particle Swarm Optimization (PSO)

Particle swarm optimization (PSO) is a computer technique that simulates the social behavior of particles to optimize the functioning of frequency control devices. It is useful for fine-tuning controller parameters in microgrid systems [2].
PSO Algorithm: PSO is a set of algorithms that involve a population of particles and are used to find control parameters. Here, each particle adjusts its position by taking samples from its neighbors and its own experience and suggests the best solution [2] [10].
Case Studies: PSO applications in microgrid frequency control demonstrate the efficiency of the technology by improving performance through parameter optimization and stabilization time reduction [2]. The adaptability and flexibility of PSO in complex energy systems have led to its use as the main tool in control optimization. PSO can adjust various controllers and their parameters, such as PID controllers, to maintain and monitor frequency stability effectively [11]. For instance, In Mary et al, PSO was utilized involving a microgrid with a high penetration rate of renewable energy sources to optimize the frequency control system parameters. The outcomes demonstrated that PSO greatly enhanced the system's capacity to sustain steady frequency despite fluctuations in renewable energy sources [2].

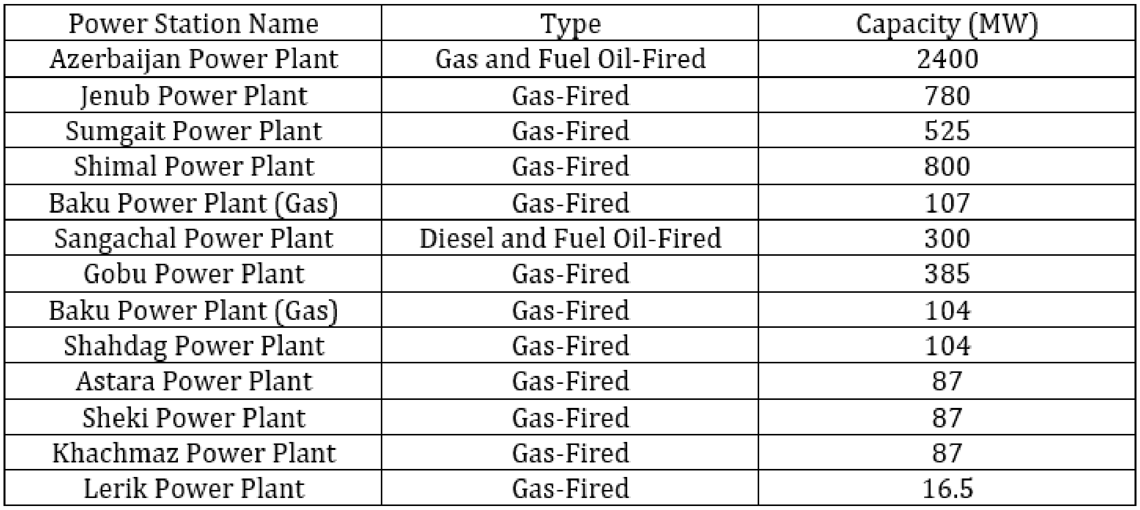
2.3.3 Adaptive Neuro-Fuzzy Inference System (ANFIS)

ANFIS combines neural network learning capabilities with fuzzy logic that enables high frequency tuning. It is designed to manage anomalies and non-linearities in power systems [2].
ANFIS Architecture: Combined with fuzzy logic neural networks, ANFIS learns from data to make decisions about abnormal modes that may occur based on fuzzy rules. This is particularly useful in complex systems [2].
Applications in Frequency Control: In Mary at all, numerous examples and studies demonstrate the effectiveness of ANFIS in microgrids to control the operation of energy resources. It can automatically adapt system frequency and load in response to production changes. ANFIS combines the strengths and advantages of neural networks and fuzzy logic to manage the complexities of today's modern power systems, offering a highly effective frequency regulation solution. The fuzzy logic component enables ANFIS to handle uncertainties and imprecise data, while the neural network component enables learning from historical data and real-time conditions. In a practical application, ANFIS has been used to monitor the output of distributed energy resources (DER) in a microgrid. By learning from past data and adapting to current conditions, ANFIS maintained a stable frequency despite fluctuations in load and production [2].

2.4 Overview of the Azerbaijan Power system.

The power system of Azerbaijan, like that of many other countries, consists of various components and infrastructure that work together to generate, transmit, distribute, and supply electricity to consumers. Here is some information about the electricity system of Azerbaijan. Azerbaijan generates electricity from a variety of sources, including natural gas, oil, hydroelectricity, and a small amount of renewable energy sources. There are one gas and fuel oil-fired power plant in the country (2400 MW Azerbaijan power plant), four gas-fired power plants (780 MW Jenub power plant, 525 MW Sumgait power plant, 800 MW Shimal power plant, 107 MW Baku power plant), one diesel and fuel oil-fired power plant (300 MW Sangachal Power Plant), and gas-fired (385 MW Gobu Power Plant, 104 MW Baku Power Plant, 104 MW Shahdag Power Plant, 87 MW Astara Power Plant, 87 MW Sheki Power Plant, 87 MW Khachmaz Power Plant, 16.5 MW Lerik Power Plant) that are tabled below

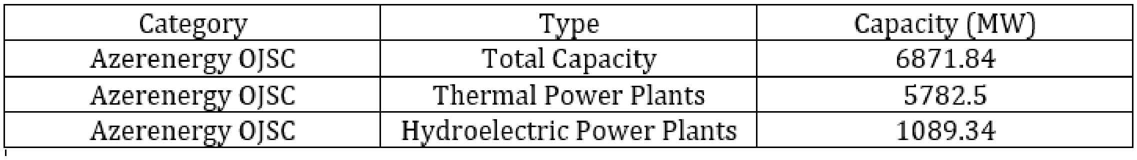
Table 2.1: Main Power Plants of Azerbaijan.



Power Station Name	Type	Capacity (MW)
Azerbaijan Power Plant	Gas and Fuel Oil-Fired	2400
Jenub Power Plant	Gas-Fired	780
Sumgait Power Plant	Gas-Fired	525
Shimal Power Plant	Gas-Fired	800
Baku Power Plant (Gas)	Gas-Fired	107
Sangachal Power Plant	Diesel and Fuel Oil-Fired	300
Gobu Power Plant	Gas-Fired	385
Baku Power Plant (Gas)	Gas-Fired	104
Shahdag Power Plant	Gas-Fired	104
Astara Power Plant	Gas-Fired	87
Sheki Power Plant	Gas-Fired	87
Khachmaz Power Plant	Gas-Fired	87
Lerik Power Plant	Gas-Fired	16.5

The total installed capacity of the Azerbaijani energy system currently stands at 7226.24 MW, comprising 5933.5 MW from thermal power plants, 1157.74 MW from hydroelectric power plants, and 136.7 MW from renewable energy sources. Of this capacity, generation facilities under the jurisdiction of Azerenergy OJSC account for 6871.84 MW, with thermal power plants contributing 5782.5 MW and hydroelectric power plants 1089.34 MW.

Table 2.2: The total installed capacity of the Azerbaijani energy system



Category	Type	Capacity (MW)
Azerenergy OJSC	Total Capacity	6871.84
Azerenergy OJSC	Thermal Power Plants	5782.5
Azerenergy OJSC	Hydroelectric Power Plants	1089.34

The transmission network of the Azerbaijani power system is responsible for transporting high-voltage electricity over long distances from power plants to substations. The unified transmission system is managed by the state energy company “Azerenergy” OJSC, which is responsible for the generation and transmission of electricity. The standard voltage levels of the Azerbaijani power transmission lines are 110 kV, 220 kV, 330 kV, 500 kV. In addition, the Azerbaijani power system is interconnected with the power systems of neighboring countries, Russia and Georgia. Frequency control in the Azerbaijani power system is carried out through a balancing bus with the Russian power system. The connection with the Georgian power system is mainly for export and plays a greater role as a load for the Azerbaijani power system.

In terms of renewable energy, in recent years Azerbaijan has shown increasing interest in the development of the renewable energy sector, especially solar and wind energy. The country's favorable geographical location allows for the potential exploitation of solar energy resources. Wind energy projects have been launched to expand the energy system and save fuel. At present, 38 MW of solar generation (24 MW Nakhichevan Solar Power Plant, 2.8 MW Sahil SPS, 2.8 MW Surakhani SPS, 2.8 MW Samukh SPS, 2.8 MW Sumgait GES, 2.8 MW Pirallahi SPS), 55.3 MW of wind generation (50 MW Yeni Yashma Vind Power Plant, 3.6 MW Yashma Baglari VPS, 1.7 MW Shurabad VPS), 6.4 MW Gobustan Hybrid ES and a solid waste incineration plant (37 MW Biomass) have been installed.

Table 2.3: Existing Renewable Energy Sources Plants in Azerbaijan

Energy Type	Project Name	Capacity (MW)
Solar	Nakhichevan Solar Power Plant	24
Solar	Sahil SPS	2.8
Solar	Surakhani SPS	2.8
Solar	Samukh SPS	2.8
Solar	Sumgait GES	2.8
Solar	Pirallahi SPS	2.8
Wind	Yeni Yashma Wind Power Plant	50
Wind	Yashma Baglari VPS	3.6
Wind	Shurabad VPS	1.7
Hybrid	Gobustan Hybrid ES	6.4
Biomass	Solid Waste Incineration Plant	37

2.4.1 Frequency control models in Azerbaijan

During the field visits, control data is collected using the existing logic diagrams of the operator screens or the manufacturer’s documentation. In general, detailed information about the AVR/PSS is available in almost all power plants, but information for the internal structure of the actuator is limited. In addition, logic diagrams and existing parameters, including some key parameters such as frequency deadband or speed reduction, cannot be observed or changed by the operator.

All available data are collected and for the remaining data similar manufacturer and unit of measurement information is used from experience of Power Plants. Example figures illustrating AVR and actuation structures are given in Figure 2.4 and Figure 2.5 respectively. Where necessary, the current parameter performances of AVR and PSS are tested through simulations.

Examples of 2 gas units of the Jenub Power Stations and the Shimal Power Stations are given in Figure 2.6 and Figure 2.7. As can be seen from the simulation results, AVRs respond to fast ramping rates, but

PSS performance is not satisfactory. Therefore, it is recommended to conduct a tuning study for all generators, considering potential inter-site oscillation modes for parameter determination, and to activate PSSs as much as possible. Since there is no determination of the exact solution data Time synchronization, it is currently not possible to determine whether inter-site oscillations occur in the system.

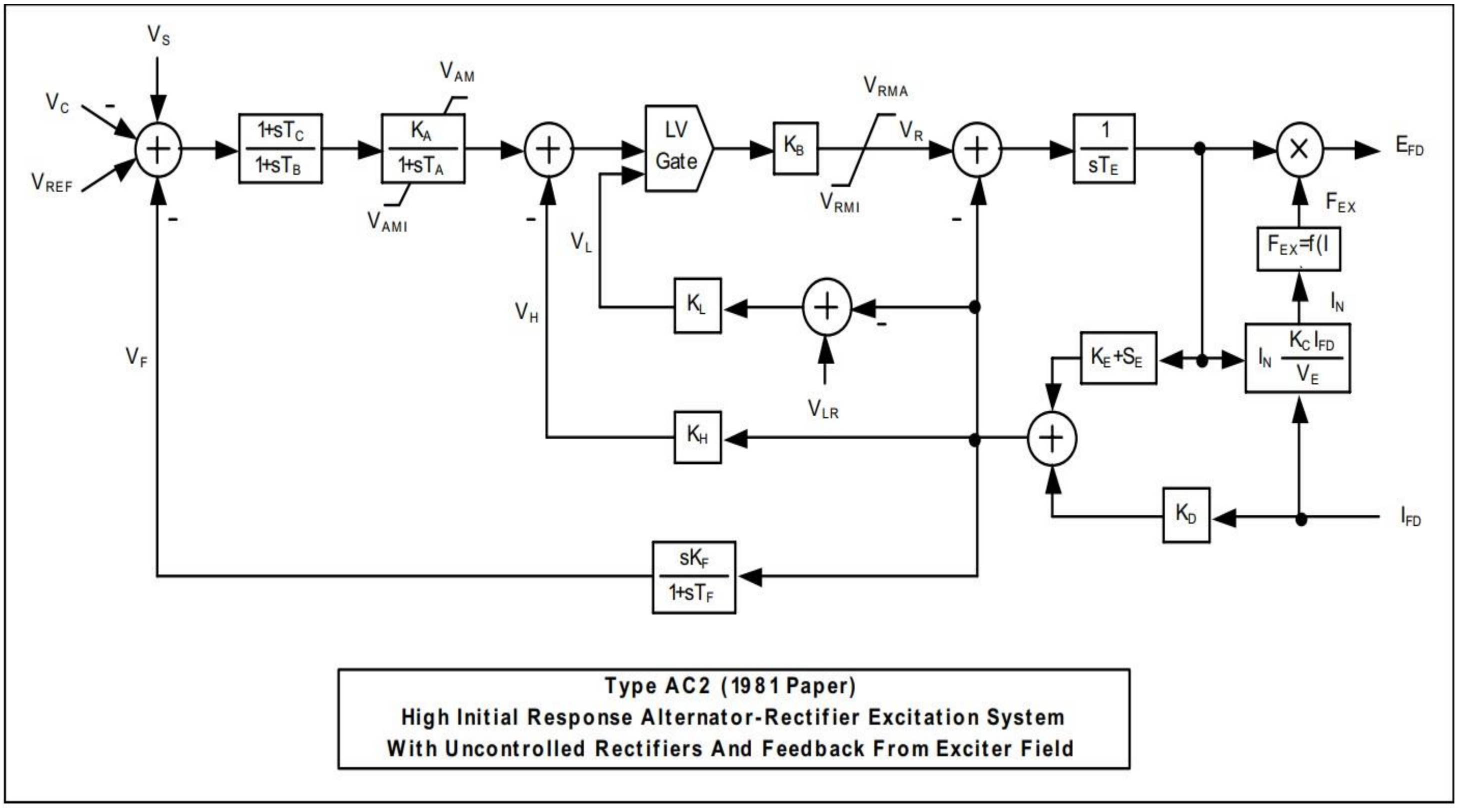


Figure 2.4: Sample manufacturer model information for AVR and PSS of Jenub Power Plant.

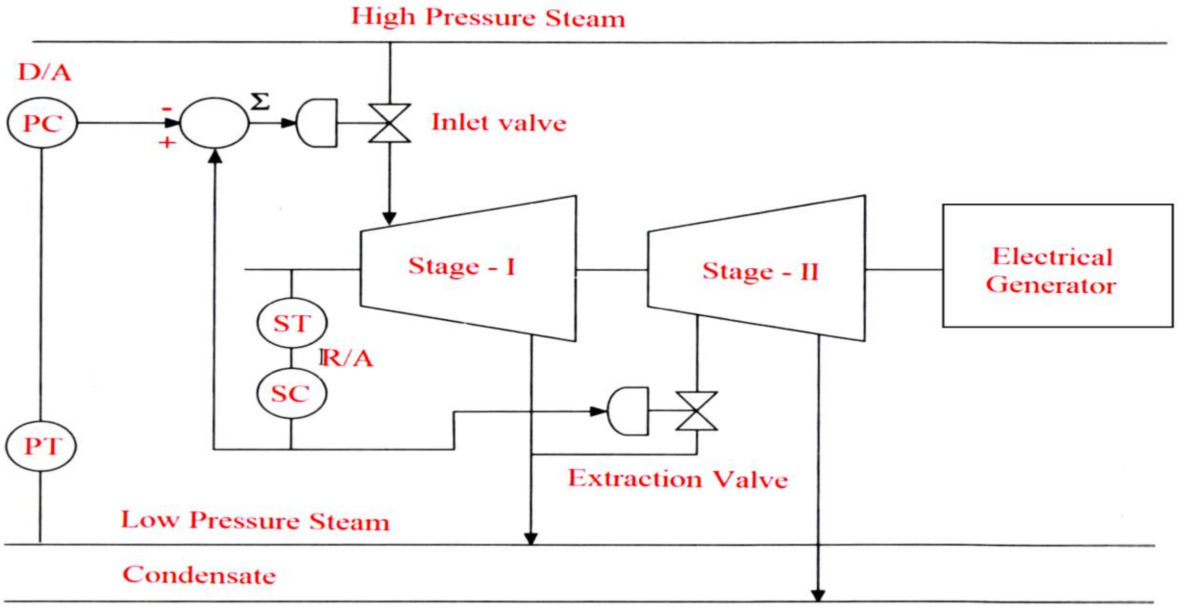


Figure 2.5: Example manufacturer information for a basic AVR model for Sumgait Power Plant

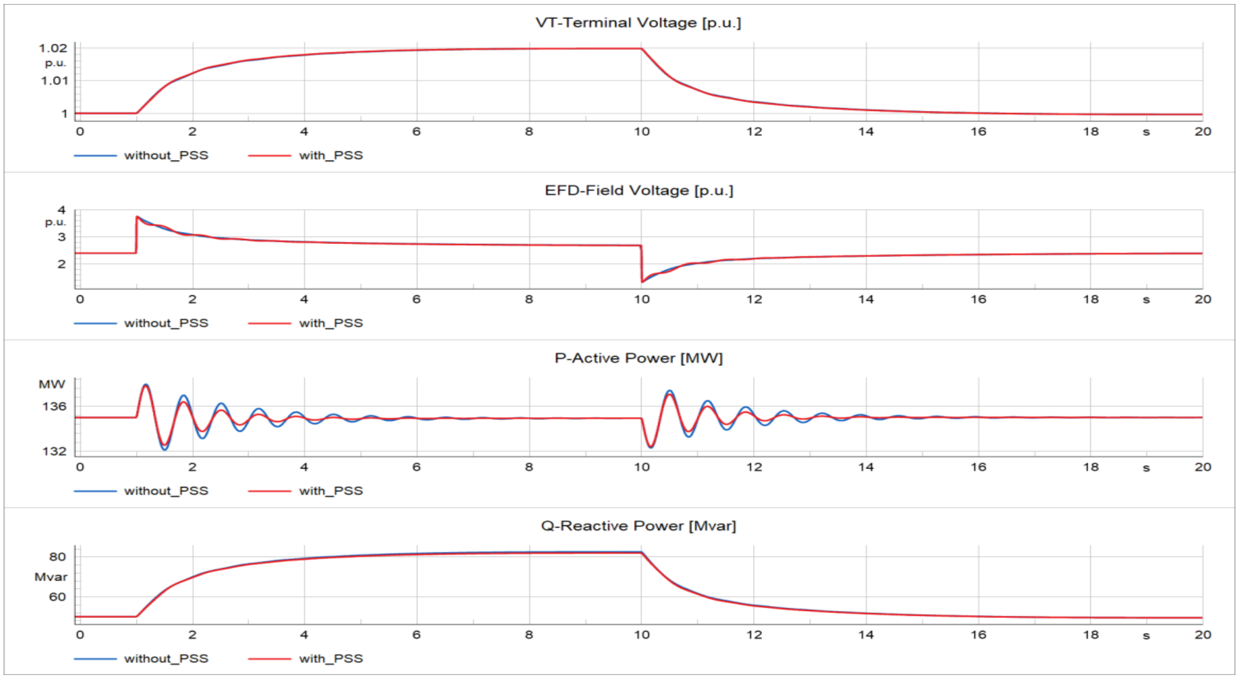


Figure 2.6: AVR and PSS performance of the Jenub Gas Power Plant.

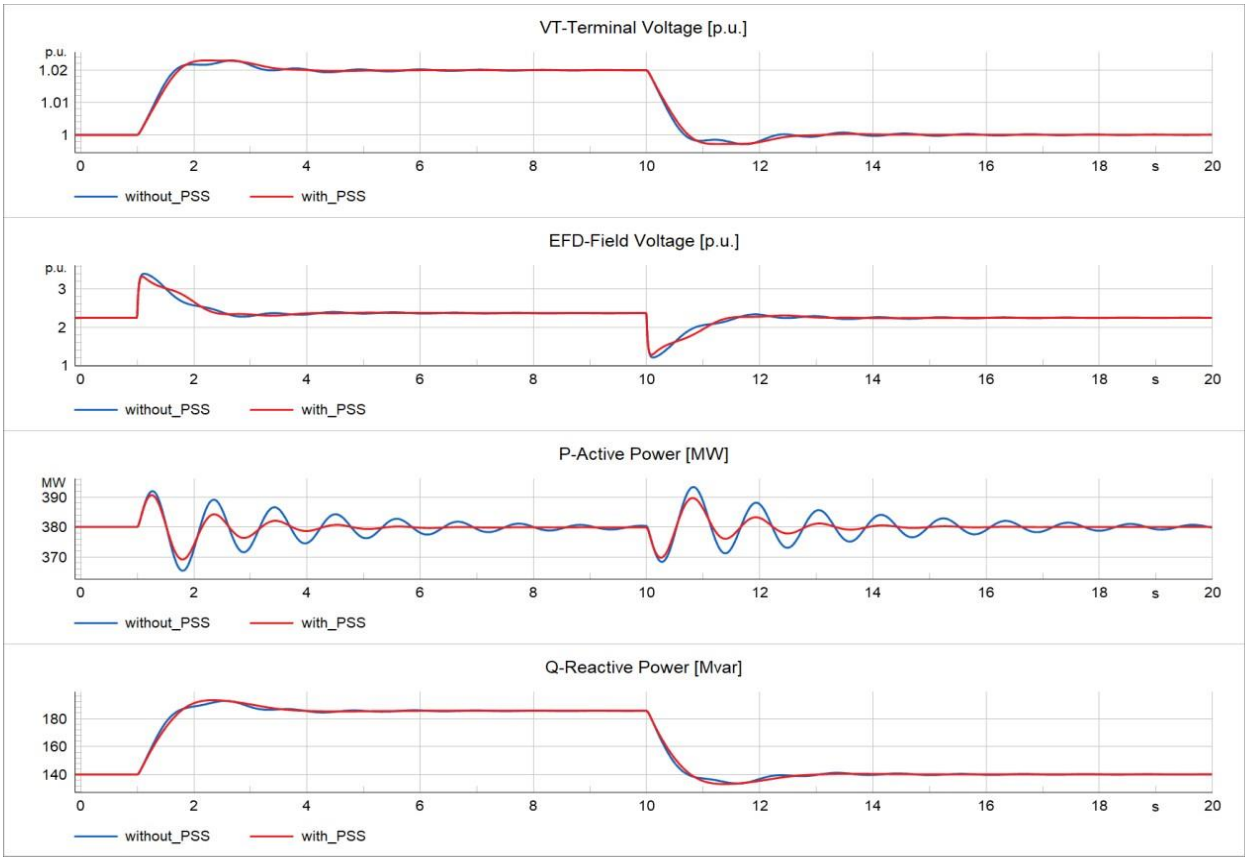


Figure 2.7: AVR and PSS performance of Simal Gas Power Plant, Unit-2.

2.4.2 Load shedding models in frequency drops.

Underfrequency load shedding (UFLS) is a standard application in power systems to prevent a complete blackout in the event of a significant active power imbalance or a lack of rotational reserve for any reason. A similar situation can also be handled by relays. Since these relays are located at the medium voltage level, the relays are not modeled in detail, but the UFLS relay All levels of underfrequency load shedding, automatic reconnection, and time-based waiting values are modeled by the load controller.

The UFLS parameters used in the Azerenergy system are given in Table 2.4, and the model structure is given in Figure 2.8.

Table 2.4: UFLS system parameters used in Azerbaijan Power System

Steps	**First**		**Second**		**Reconnect**		**Load [MVt]**
	F [Hz]	**T [sec]**	**F [Hz]**	**T [sec]**	**F [Hz]**	**T [sec]**	
-	49.5	0.2	-	-	49.8	25	51.30
	49.2	0.2	-	-	49.8	30	116.70
1	48.8	0.2	49	5	49.8	50	53.07
	48.8	0.2	49	10	49.8	55	53.07
	48.8	0.2	49	15	49.8	60	53.07

2	48.6	0.2	49	15	49.75	65	54.63
	48.6	0.2	49	20	49.7	70	54.63
	48.6	0.2	48.9	20	49.7	50	54.63
3	48.4	0.2	48.9	25	49.6	45	80.00
	48.4	0.2	48.9	30	49.7	65	80.00
4	48.2	0.2	48.9	30	49.6	55	51.90
	48.2	0.2	48.9	30	49.7	50	51.90
	48.2	0.2	48.9	35	49.7	65	51.90
5	48	0.2	48.9	35	49.75	35	51.00
	48	0.2	48.8	35	49.6	30	51.00
	48	0.2	48.8	35	49.7	50	51.00
6	47.8	0.2	48.8	35	49.75	60	82.65
	47.8	0.2	48.8	40	49.7	75	82.65
7	47.6	0.2	48.8	40	49.65	35	71.50
	47.6	0.2	48.8	45	49.65	45	71.50
8	47.4	0.2	48.8	45	49.65	35	76.05
	47.4	0.2	48.8	50	49.6	40	76.05
9	47.2	0.2	48.8	50	49.65	35	80.35
	47.2	0.2	48.7	50	49.65	30	80.35
10	47	0.2	48.7	50	49.65	10	84.20
	47	0.2	48.7	55	49.7	25	84.20
11	46.8	0.2	48.7	60	49.7	25	68.00
	46.8	0.2	48.7	60	49.55	30	68.00
12	46.6	0.2	48.7	65	49.5	20	75.50
	46.6	0.2	48.7	65	49.7	10	75.50

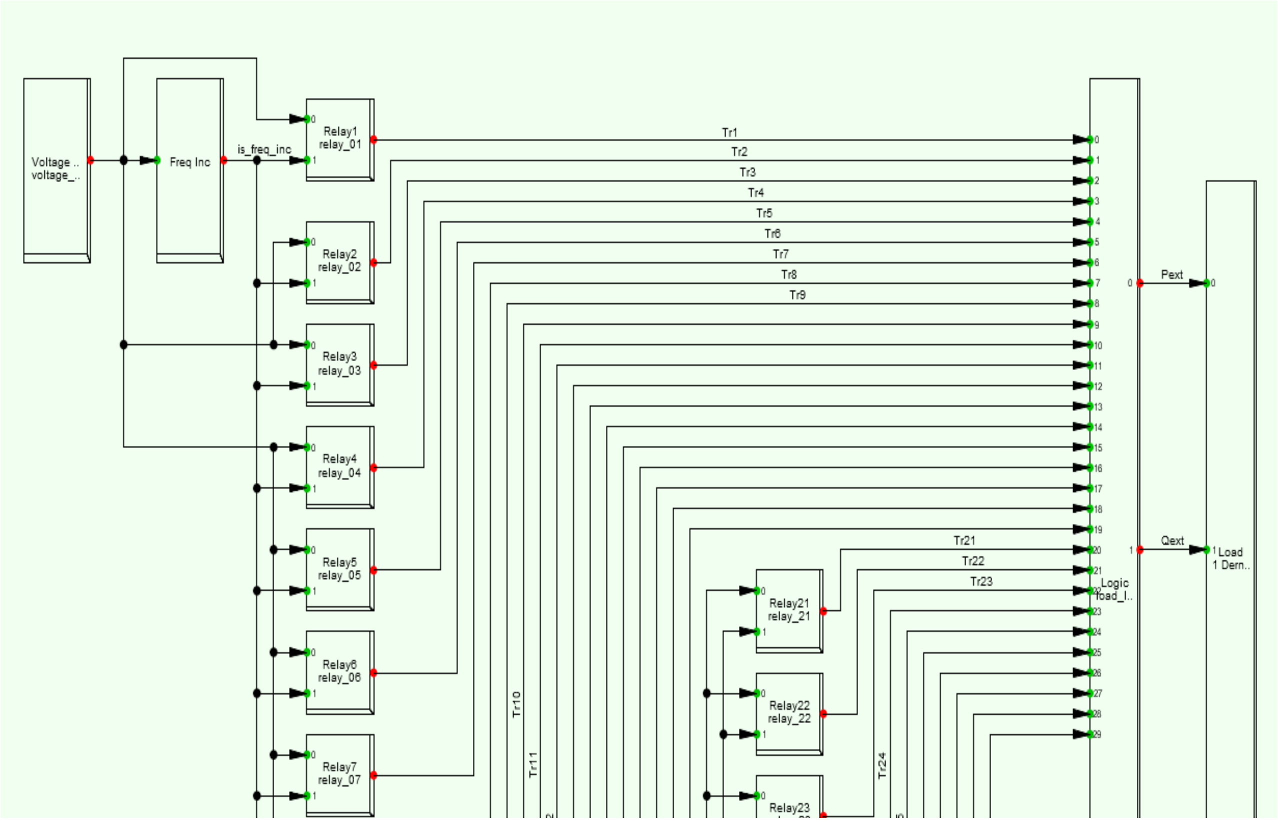


Figure 2.8: UFLS model structure

2.4.3 Special Protection Systems.

Special protection systems are presented in two groups: Opening of interstate lines and generators.

Details of special protection systems of interstate lines are given below:

Russia – Azerbaijan Electrical Power Line (330 kV Khachmaz – Derbent Overhead Line):

- Load flow direction from Russia to Azerbaijan:
  - Activation: 100 – 460 MW with a delay of 1 – 2 seconds
  - Result: Opening of the line
- Load flow direction from Azerbaijan to Russia:
  - Activation: 400 MW with a delay of 0.8 – 1.2 seconds

Result: Generator opening in the Azerbaijani energy system

Georgia-Azerbaijan EPL (500 kV Samukh Gardabani, 330 kV 1.2 Gardabani overhead line)

- Load flow direction from Georgia to Azerbaijan:
  - Activation: 300 – 800 MW with a delay of 0.6 seconds
  - Result: Opening of the line
- Load flow direction from Azerbaijan to Georgia:
  - Activation: 1.5 – 2 seconds 50 – 600 MW

- Conclusion: First the generator is turned on, then the lines in the Azerbaijani energy system

- Information on the loads turned on during the generator start (to minimize the active power imbalance) is given in Table 2.5.

Table 2.5: Information on the loads turned on during the generator start

Tripped Generator	Activ Power of Generator (MVt)	Time Delay (Sec)	Maximal Load	Avarage Load	Minimum Load
			Opened load (MVt)	Opened Load (MVt)	Opened Load (MVt)
Simal BQQ1	200	0.1	200	153	77
Simal BQQ1	250	0.1	271	207	104
Simal BQQ1	300	0.1	322	246	124
Simal BQQ1	350	0.1	348	266	134
Simal BQQ1	370	0.1	395	302	152
Simal BQQ2	200	0.1	121	93	46
Simal BQQ2	250	0.1	203	155	78
Simal BQQ2	300	0.1	245	187	94
Simal BQQ2	350	0.1	277	212	106
Simal BQQ2	380	0.1	303	232	116
Cenub QT1	-	0.1	132	101	51
Cenub QT2	-	0.1	100	76	38
Cenub QT3	-	0.1	196	150	75
Cenub QT4	-	0.1	92	70	35
Cenub BT1	-	0.1	232	177	89
Cenub BT2	-	0.1	288	220	111
Sumgaıt QT1	-	0.1	255	195	98
Sumqayıt QT2	-	0.1	217	166	83
Sumgait BT1	-	0.1	77	59	30
AZ IES TG1	-	0.1	175	134	67
AZ IES TG2	-	0.1	132	101	51
AZ IES TG3	-	0.1	108	83	41
AZ IES TG4	-	0.1	128	98	49
AZ IES TG5	-	0.1	123	94	47
AZ IES TG6	-	0.1	104	80	40
AZ IES TG7	-	0.1	80	61	31
AZ IES TG8	-	0.1	172	132	66

To simplify the modeling, the specific protection functions of the line connected to the operation are modeled in the dynamic simulation based on the parameters provided. In addition, the load opening after an individual generator opening is not modeled as a function, but the load opening i after a real generator opening event is manually determined. Thus, the model complexity is reduced without losing details in the simulations.

2.4.4 Investigating the consequences of a real opening at the Shimal Power Plant.

The dynamic behavior of the overall system is verified using real system event data from April 4, 2023. On this particular day, the system was operating in island mode disconnected from Russia and Georgia. Pre-event system conditions are collected as snapshots from the SCADA system to determine the number of generators in service from each power plant and generation levels, the total system load, and the flows on specific main lines. Similar conditions are created in the simulation model with the initial conditions determined through the SCADA snapshots, and the opening of a generator from the Shimal Power Plant is defined as a system event for the simulation. The simulation is performed for 100 seconds with all features including UFLS. The measured and simulated frequency results are given in Figure 2.9.

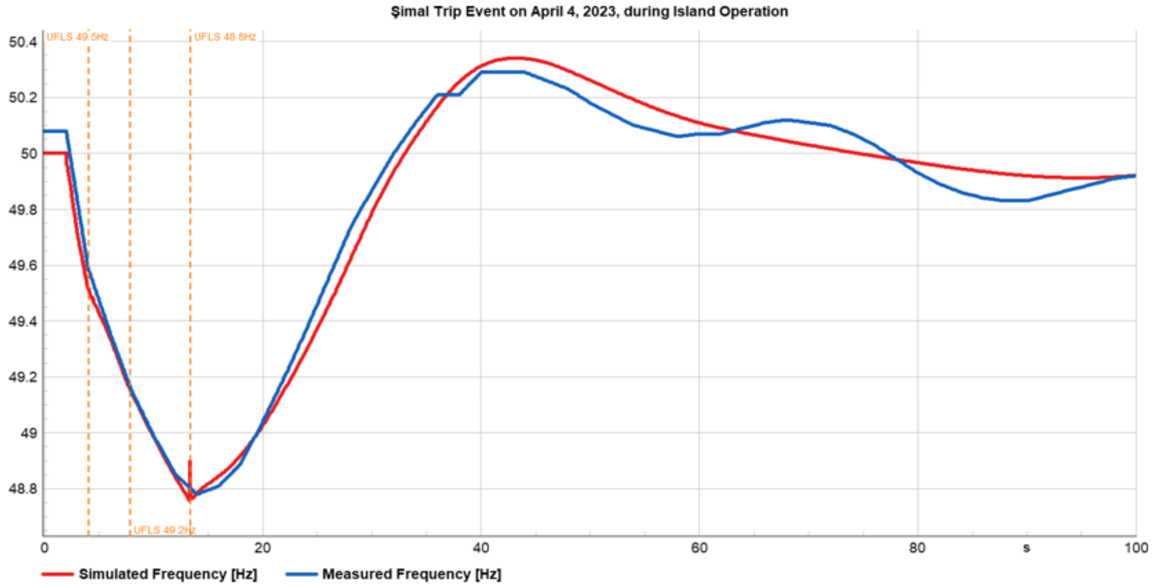


Figure 2.9: Shimal Power Plant trip on April 4, 2023, during island Operation and its frequency deviation analysis.

As can be seen in the figure, the system behavior is clearly represented, including the activation times of the UFLS relays. The only feature that is not clearly visible in the model is the water level fluctuation at the Mingachevir HPS, which is the cause of the slow oscillation behavior in the measured system frequency that can be observed after 40 seconds

CHAPTER THREE

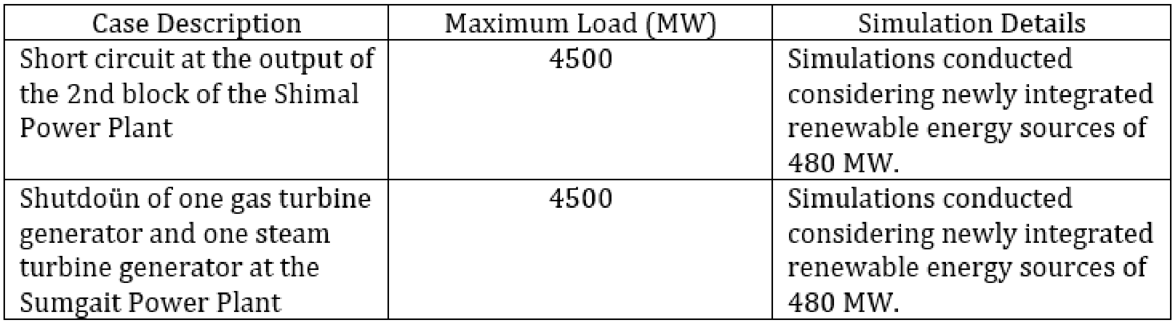
METHODOLOGY

3.1 Research Methods and Architecture.

As a result of our research conducted at many Power Plants, substations and the general central dispatch service of the Azerenergy , we have clarified which methods we will use to complete our research and which simulation tool we will use. As a guideline, as stated in the purpose of the research section, the integration of renewable energy sources into the system and the connection of new sources with an additional 480 MW capacity to the energy system in 2025 will lead to large fluctuations in the system due to the stable maintenance of the frequency of the energy system and the participation of large-power generators shutdown in the system.

As a research direction, the cases of short circuit at the output of the 2nd block of the Shimal Power Plant and the opening of one of the gas turbine generators and the steam turbine generator at the Sumgait Power Plant were examined, with the maximum load of the energy system being 4500 MW, and simulations were conducted using the DigSILENT Powerfactory program and real results were obtained. When simulating the listed accidents, the loads of newly integrated renewable energy sources of 480 MW were considered. At the same time, in cases of shutdown of the units as a result of an accident, their approximate loads were taken to be close to 400MW.

Table 3.1: Simulation cases and conditions



Case Description	Maximum Load (MW)	Simulation Details
Short circuit at the output of the 2nd block of the Shimal Power Plant	4500	Simulations conducted considering newly integrated renewable energy sources of 480 MW.
Shutdoün of one gas turbine generator and one steam turbine generator at the Sumgait Power Plant	4500	Simulations conducted considering newly integrated renewable energy sources of 480 MW.

The Shefeq ,Absheron and Perekushkul stations are considered as three renewable energy sources with a capacity of 480 MW, which are being used to research and simulated. The connection diagrams of these two renewable energy stations to the power system are shown in the figure 3.1,3.2 and 3.3.

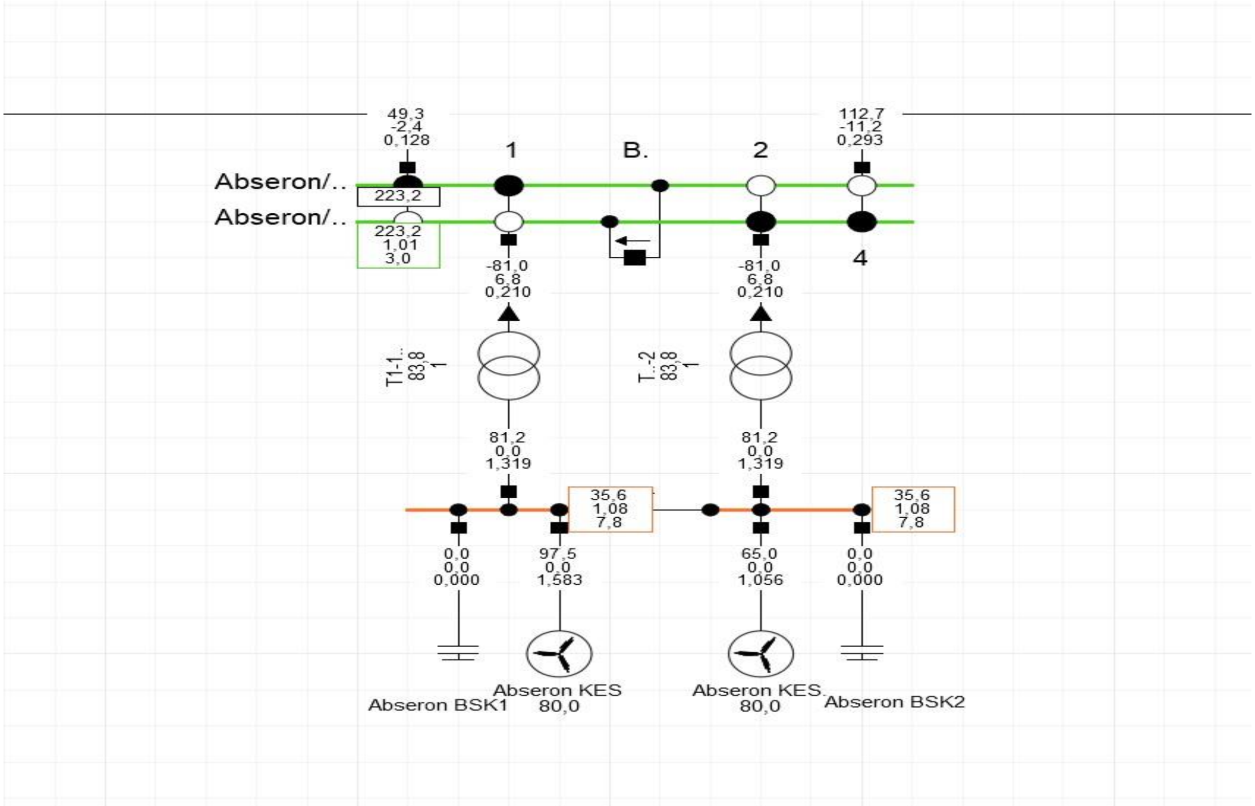


Figure 3.1: Connection diagram of the Absheron wind Power Plant to the energy system.

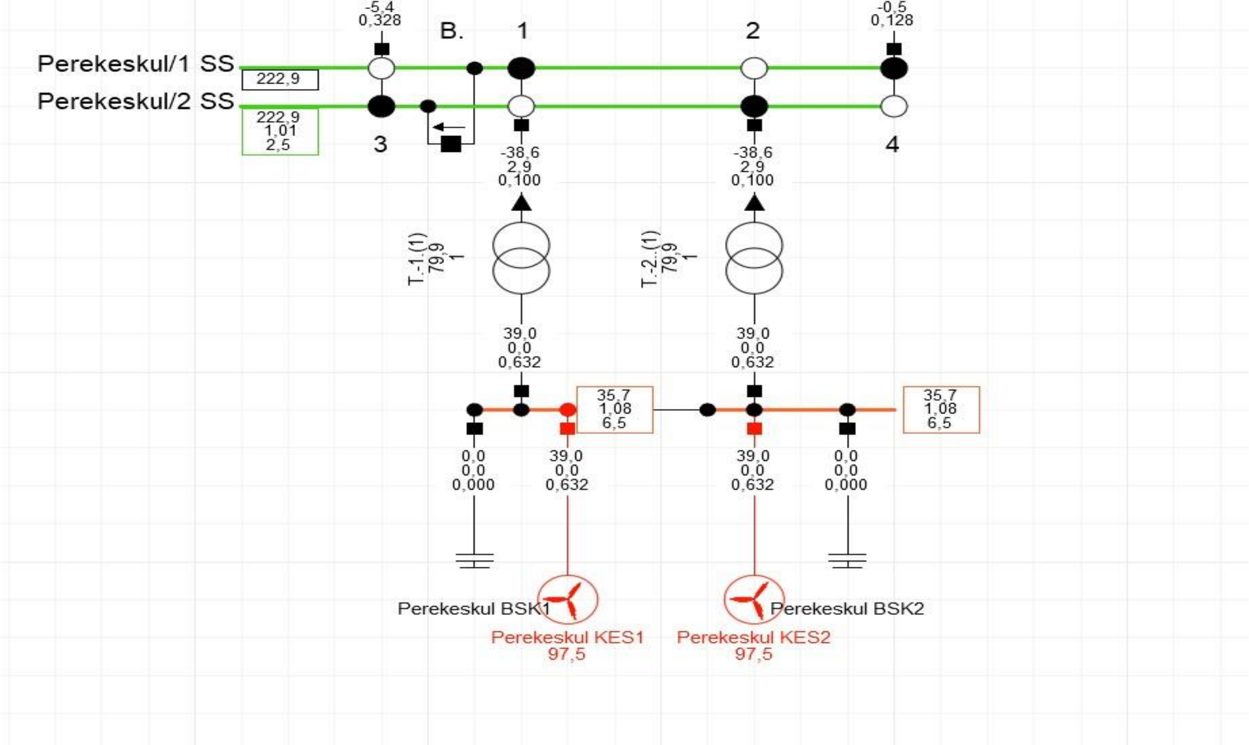


Figure 3.2: Connection diagram of the Perekeshkul wind Power Plant to the energy system.

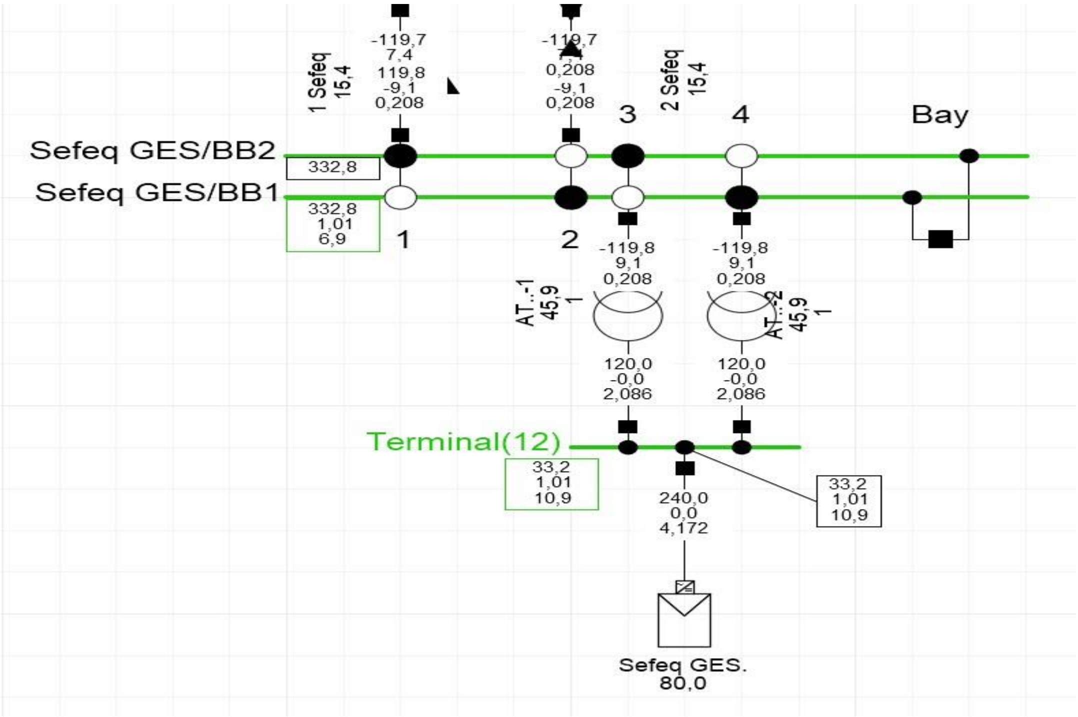


Figure 3.3: Connection diagram of the Shefeq solar Power Plant to the energy system

3.1.1 Short circuit in the output switch of the 2nd block at Shimal Power Plant.

The 2nd block generator of the Shimal Power Plant is one of the largest generators in Azerbaijan in terms of generation capacity. In the first case, we will look at the tripping of this generator block becouse of a short circuit in the output switch and how this shutdow affects the frequency in the energy system where renewable energy sources are included. It should be noted that during this incident , the Derbent Power Transmission Line between Russia and Azerbaijan will be disconnected as a result of the operation of the SPS, preventing the flow of up to 400 MW of load through the Derbend line. Otherwise, the technical parameters and physical parameters of the Derbent Power Transmission line will not allow the transport of this load and additional accidents will be inevitable. To investigate the effects of this accident, the frequency changes caused by it at the first block of the Shimal Power Plant, the Derbent Power Transmission Line, and the Azerbaijan Power Plant will be determined through simulation by the DigSILENT Powerfactory program. Figure 3.4 shows the connection diagram of the general Shimal Power Plant.

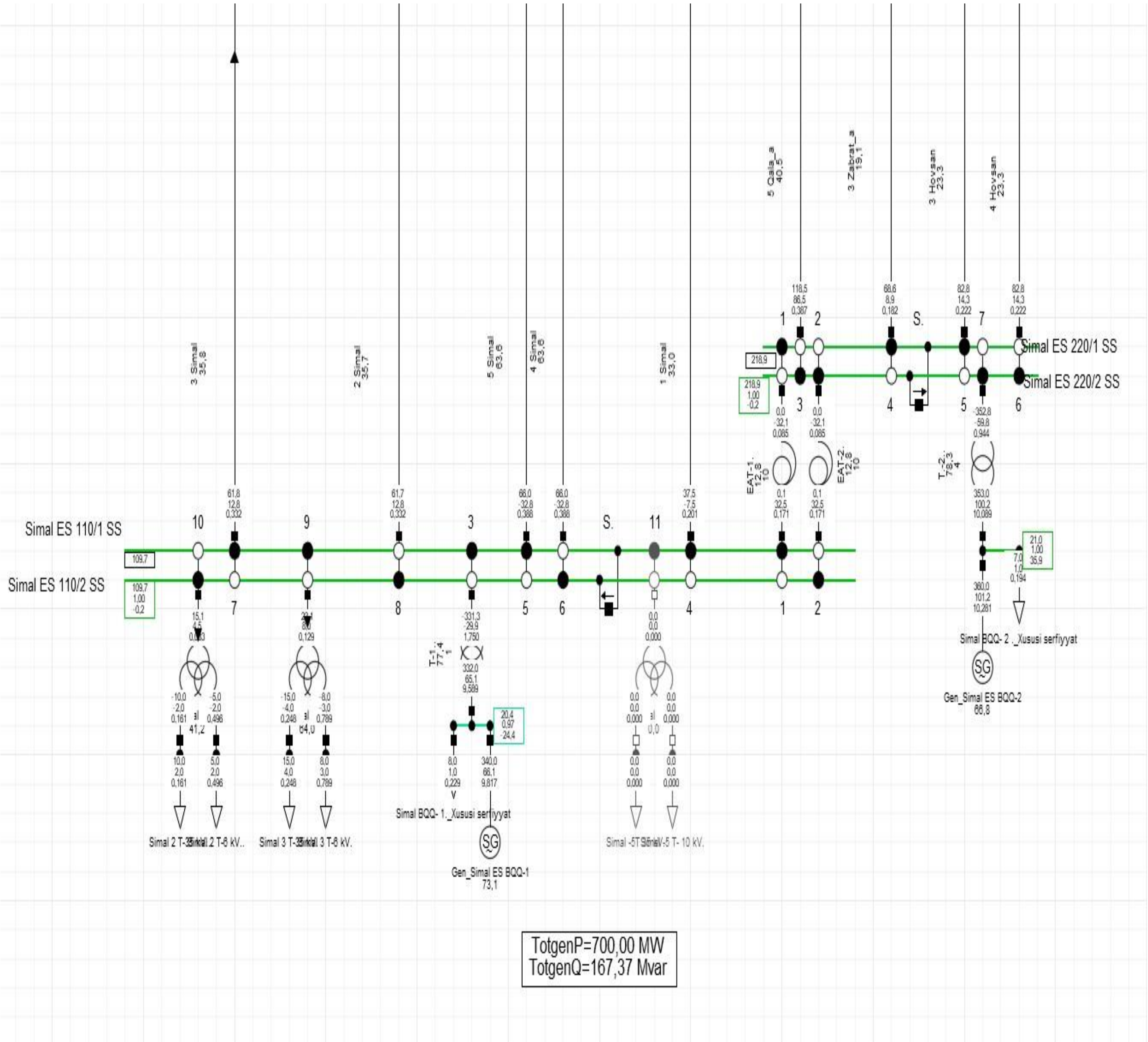
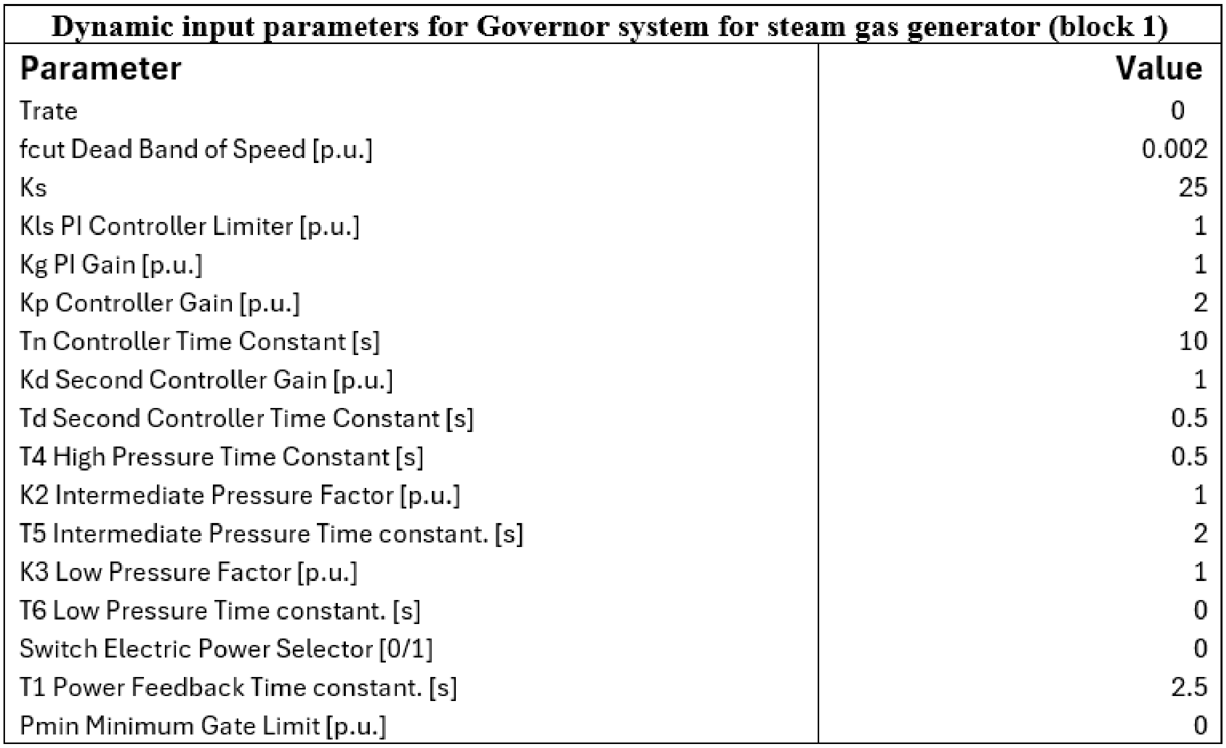


Figure 3.4: The one line connection diagram of the general Shimal Power Plant.

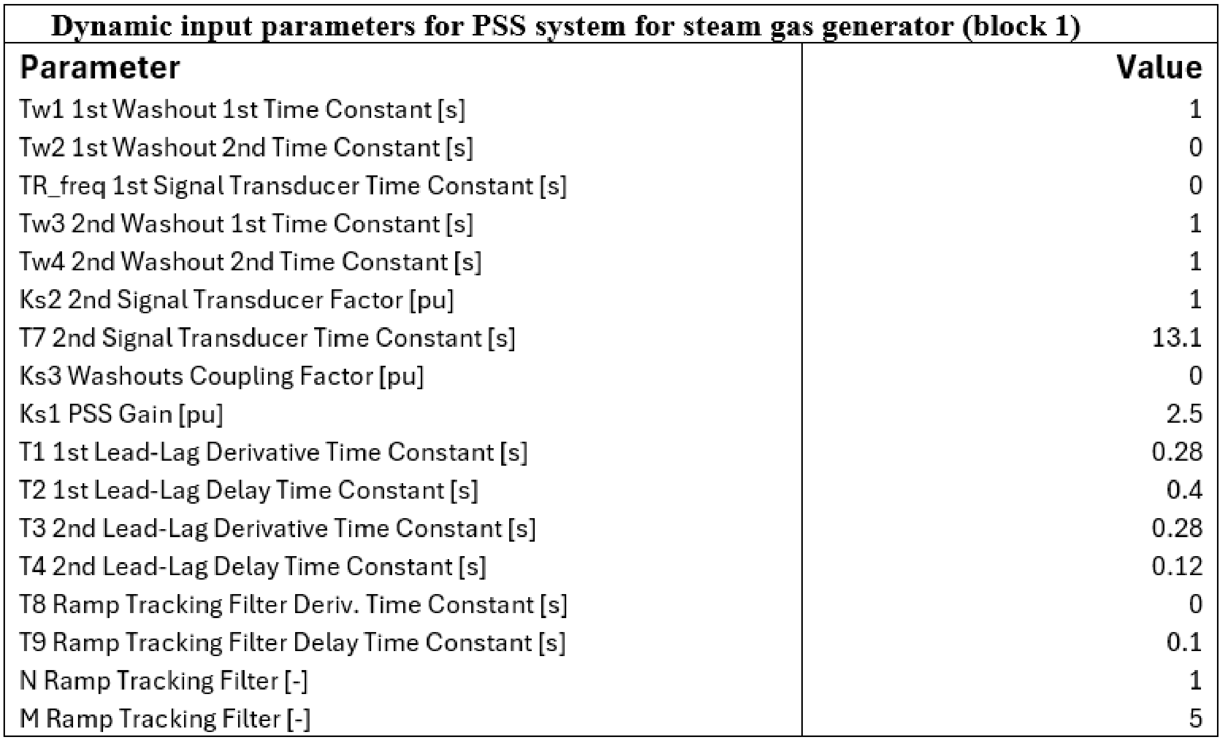
The input parameters specific to the system and Block-1 at the time of starting the simulation are listed below.

Table 3.2: Dynamic input parameters for Governor system for steam gas generator (block 1)



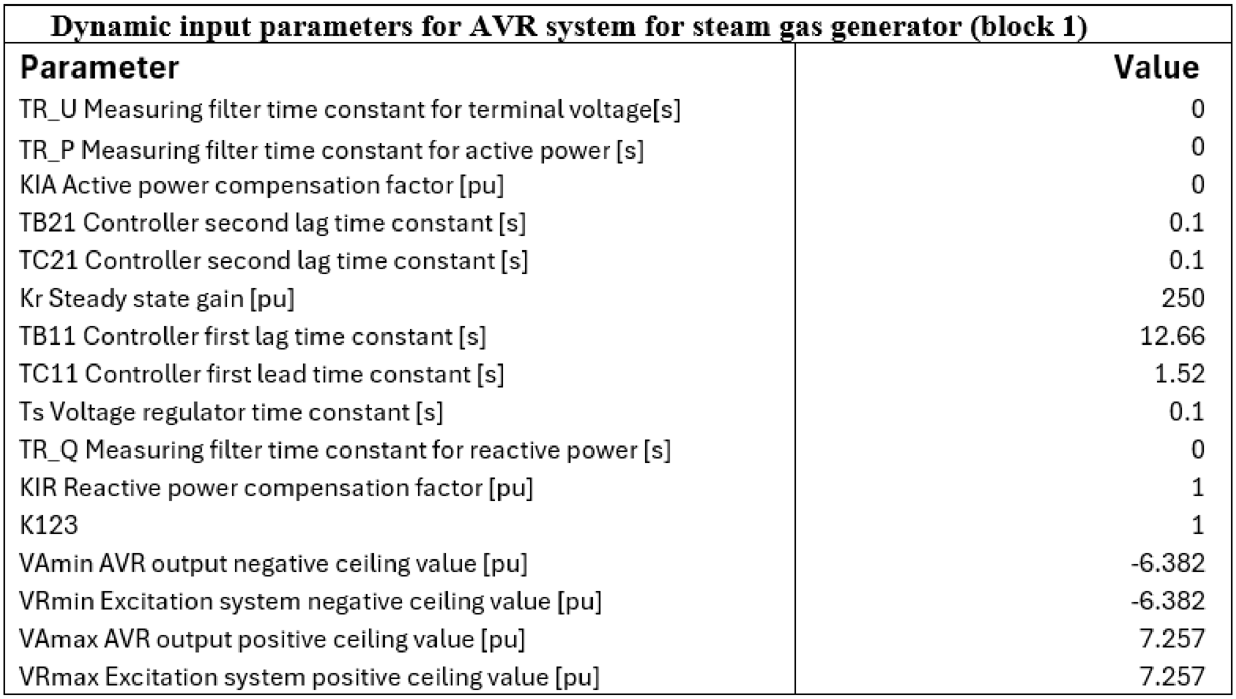
Dynamic input parameters for Governor system for steam gas generator (block 1)	
Parameter	**Value**
Trate	0
fcut Dead Band of Speed [p.u.]	0.002
Ks	25
Kls PI Controller Limiter [p.u.]	1
Kg PI Gain [p.u.]	1
Kp Controller Gain [p.u.]	2
Tn Controller Time Constant [s]	10
Kd Second Controller Gain [p.u.]	1
Td Second Controller Time Constant [s]	0.5
T4 High Pressure Time Constant [s]	0.5
K2 Intermediate Pressure Factor [p.u.]	1
T5 Intermediate Pressure Time constant. [s]	2
K3 Low Pressure Factor [p.u.]	1
T6 Low Pressure Time constant. [s]	0
Switch Electric Power Selector [0/1]	0
T1 Power Feedback Time constant. [s]	2.5
Pmin Minimum Gate Limit [p.u.]	0

Table 3.3: Dynamic input parameters for PSS system for steam gas generator (block 1)



Dynamic input parameters for PSS system for steam gas generator (block 1)	
Parameter	**Value**
Tw1 1st Washout 1st Time Constant [s]	1
Tw2 1st Washout 2nd Time Constant [s]	0
TR_freq 1st Signal Transducer Time Constant [s]	0
Tw3 2nd Washout 1st Time Constant [s]	1
Tw4 2nd Washout 2nd Time Constant [s]	1
Ks2 2nd Signal Transducer Factor [pu]	1
T7 2nd Signal Transducer Time Constant [s]	13.1
Ks3 Washouts Coupling Factor [pu]	0
Ks1 PSS Gain [pu]	2.5
T1 1st Lead-Lag Derivative Time Constant [s]	0.28
T2 1st Lead-Lag Delay Time Constant [s]	0.4
T3 2nd Lead-Lag Derivative Time Constant [s]	0.28
T4 2nd Lead-Lag Delay Time Constant [s]	0.12
T8 Ramp Tracking Filter Deriv. Time Constant [s]	0
T9 Ramp Tracking Filter Delay Time Constant [s]	0.1
N Ramp Tracking Filter [-]	1
M Ramp Tracking Filter [-]	5

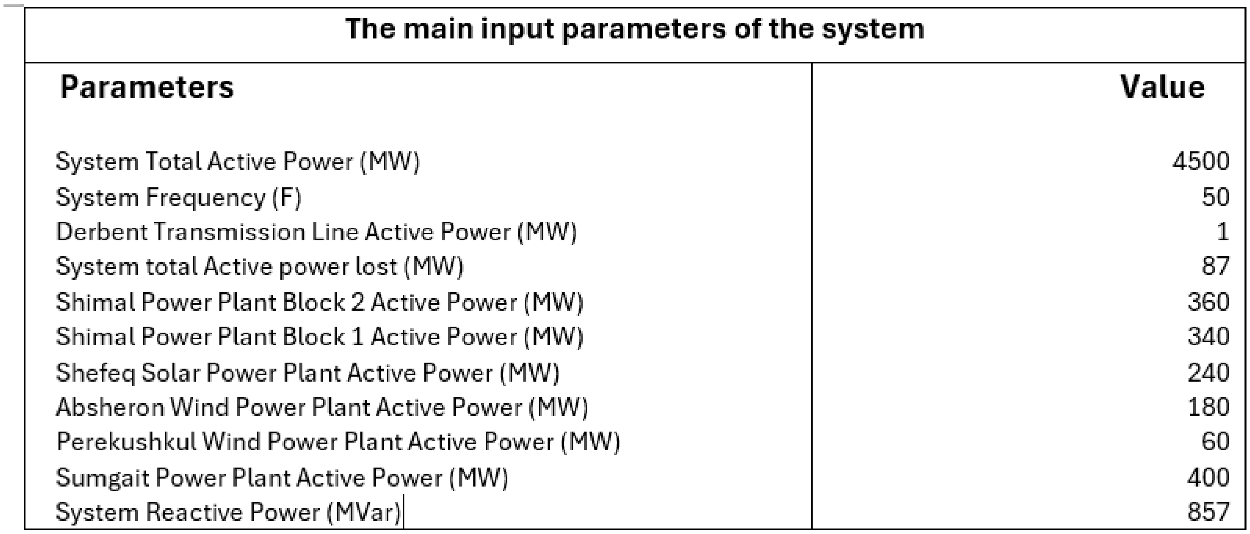
Table 3.4: Dynamic input parameters for AVR system for steam gas generator (block 1)



Dynamic input parameters for AVR system for steam gas generator (block 1)

Parameter	Value
TR_U Measuring filter time constant for terminal voltage[s]	0
TR_P Measuring filter time constant for active power [s]	0
KIA Active power compensation factor [pu]	0
TB21 Controller second lag time constant [s]	0.1
TC21 Controller second lag time constant [s]	0.1
Kr Steady state gain [pu]	250
TB11 Controller first lag time constant [s]	12.66
TC11 Controller first lead time constant [s]	1.52
Ts Voltage regulator time constant [s]	0.1
TR_Q Measuring filter time constant for reactive power [s]	0
KIR Reactive power compensation factor [pu]	1
K123	1
VAmin AVR output negative ceiling value [pu]	-6.382
VRmin Excitation system negative ceiling value [pu]	-6.382
VAmax AVR output positive ceiling value [pu]	7.257
VRmax Excitation system positive ceiling value [pu]	7.257

Table 3.5: Main input parameters of the simulation.



The main input parameters of the system

Parameters	Value
System Total Active Power (MW)	4500
System Frequency (F)	50
Derbent Transmission Line Active Power (MW)	1
System total Active power lost (MW)	87
Shimal Power Plant Block 2 Active Power (MW)	360
Shimal Power Plant Block 1 Active Power (MW)	340
Shefeq Solar Power Plant Active Power (MW)	240
Absheron Wind Power Plant Active Power (MW)	180
Perekushkul Wind Power Plant Active Power (MW)	60
Sumgait Power Plant Active Power (MW)	400
System Reactive Power (MVar)	857

In order to properly perform the simulations, the main input parameters of the system are first determined, and after entering the dynamic parameters of particular importance for the equipment to be simulated, an artificial short circuit is created at a designated point. Even if the consequences of a short circuit are felt in all equipment of the system, more critical points are identified as simulation points. In our first case, the Derbent Power Transmission line, 1st block of the Shimal Power Plant, and the Azerbaijan Power Plant were identified as simulation points. Detailed information about all the results obtained will be provided in the results section and the trends obtained will be shown.

3.1.2 Gas Turbine Generator - 2 and Steam Generator outage at Sumgayit Power P lant.

Sumgait Power Plant is considered one of the most modern stations built by SIEMENS. Its total capacity is 526 MW, and considering some technological processes, this station operates with a load of 450 MW per year, excluding repair periods. The Sumgait Power Plant has great support in frequency regulation. As such, this station has the ability to instantly raise and lower the load. Sumgait Power Plant is far ahead in terms of its efficiency. The technology used here minimizes temperature losses. The system, which is a combination of two gas turbine generators and one steam turbine generator, is very efficient and costeffective. Considering the above-mentioned features, any unplanned shutdown or accident at the Sumgait power plant will have a very negative impact on the system and will lead to a sharp fluctuation in the frequency of the energy system. Without the Sumgait power plant, the system cannot be considered fully stable. Taking all these criticalities into account, Sumgait Power Plant was taken as one of the simulation points. A technological system was designed at this plant so that if any of the Gas Turbine Generators stops working for any reason, the Steam Turbine Generator automatically stops working and only one Gas Turbine Generator remains in operation.

The changes caused by the accident at the Sumgait Power Plant impact on the Derbent Power Transmission Line, the Shimal Power Plant, and the Azerbaijan Power Plants will be simulated using the DigSILENT Powerfactory program.

In our simulation Gas turbine generator 2 and steam turbine generator shut down due to technological process disruption. At the time of the trip, the load of Gas Turbine Generator 1 was 125 MW, and the load of Steam Turbine Generator 2 was 140 MW. This means that 265 MW of load was suddenly lost from the system. When the simulation was performed, the load of the Derbent Power Transmission line was assumed to be approximately 1 MW. There has been almost no energy exchange with neighboring countries, as can be seen in more detail in the table below.

Table 3.6: Total active and reactive power of the energy system and energy exchange schedule with neighboring countries.

Name	Total P gen. MW	Total Q gen. Mvar	Loads, P MW	Loads, Q Mvar	Interchange Flow, P MW	Interchange Flow, Q Mvar	Losses, P MW	Losses, Q Mvar	Export, P MW	Export, Q Mvar	Import, P MW	Import, Q Mvar
99 XX	0,0	0,0	0,0	0,0	0,0	-0,0	0,0	0,0	168,4	111,6	168,4	111,6
Azerbaijan	4499,3	857,0	4410,5	1589,6	1,7	-111,6	87,1	-690,2	85,1	0,0	83,4	111,6
Georgia	2352,5	797,9	1881,0	879,7	-0,6	26,7	47,8	-384,9	83,4	26,7	84,0	0,0
Russia	0,0	41,5	0,0	0,0	-1,1	84,8	0,1	-43,3	0,0	84,8	1,1	0,0

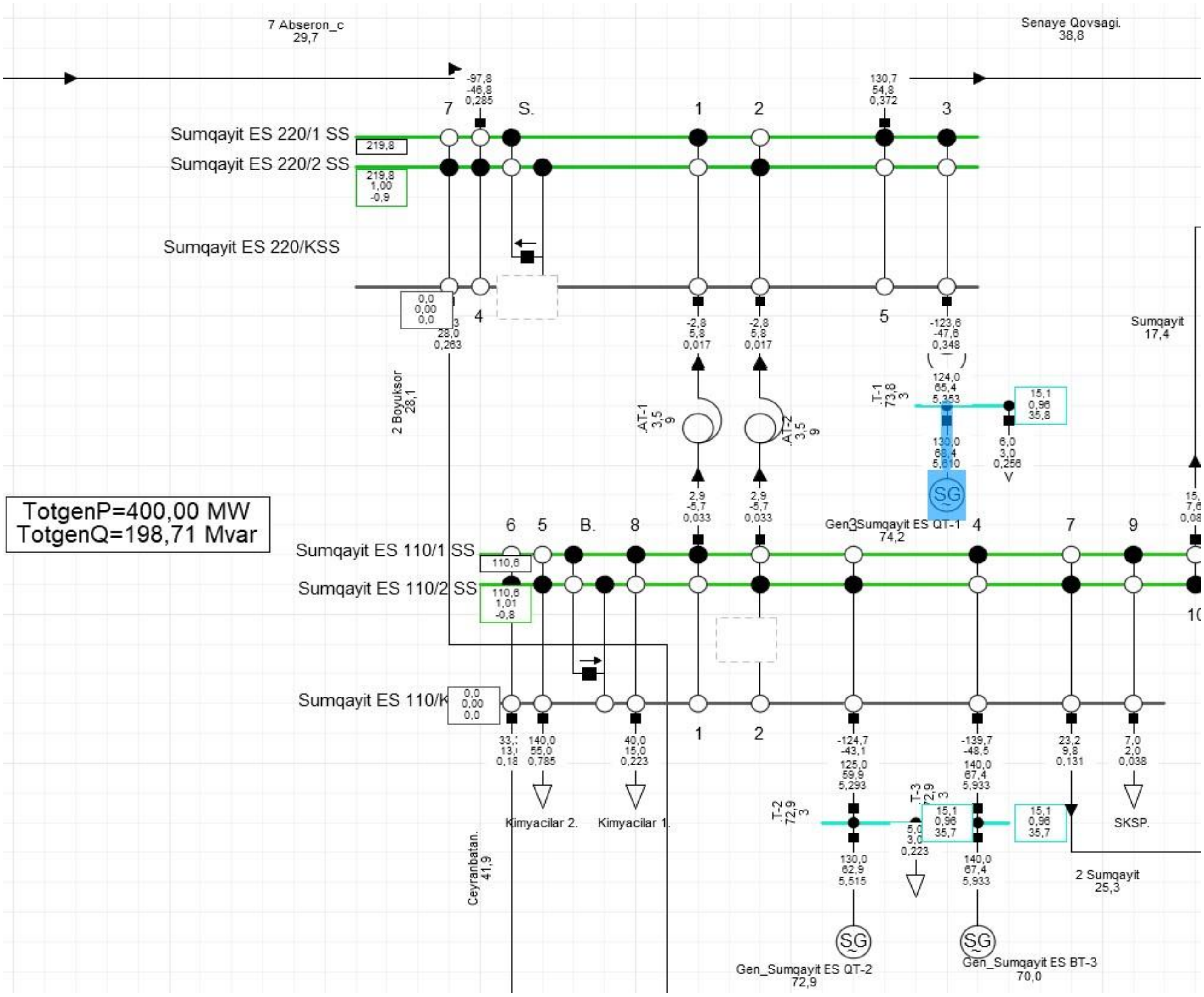
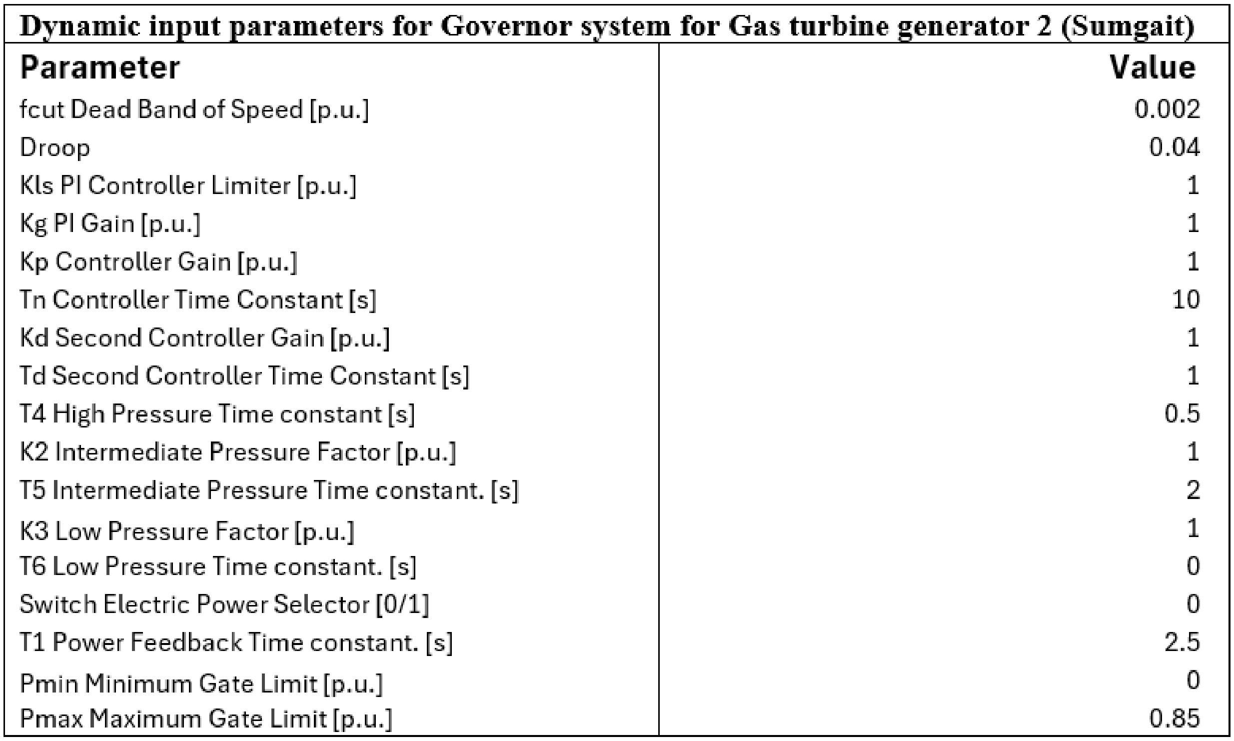


Figure 3.5**:** The one line connection diagram of the general Sumgait Power Plant.

The input parameters specific to the system and Gas turbine generator -2 at Sumgait Power Plant at the time of starting the simulation are listed below.

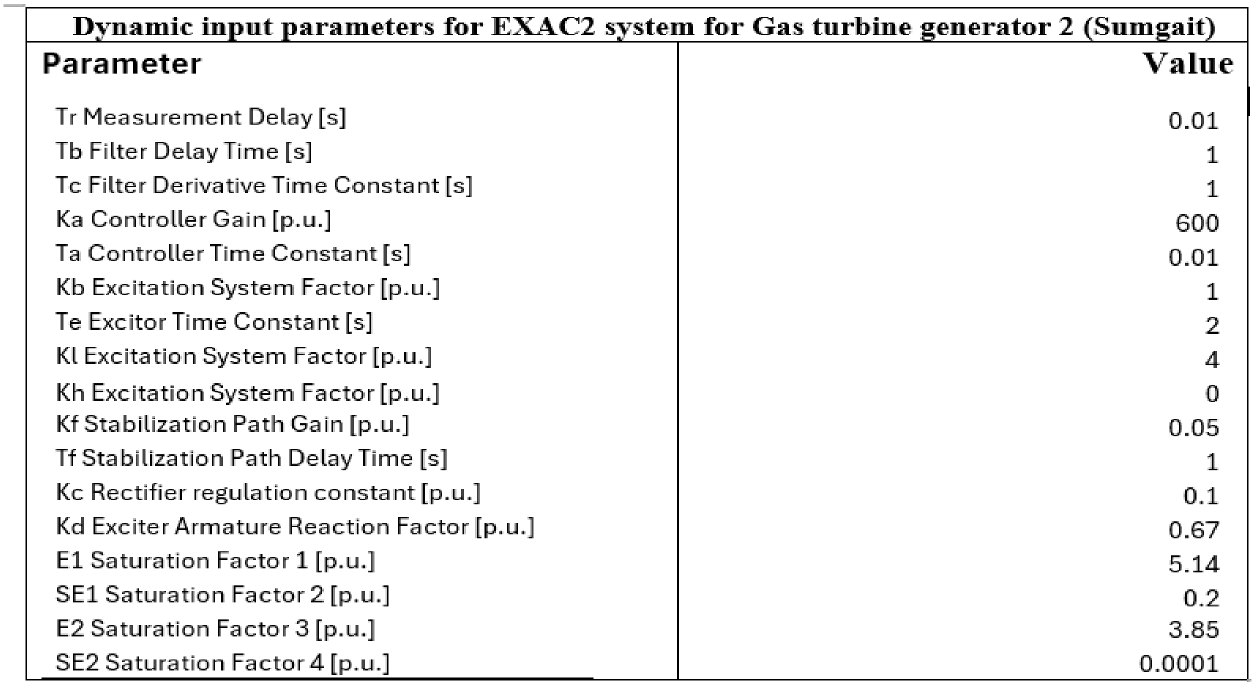
Table 3.7: Dynamic input parameters for Governor system for Gas turbine generator 2 of the Sumgait Power Plant



Dynamic input parameters for Governor system for Gas turbine generator 2 (Sumgait)

Parameter	Value
fcut Dead Band of Speed [p.u.]	0.002
Droop	0.04
Kls PI Controller Limiter [p.u.]	1
Kg PI Gain [p.u.]	1
Kp Controller Gain [p.u.]	1
Tn Controller Time Constant [s]	10
Kd Second Controller Gain [p.u.]	1
Td Second Controller Time Constant [s]	1
T4 High Pressure Time constant [s]	0.5
K2 Intermediate Pressure Factor [p.u.]	1
T5 Intermediate Pressure Time constant. [s]	2
K3 Low Pressure Factor [p.u.]	1
T6 Low Pressure Time constant. [s]	0
Switch Electric Power Selector [0/1]	0
T1 Power Feedback Time constant. [s]	2.5
Pmin Minimum Gate Limit [p.u.]	0
Pmax Maximum Gate Limit [p.u.]	0.85

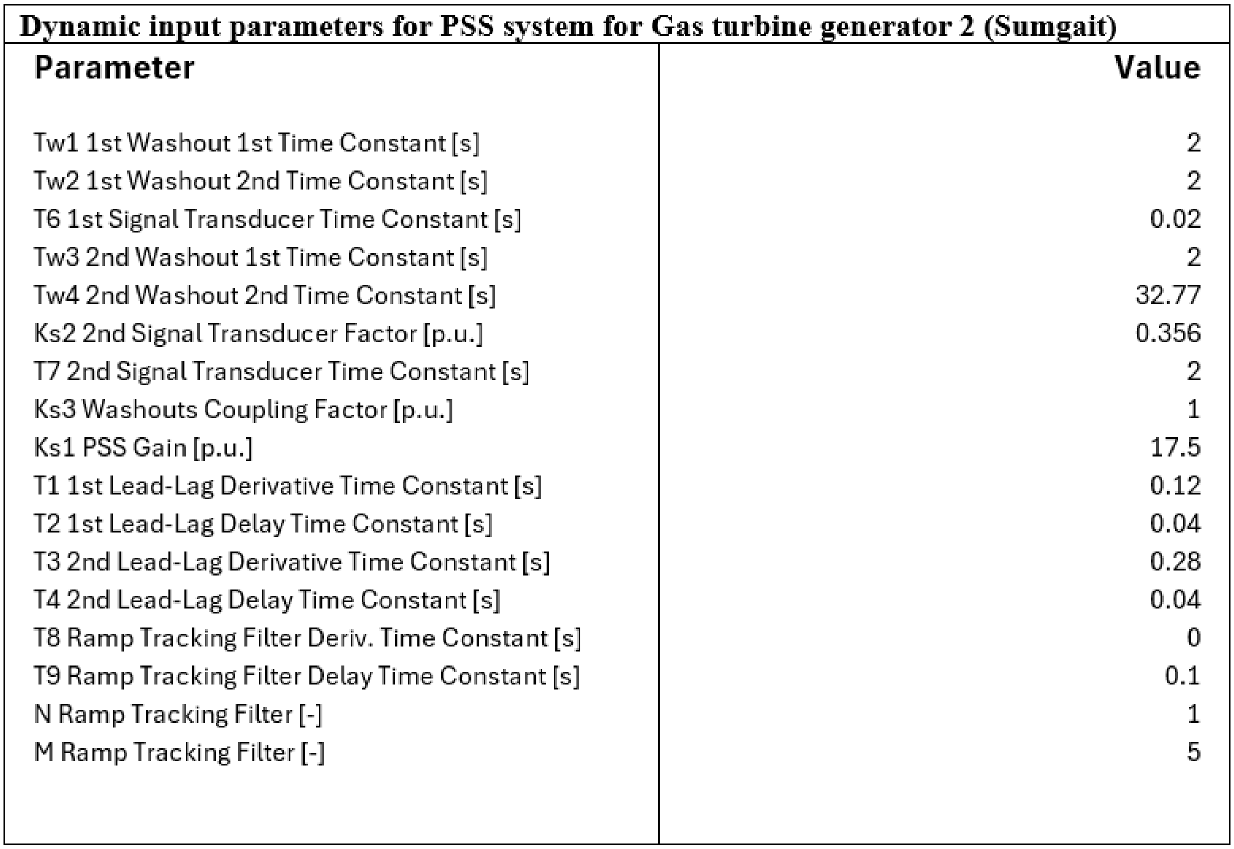
Table 3.8: Dynamic input parameters for EXAC2 system for Gas turbine generator 2 at Sumgait PS



Dynamic input parameters for EXAC2 system for Gas turbine generator 2 (Sumgait)

Parameter	Value
Tr Measurement Delay [s]	0.01
Tb Filter Delay Time [s]	1
Tc Filter Derivative Time Constant [s]	1
Ka Controller Gain [p.u.]	600
Ta Controller Time Constant [s]	0.01
Kb Excitation System Factor [p.u.]	1
Te Excitor Time Constant [s]	2
Kl Excitation System Factor [p.u.]	4
Kh Excitation System Factor [p.u.]	0
Kf Stabilization Path Gain [p.u.]	0.05
Tf Stabilization Path Delay Time [s]	1
Kc Rectifier regulation constant [p.u.]	0.1
Kd Exciter Armature Reaction Factor [p.u.]	0.67
E1 Saturation Factor 1 [p.u.]	5.14
SE1 Saturation Factor 2 [p.u.]	0.2
E2 Saturation Factor 3 [p.u.]	3.85
SE2 Saturation Factor 4 [p.u.]	0.0001

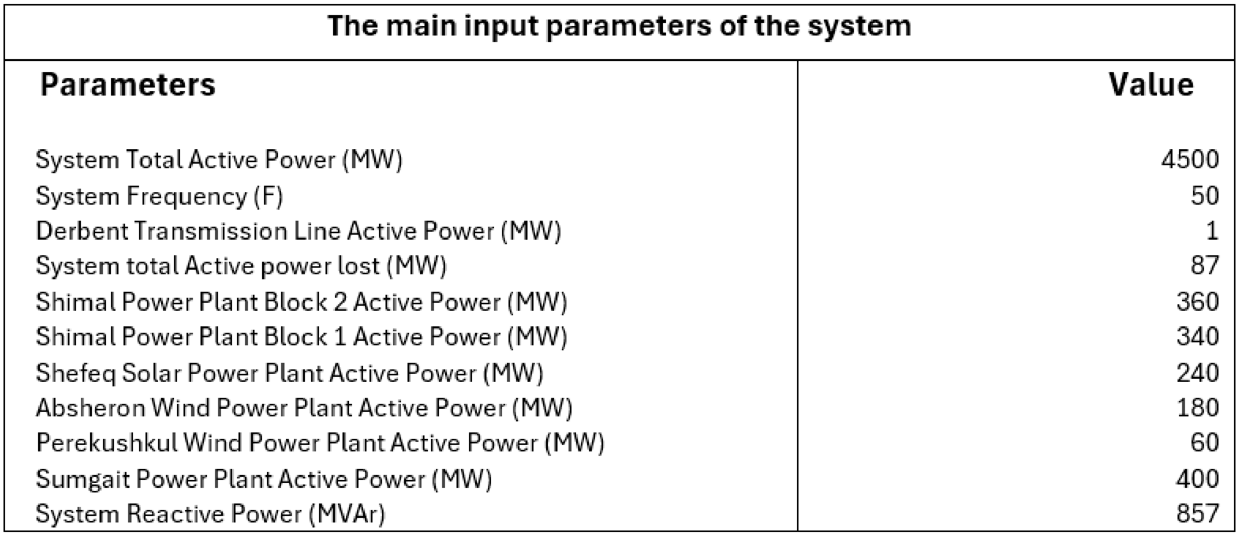
Table 3.9: Dynamic input parameters for PSS system for Gas turbine generator 2 for Sumgait PS



Dynamic input parameters for PSS system for Gas turbine generator 2 (Sumgait)

Parameter	Value
Tw1 1st Washout 1st Time Constant [s]	2
Tw2 1st Washout 2nd Time Constant [s]	2
T6 1st Signal Transducer Time Constant [s]	0.02
Tw3 2nd Washout 1st Time Constant [s]	2
Tw4 2nd Washout 2nd Time Constant [s]	32.77
Ks2 2nd Signal Transducer Factor [p.u.]	0.356
T7 2nd Signal Transducer Time Constant [s]	2
Ks3 Washouts Coupling Factor [p.u.]	1
Ks1 PSS Gain [p.u.]	17.5
T1 1st Lead-Lag Derivative Time Constant [s]	0.12
T2 1st Lead-Lag Delay Time Constant [s]	0.04
T3 2nd Lead-Lag Derivative Time Constant [s]	0.28
T4 2nd Lead-Lag Delay Time Constant [s]	0.04
T8 Ramp Tracking Filter Deriv. Time Constant [s]	0
T9 Ramp Tracking Filter Delay Time Constant [s]	0.1
N Ramp Tracking Filter [-]	1
M Ramp Tracking Filter [-]	5

Table 3.10: The main input parameters of the system for simulation



The main input parameters of the system

Parameters	Value
System Total Active Power (MW)	4500
System Frequency (F)	50
Derbent Transmission Line Active Power (MW)	1
System total Active power lost (MW)	87
Shimal Power Plant Block 2 Active Power (MW)	360
Shimal Power Plant Block 1 Active Power (MW)	340
Shefeq Solar Power Plant Active Power (MW)	240
Absheron Wind Power Plant Active Power (MW)	180
Perekushkul Wind Power Plant Active Power (MW)	60
Sumgait Power Plant Active Power (MW)	400
System Reactive Power (MVAr)	857

As a previous simulation, in order to roperly perform the simulations, the main input parameters of the system are first determined, and after entering the dynamic parameters of particular importance for the equipment to be simulated, an artificial problem is created at a designated point that is the Gas Turbine Generator and Steam Turbine Generator switches off due to a reason arising in the technological process. Even if the consequences of a shutdown are felt in all equipment of the system, more critical points are identified as simulation points. In our second case, the Derbent Power Transmission line, Gas turbine generator 2 in Sumgait Power Plant, and the Azerbaijan Power Plant were identified as simulation points. Detailed information about all the results obtained will be provided in the results section and the trends obtained will be shown.

3.2 Calculations for Load-Frequency and Automatic Generation Control.

The main important element of maintaining a stable frequency in the system is maintaining a normal balance between the generated load and the consumed load. Since the frequency directly depends on this balance, the overall frequency of the system can increase or decrease with a change in the load balance. It is possible to perform calculations for Load Frequency Control and Automatic Generation Control systems, considering the existing parameters of the Azerbaijani energy system.

3.2.1 Load-Frequency Control (LFC) .

The purpose of LFC is to control load balancing. If any mismatch occurs, it immediately returns the frequency (50 or 60 Hz) to its nominal value.

The equation of the frequency deviation is

$$\Delta f = \frac{-\Delta P}{\beta}$$

Where:

- Δf - Frequency deviation (Hz)
- ΔP- Change in power demand or supply (MW)
- β -Frequency bias coefficient (MW/Hz)

The calculation of β is carried out using the following formula:

$$\beta = \frac{\text{Total Capacity of the System (MW)}}{\text{Nominal Frequency (Hz)}}$$

Since the maximum consumption of the Azerbaijani energy system is taken to be 4500MW, we can determine β based on this formula.

$$\beta = \frac{4500}{50} = 90\,\text{MW/Hz}.$$

ΔP - Considering our total load, 30 MW was taken as an approximation.

$$\Delta f = \frac{-30}{90} = -0.333\,\text{Hz}.$$

Deviation of -333 Hz indicates that the consumption has exceeded the generation, and this means that the frequency value has dropped to 49.667 Hz. If this is not eliminated soon, it will lead to very negative effects for the system.

3.2.2 Automatic Generation Control (AGC)

Considering the parameters of Azerbaijan's energy demand, a calculation was made for AGC, which we can directly apply to the Derbent Power Transmission Line.

3.2.2.1 Tie-Line Power Flow (ΔPtie)

The equation for tie-line power flow is

$$\Delta P_{\text{tie}} = T_{ij} \cdot (\Delta f_i - \Delta f_j)$$

- Tij=0.8MW/Hz (tie-line synchronizing coefficient)
- Δfi=0.05 Hz (frequency deviation in area that can be consider Azerbaijan)
- Δfj=−0.02 Hz (frequency deviation in area that can be consider Russia)

Tie-line synchronizing coefficient can be found by the following equation:

$$T_{ij} = \frac{\Delta P_{\text{tie}}}{\Delta f_i - \Delta f_j}$$

The following calculating value was obtained for ΔP_{tie}

$\Delta P_{\text{tie}}=0.8\cdot (0.05-(-0.02))$
$\Delta P_{\text{tie}}=0.8\cdot (0.05+0.02)$
$\Delta P_{\text{tie}}=0.056\text{MW}$.

The result shows that if the load flow from area i to area j and its value exceeds 0.056 MW, then the AGC system will be activated and mitigate the frequency change.

3.2.2.2 AGC Control Signal.

The AGC control signal combines two factors:

- Frequency deviation (Δf): Measures imbalance within a single area.
- Tie-line power deviation (ΔPtie): Measures power imbalance between areas.

It is calculated by following equation: $\Delta P_{\text{AGC}} = K_R \cdot \Delta f + K_T \cdot \Delta P_{\text{tie}}$

Where:

- ΔP_{AGC} Control signal to adjust generator output (MW)
- K_R : Frequency control gain (MW/Hz), sensitivity to frequency deviation. (0.1MW/Hz)
- K_T : Tie-line power control gain (MW/MW), sensitivity to tie-line flow deviations. (0.2MW/MW)
- Δ_f : Frequency deviation (Hz). (−0.333Hz)
- ΔP_{tie}: Tie-Line Power Flow (0.056MW)

K_R and K_T are calculated by following equations:

$$K_R = \frac{\Delta P}{\Delta f} \qquad\qquad K_T = \frac{\Delta P_{\text{AGC}}}{\Delta P_{\text{tie}}} = \frac{0.01}{0.05} = 0.2\,\text{MW/MW}.$$

$$\Delta P_{AGC} = (0.1\cdot(-0.333)) + (0.2\cdot 0.056) = -\,0.0221\text{MW}$$

3.2.2.3 Summary of Results

All input parameters used in the calculation part of the master thesis are real parameters of the Azerbaijani energy system. With the results obtained from the calculations, we obtained the final threshold values necessary for the activation of the LFC and AGC systems in our energy system. As a result of calculations, we were able to find that the frequency deviation value of 49.677 is a dangerous limit for our system. The final threshold value for activating the AGC control signal of the system was found to be − 0.0221MW.

CHAPTER FOUR

RESEARCH RESULTS

After the integration of renewable energy sources in the Azerbaijani energy system, we conducted many studies to investigate the problems arising in frequency control methods and find ways to solve these problems in real situations, and we obtained real results by simulating these studies with special programs. As a result of the analysis of these results, the changes occurring in the system, the frequency and power trends were clearly determined with diagrams and trends. The main purpose of the study is to determine the operating time of SPS systems during the opening of large-power generators in the system, the value of energy flows occurring on the Derbent Power Transmission line, and what problems these changes cause at the Azerbaijani power plant. How to improve the results obtained in the coming years and which methods to use will be explained step by step in the results section.

4.1 Short circuit in the output switch of the 2nd block at Shimal Power Plant.

The first simulation experiment was conducted with the power system load of 4500 MW and the addition of 480 MW of new renewable energy sources. For the simulation, a short circuit was created in the output switch of 2nd Block of the Shimal Power Plant and the result of this shutdown was determined as a result of simulations at 1th Block of the Shimal Power Plant, Sumgait Power Plant, Derbent Power Transmission Line and Azerbaijan Power Plant.

The opening of the switch of the 2nd block after the short circuit can be seen more clearly in the figure 4.1.

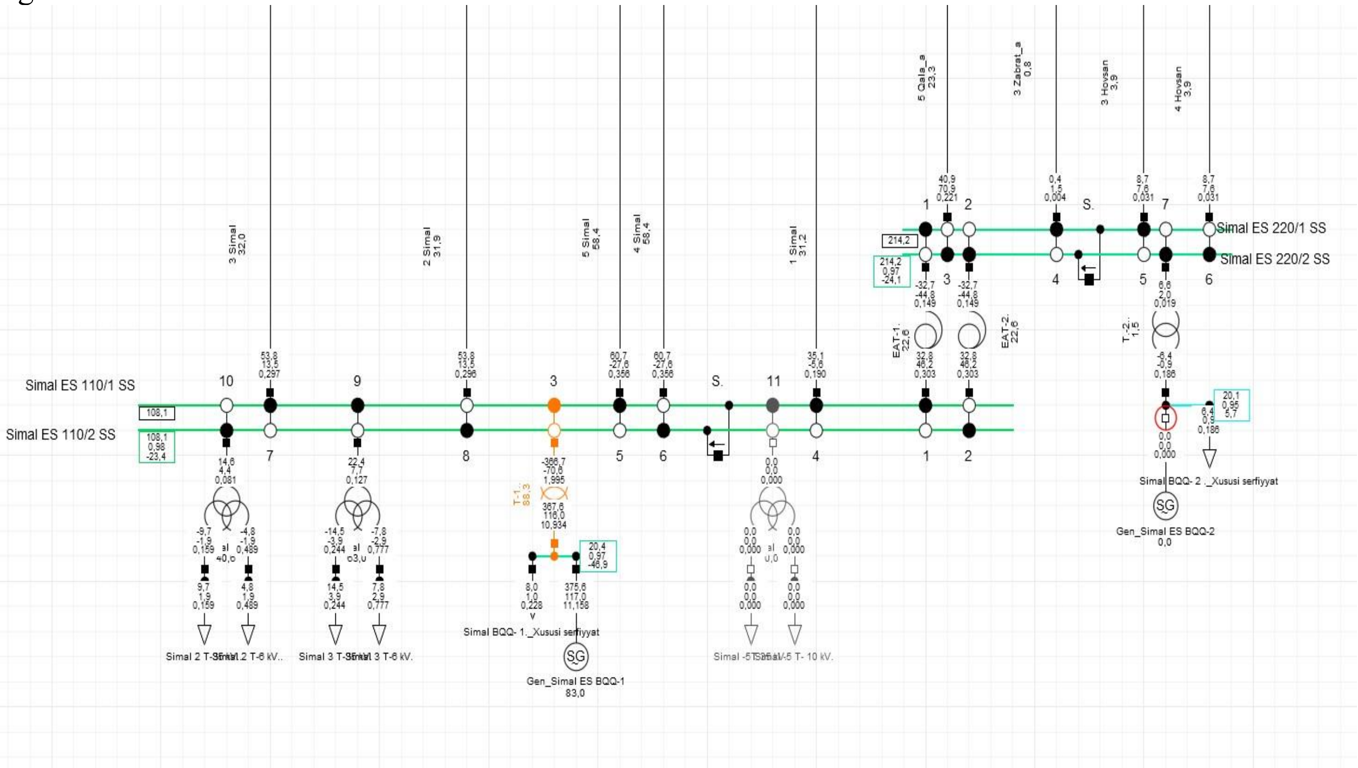


Figure 4.1: Shimal Power Plant connection diagram after 2nd block shutdown.

Initially, when comparing the diagrams of the Shimal Power Plant before and after the short circuit and the real electrical parameters on them, it is observed that the active load of the 1st block suddenly increased from 340 MW to 375 MW by means of automative activation of AGC. In addition, a decrease in voltage from 218 kV to 214 kV was observed at the 220 kV substation, and a decrease in voltage from 109 kV to 108 kV at the 110 kV substation. As a result of the decrease in reactive energy, a total of 80 MVAr of reactive energy flowed from the 110 kV substation to the 220 kV substation through the EAT 1 and EAT 2 autotransformers located between the 110 kV and 220 kV substations in Shimal Power plant. It is clear from Figure 4.2 that the load of 1st Block suddenly increases to 390 MW at the moment of short circuit and starts to fluctuate and settles at 375 MW approximately 8 seconds later.

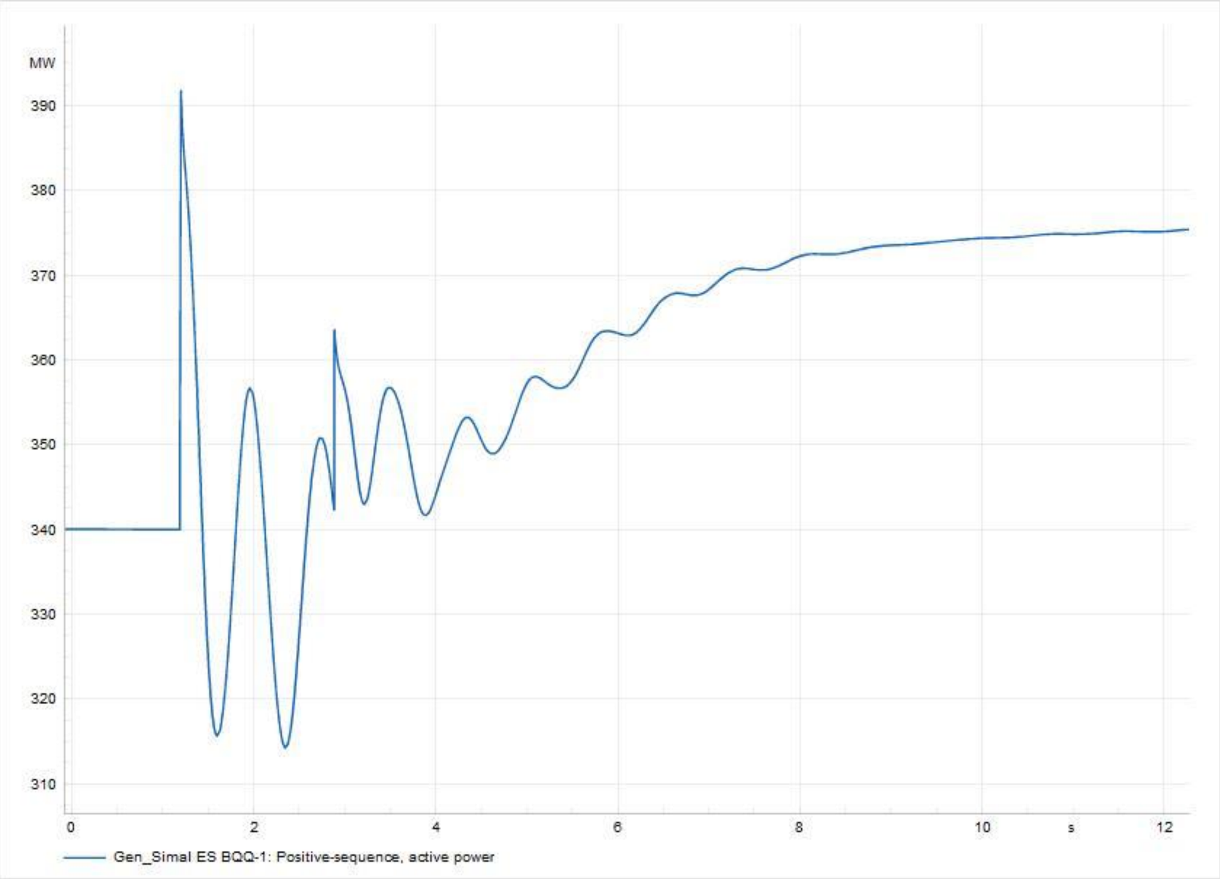


Figure 4.2: Active power fluctuation of 1st Block at Shimal Power Plant after short circuit.

The sudden release of 340 MW of power in the power system is a significant difference between production and consumption in the system, which leads to a sudden sharp decrease in the frequency of the system proportional to the load. As soon as this power shortage is felt, approximately 380 MW of load begins to flow from Russia to Azerbaijan via the Derbent Power Transmission line, creating a sharp overload that is not specific to this line, which in turn negatively affects the stability of the Russian power system. Therefore, the SPS on the line automatically shuts down the Derbent Power Transmission line after 2.88 seconds.

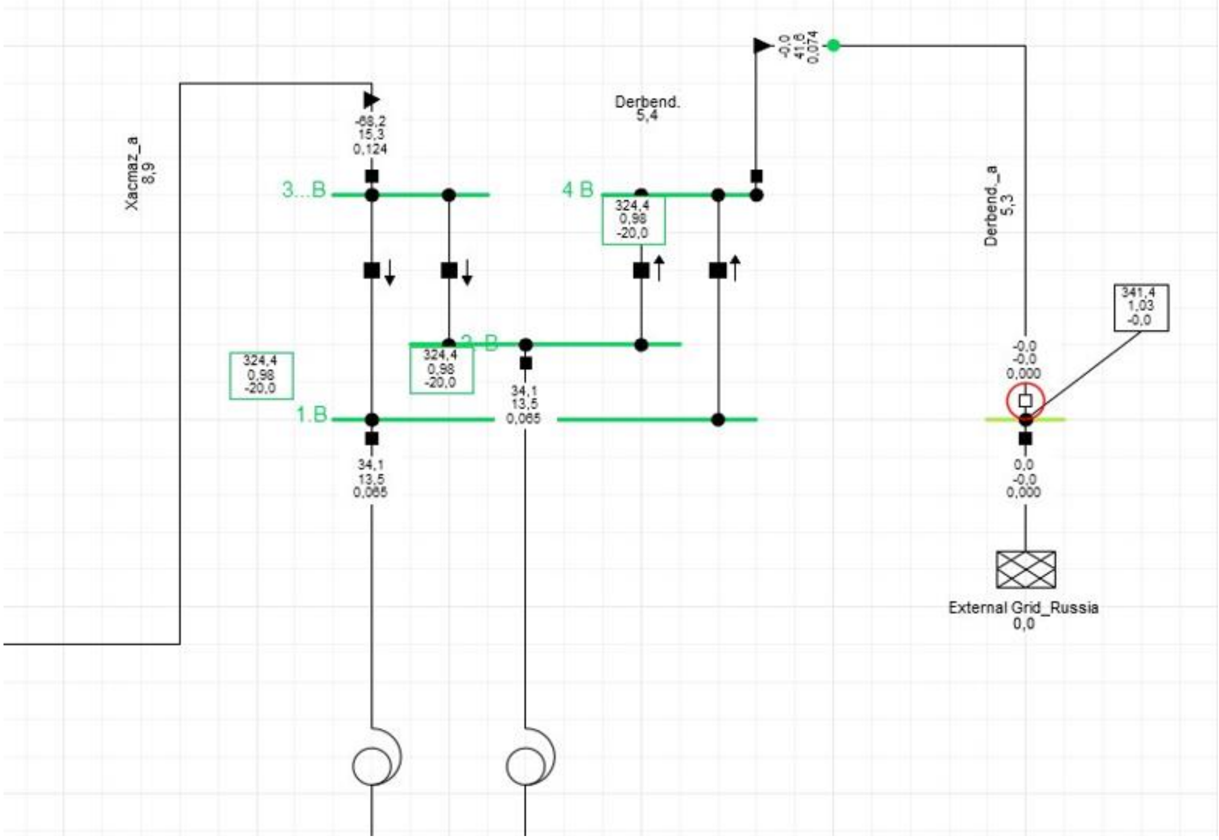


Figure 4.3: The connection diagram of Derbent Power Transmission line after short circuit

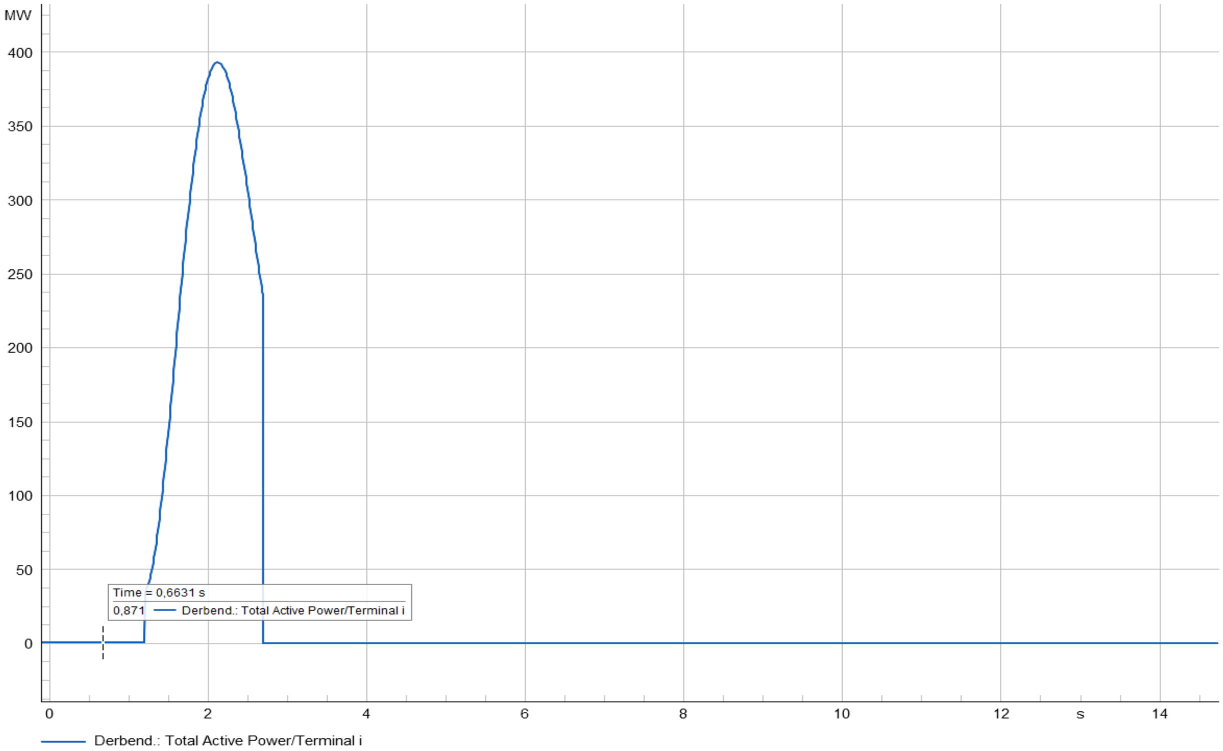


Figure 4.4: Trend showing sudden increase in load on Derbent Tower Transmission line.

Until the SPS is activated, the load flactuations caused by the short circuit at the Shimal Power Plant lead to frequency flactuations on the Derbent Power Transmission Line. This also means frequency flactuations in the Russian energy system.

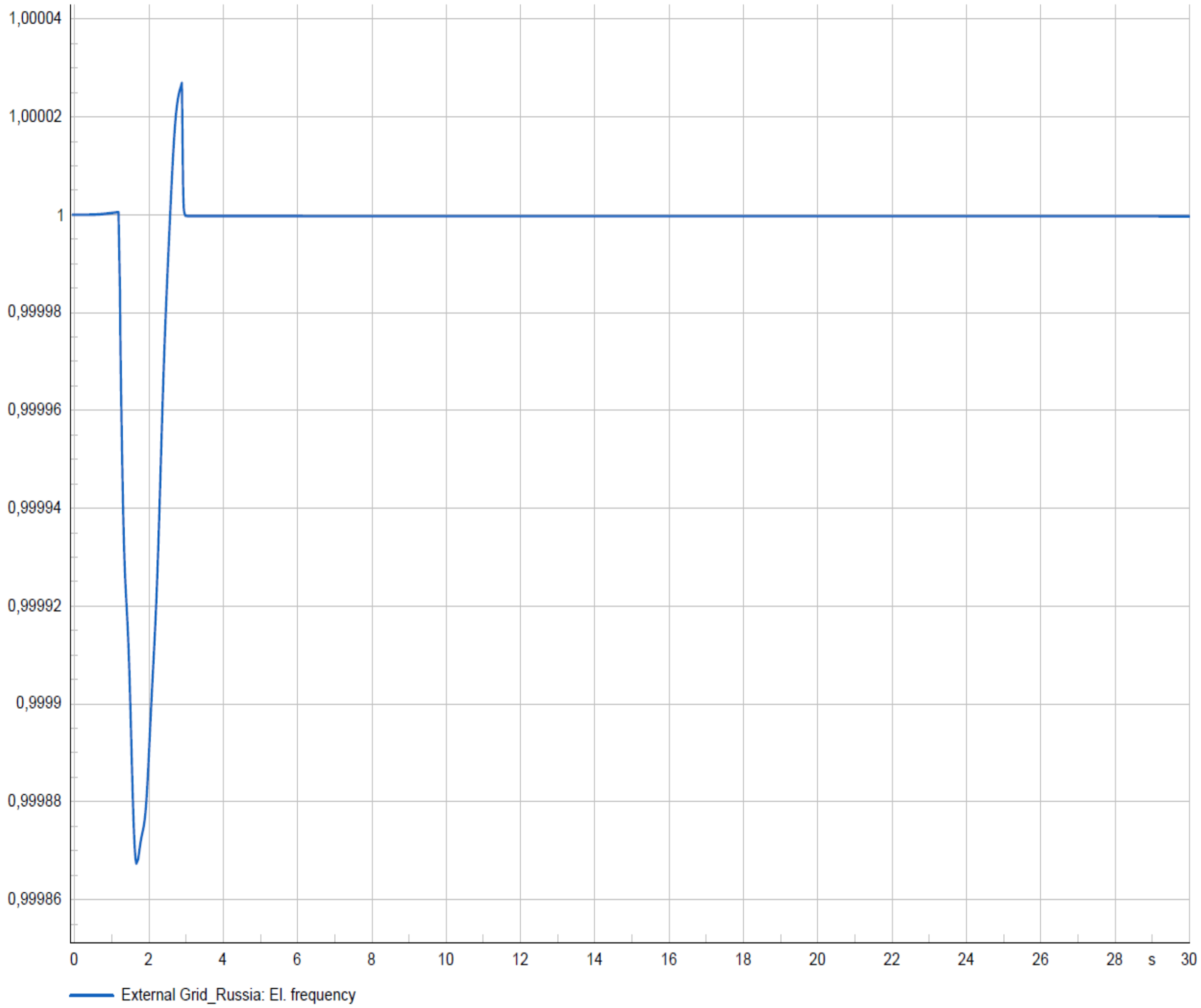


Figure 4.5: Frequency flactuations on the Derbent Power Transmission Line

The consequences of the short circuit that occurred in the 2nd block of the Shimal Power Plant do not end there. It can be said that this is felt in almost all the equipment of the power system. To determine how this accident was felt in the Azerbaijan Power Plant, which is the main energy producer of our power system, the rotor angle of the Turbine Generator 1 was monitored, and sharp fluctuations were observed. Figure 4.6 shows the results of the simulation of fluctuation.

The simulation results show that the shutdown of the 2nd block of the Shimal power plant affects the operation of the overall system and can also lead to the complete shutdown of large power plants supplied by the system. Simultaneously, it also has a negative impact in terms of shortening the life of equipment powered by an unstable system.

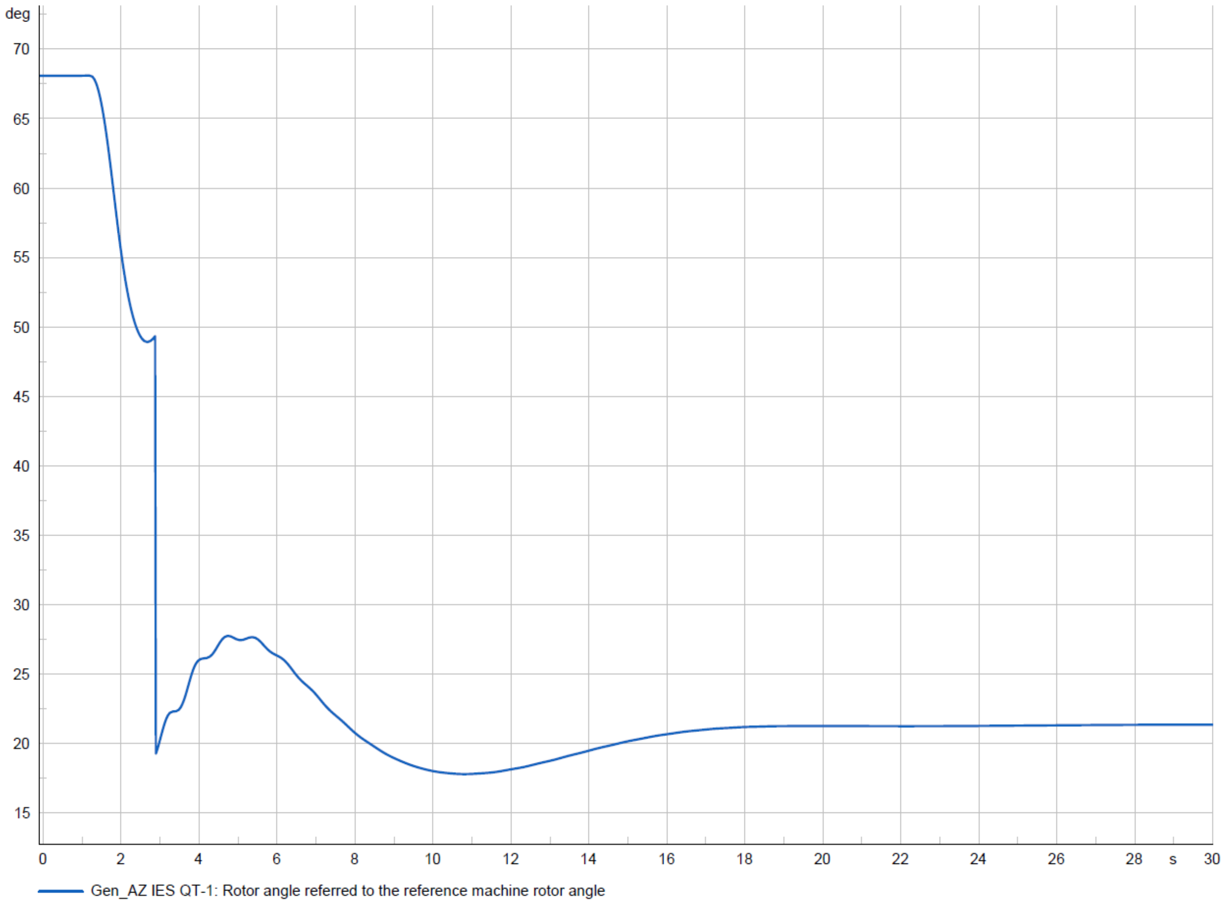


Figure 4.6: Rotor angle fluctuation in the 1st gas turbine generator of the Azerbaijan power plant

4.2 Gas Turbine Generator -2 and Steam Generator outage at Sumgait Power Plant.

The second simulation will examine the changes that will occur in the Derbent Power Transmission Line and the Azerbaijan power plant after the simultaneous shutdown of the 2nd Gas Turbine Generator and the Steam Turbine Generator because of a technological process disruption at the Sumgait Power Plant, one of the most modern and important power plants in Azerbaijan. The second simulation experiment was conducted with the power system load of 4500MW and the addition of 480MW of new renewable energy sources. The active power of the Sumgait power plant at the time of its opening was considered as 394 MW. During these simulations, conducted on the plot project planned for 2025, the integration of the Shefeq, Abseron and Perekushkul stations, which are under construction, into the system was taken into account. The load of the Derbent Power Transmission Line is taken to be approximately 1 MW, which in real operating conditions is approximately 1 MW. The direction of the load flow changes several times during the day. Figure 4.7 shows the connection diagram of the Sumgait Power Plant after the generators stopped.

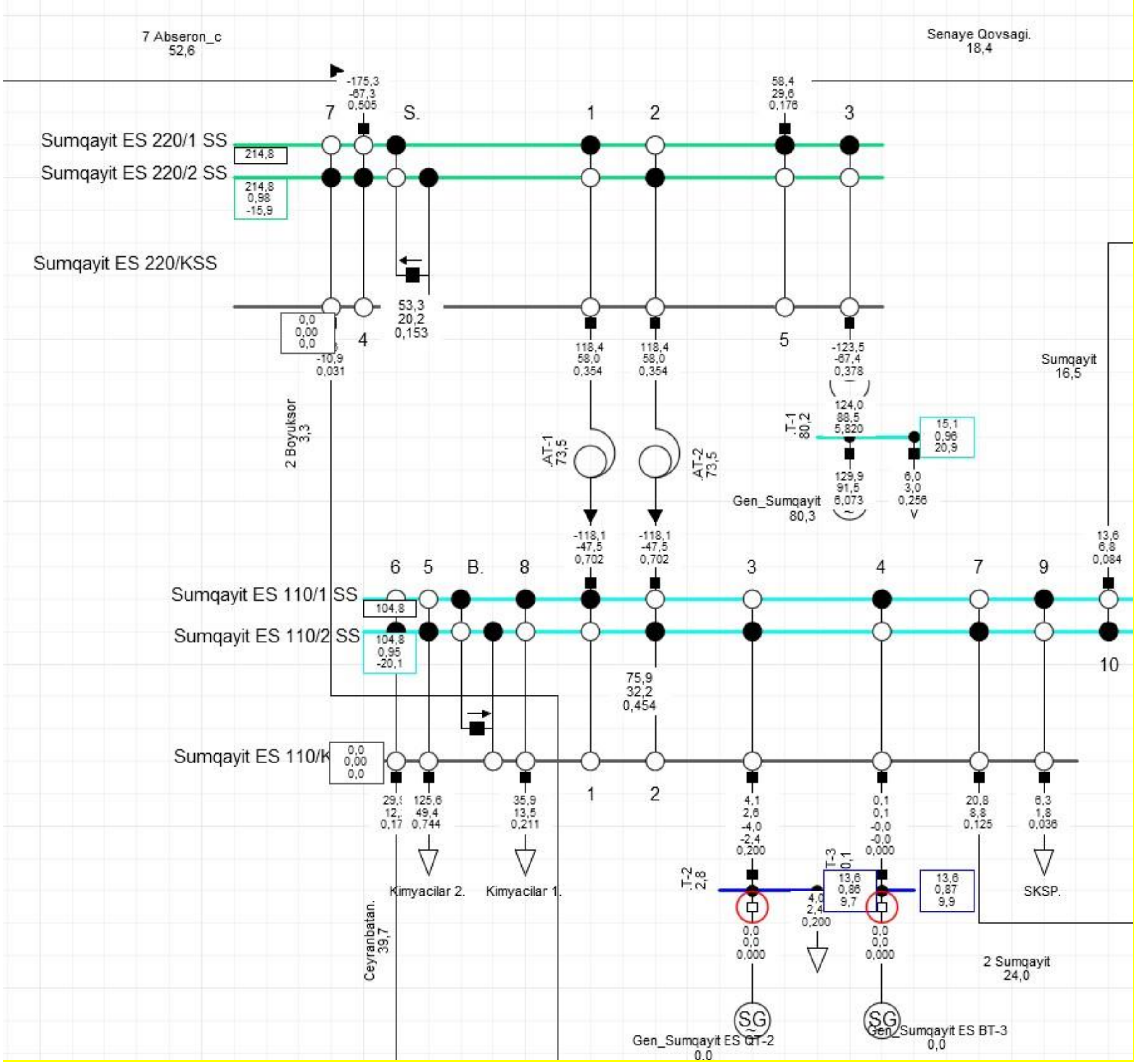


Figure 4.7: The connection diagram of the Sumgait Power Plant after the generators stopped.

Initially, when comparing the diagrams of the Sumgait Power Plant before and after the generators trip and the real electrical parameters on them, it is observed that the active load of the 1st Gas turbine generator increased from 124 MW to 129 MW by means of automative activation of AGC. In addition, a decrease in voltage from 219 kV to 214 kV was observed at the 220 kV substation, and a decrease in voltage from 110kV to 104 kV at the 110 kV substation. As a result of the decrease in active and reactive energy, a total of 256 MW of active and 116 MVAr reactive energy flowed from the 220 kV substation to the 110 kV substation through the ATA -1 and ATA - 2 autotransformers located between the 110 kV and 220 kV substations in Sumgait Power Plant. After simulating an artificial shutdown of the generators, the frequency trend of Gas Turbine Generator 1 was extracted to determine how it would behave in operation. Figure 4.8 shows the frequency deviation trend of Gas Turbine Generator-1 after simulation.

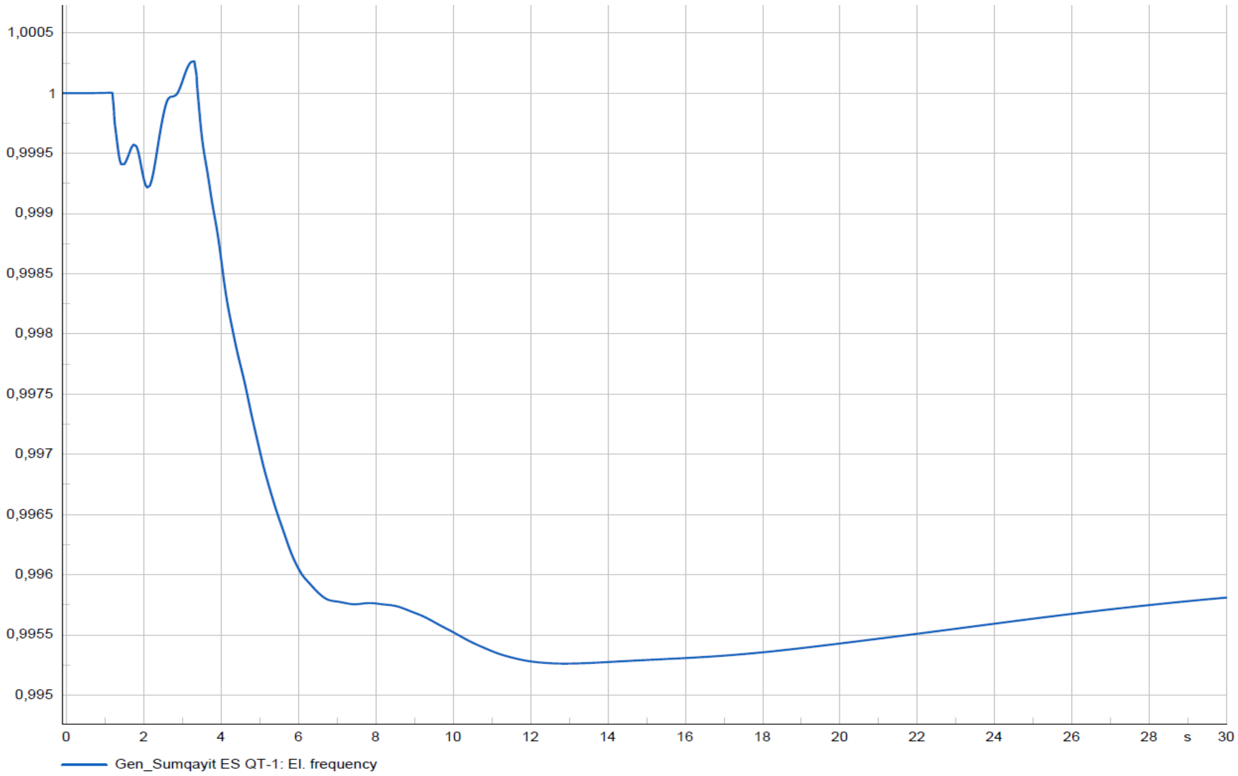
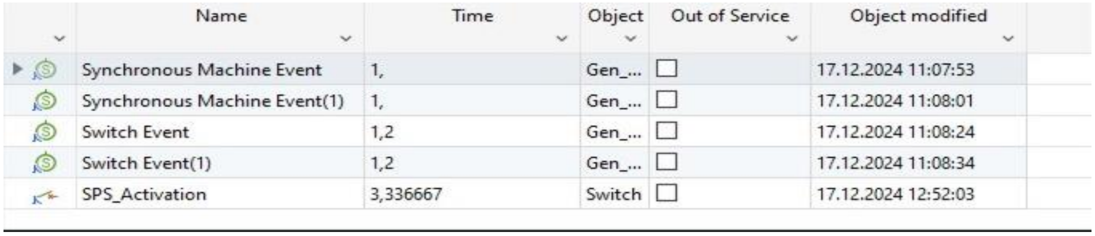


Figure 4.8: The frequency deviation trend of Gas Turbine Generator-1 after simulation.

As in the first simulation, in the second simulation, the load flow from Russia to Azerbaijan starts from the Derbent Power Transmission Line with a momentary loss of load from the system, in which case the SPS is activated and opens the Derbent line after 3.33 seconds. This is also clearly visible in the event section of the DigSILENT Powerfactory program that is mentioned on Figure 4.9.



Name	Time	Object	Out of Service	Object modified
Synchronous Machine Event	1,	Gen_...	☐	17.12.2024 11:07:53
Synchronous Machine Event(1)	1,	Gen_...	☐	17.12.2024 11:08:01
Switch Event	1,2	Gen_...	☐	17.12.2024 11:08:24
Switch Event(1)	1,2	Gen_...	☐	17.12.2024 11:08:34
SPS_Activation	3,336667	Switch	☐	17.12.2024 12:52:03

Figure 4.9: Event table of DigSILENT Powerfactory program after generators trip in Sumgait Power Plant.

In Sumgait Power Plant, the sudden stopping of two generators in the system causes a loss of approximately 270 MW of power, equal to their capacity, at which time the load flow from the Derbent Power Transmission line to 270 MW occurs, which opens the switch of the line by activating the SPS. In this case, fluctuations occur in the frequency of the Derbent Power Transmission Line as well . The simulated states of each case can be seen more clearly in figure 4.10 and figure 4.11

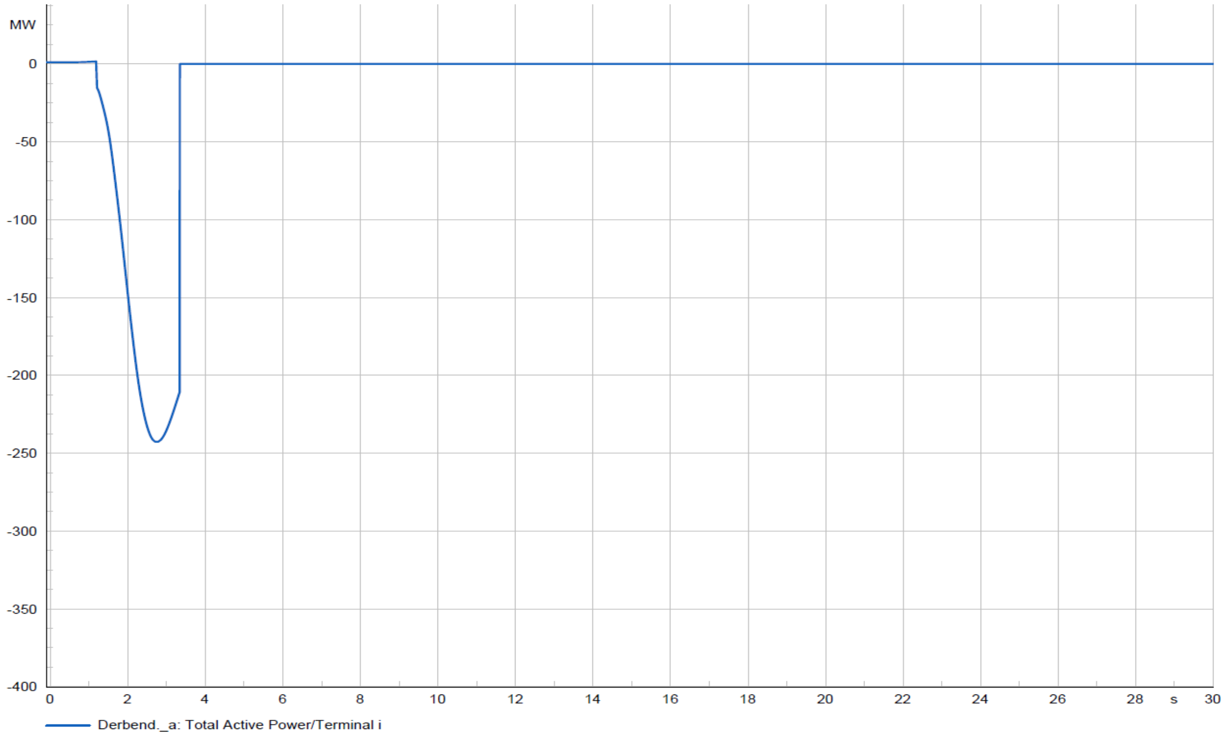


Figure 4.10: Trend showing sudden increase in load on Derbent Power Transmission Line after incident at Sumgait Power Plant

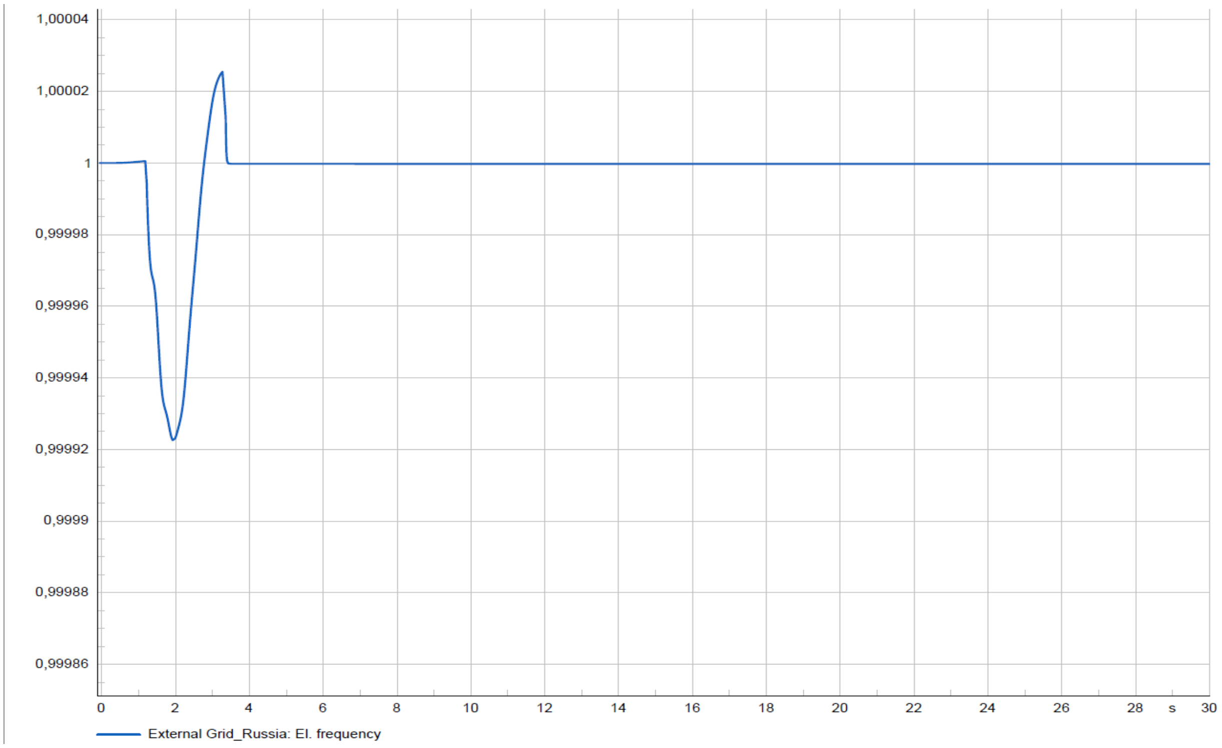


Figure 4.11: Frequency flactuations on the Derbent Power Transmission Line after incident at Sumagit Power Plant

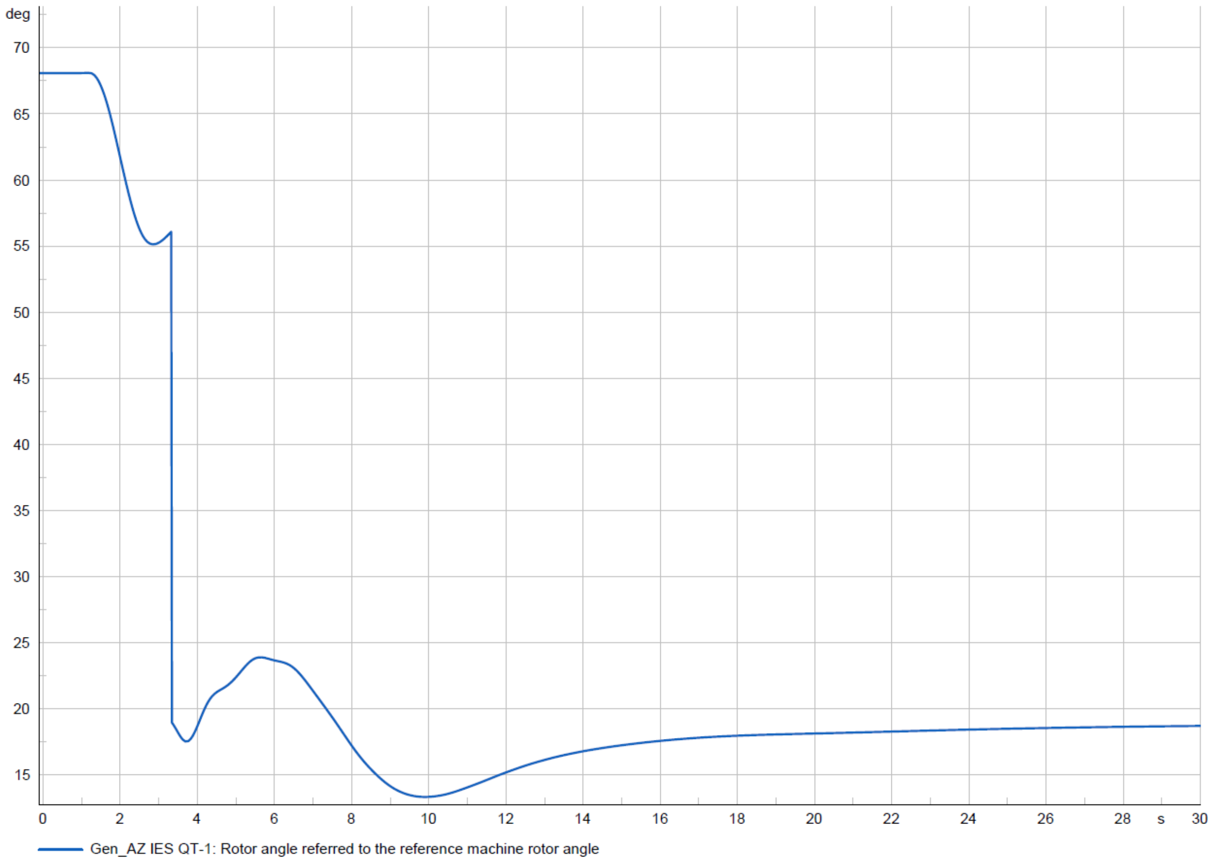


Figure 4.12: Rotor angle fluctuation in the 1st gas turbine generator of the Azerbaijan Power Plant after incident at Sumgait Power Plant.

All simulation results show that with the increase in renewable energy sources in the system, maintaining the stability of the system's frequency will be more difficult in 2205 than in previous years. If the increase in frequency fluctuations is not prevented and new types are not taken, it will become even more severe. Problems in frequency regulation will lead to the complete collapse of the system and disruptions in the work of individual enterprises.

4.3. Comparison of simulation results .

When comparing the results of the two simulations, it can be said that the results are consistent with each other. The differences were only in the opening time of the Derbent Power Transmission Line and the rotor angle of the Azerbaijan Power Plant. The explanation of why these differences arises, by giving separate explanations, is that the Derbent Power Transmission Line takes more load when there is a short circuit in the 2nd block of the Shimal power plant, so the operation of the SPS is directly proportional to the load flowing through this line opens the line in 2.88 seconds. In the second case, the Derbent Power Transmission Line opens a little later, which is because, unlike the first case, the amount of load flowing from Russia to us through the line is less. In the second case, the switch opening time was 3.33 seconds.

As for the differences in rotor angles, the situation is a little different here. Thus, even though the opening of the Sumgait power plant created a load deficit of 270 MW in the system, the deviation in the rotor angle of the 1st generator of the Azerbaijan Power Plant is greater. However, during the shutdown of the second unit of the Shimal power plant, the load is 360 MW.

Table 4.1: Simulation Case Analysis.

Case	Derbent Line Opening Time (s)	Load Deficit (MW)	Rotor Angle Deviation (Location)
Short Circuit at Shimal Power Plant (2nd Block)	2.88	360	Higher at Azerbaijan Power Plant (1st Generator)
Shutdown of Sumgait Power Plant Units	3.33	270	Lower at Azerbaijan Power Plant (1st Generator)

4.4. New proposals to increase the efficiency of frequency regulation in Azerbaijan.

Several projects are being developed in Azerbaijan to regulate the frequency of electricity. The implementation of these projects is becoming a very important point. The reason for this is the increasing pace of renewable energy sources every year and the negative effects they have on the reliability of the system. In this Master thesis, a few proposals made in the direction of frequency regulation and simulations conducted on them will be discussed.

Several projects are being developed in Azerbaijan to regulate the frequency of electricity. The implementation of these projects is becoming a very important point. The reason for this is the increasing pace of renewable energy sources and their negative effects on the reliability of the system. In this master thesis, we will discuss a few proposals made in the direction of frequency regulation and the simulations conducted on them. From the simulation results, we learned that when large-power generators are turned on in the system, the Derbend Power Transmission Line is loaded, which is automatically opened by the SPS to prevent the collapse of the Russian energy system. Although the main purpose of the Derbend line is to maintain a stable frequency in the Azerbaijani energy system, it is not designed to meet sudden load increases. The operating time of the SPS on the Derbend line starts from 1.5 seconds and can be extended depending on the amount of load. Considering all these parameters, other effective methods that have an effect faster than the mentioned 1.5 seconds can be useful for the system.

4.4.1 Installation of a battery system

One of the projects being worked on is the installation of a battery system, which is an innovation in the Azerenergy system. The purpose of this system is to immediately transfer additional energy to the system during power outages by constantly operating the energy system in saturation mode, thereby preventing the frequency drop in the system. This system can be compared to the working principle of the UPS system used to feed power critical equipment in factories. However, a final decision has not been made on where to install this system. Studies are being conducted at the Absheron and Yashma substations, and a final decision has not yet been made on which substation will be more effective. Since Absheron substation is the largest substation in Azerbaijan, it seems that installing a battery system here would be more effective. Absheron substation plays the role of a hub, where several nationally important power transmission lines are connected and distributed. The installation of a battery system at the Yasma substation seems important because, since this substation is close to the Derbent Power Transmission Line, it can prevent the SPS from operating there more quickly. The final decision will be made after field testing and simulations, and then construction and installation work will begin. The project drawings for the installation of the battery system at both substations are shown in figure 4.13 and figure 4.14. Since this project was not approved, this system was not considered in our simulations.

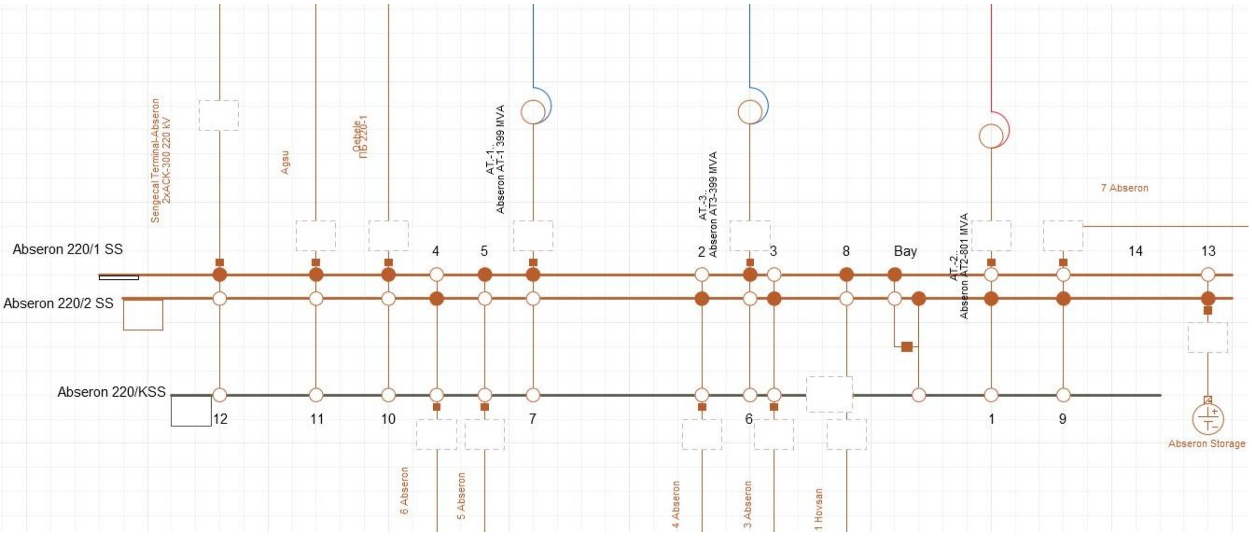


Figure 4.13: Connection diagram of the newly designed battery system to the Absheron substation.

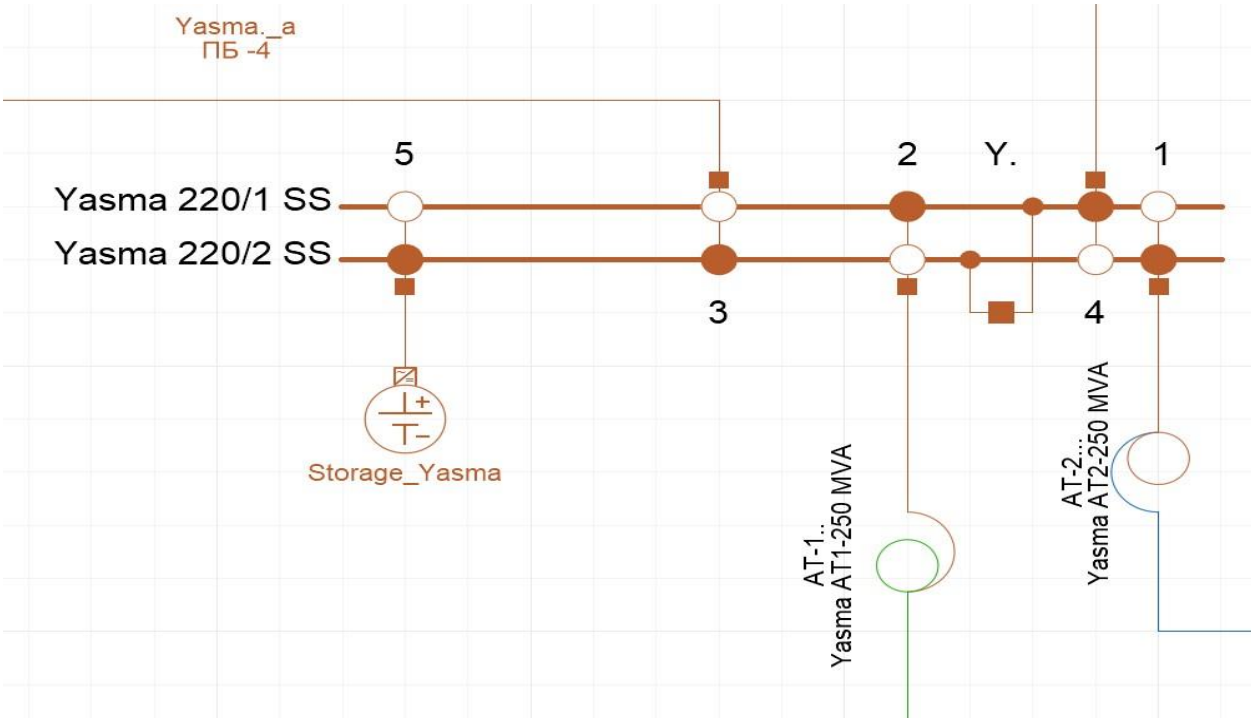


Figure 4.14: Connection diagram of the newly designed battery system to the Yashma substation

4.4.2 Reconfiguration of AGC and PSS systems at Sumgait, Shimal and Jenub Power Plants.

The 3 new power stations built in Azerbaijan in recent years, Sumgait, Jenub and Shimal, are among the 3 main power stations where frequency stability is maintained and PSS and AGC systems respond more effectively. After these stations were built, the input parameters given to the PSS and AGC systems by the third party and manufacturer were kept unchanged, and over time, with the increase in load and production in the system, the AGS and PSS systems can no longer be effective. Systems that cannot operate at full capacity will naturally not be able to respond to system failures at full capacity.

Below are simulations of the results obtained from the adjustment works carried out at the Sumgait and Shimal Power Plants. Adjustment works at the Jenub Power Plant are expected to begin in 2025.

4.4.2.1 Tests Related to the AGC System at Shimal Power Plant.

The ability of the Generation Block to receive the active power setpoint directly via the AGC system was tested with the values sent directly. For this purpose:

- Direct communication with the AGC system was ensured,
- The maximum and minimum load limits of the generation unit were determined in the AGC system
- Signal matching was performed, and the power plant was brought into a state of being able to receive instructions from the AGC system.
- Initially, it was confirmed that communication was ensured by simply checking the parameter transmission without switching the generator unit to Remote Control mode.
- Then, the arrival of the fixed active power setpoint sent via the AGC to the generation unit and the change in the load were investigated. (Figure 4.15)

The compliance of the adjustment parameters and the overall performance at the plant level will be checked separately after the adjustment work in block 2 is completed.

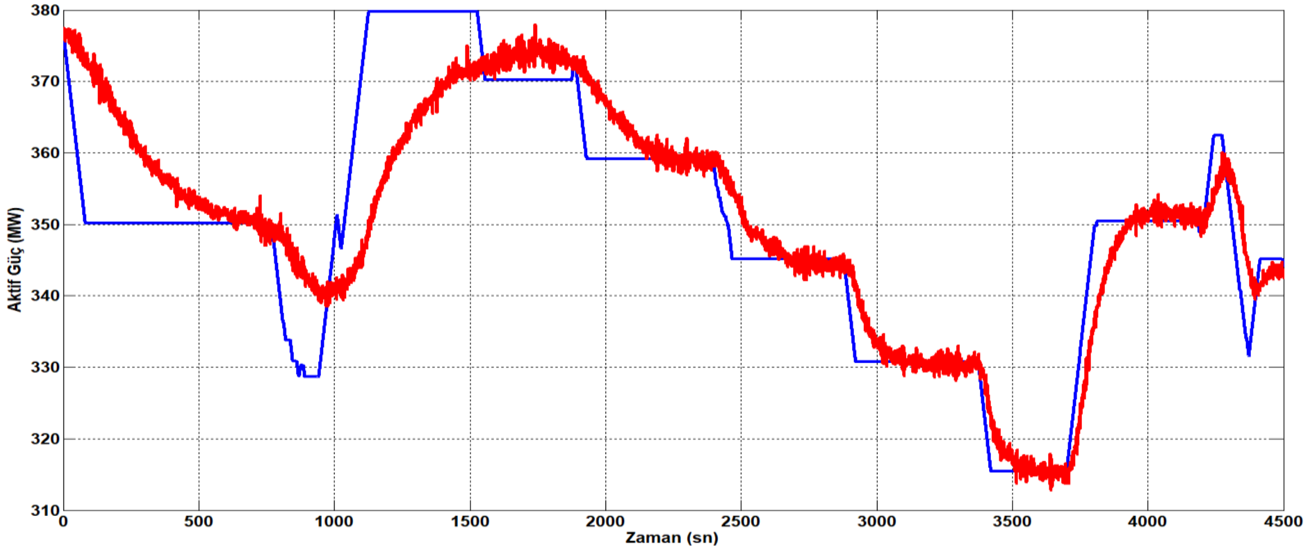


Figure 4.15: AGC test results at Shimal Power Plant, 2nd Block.

4.4.2.2 Frequency Response Tests at Shimal Power Plant.

Frequency response tests were conducted to examine the responses of the Generating Unit to different oscillation frequencies and the performance of the PSS. Figure 4.16 shows the results of the frequency response analyses with and without PSS. It was observed that the PSS parameters of the Generating Unit help in reducing oscillations in the required frequency range.

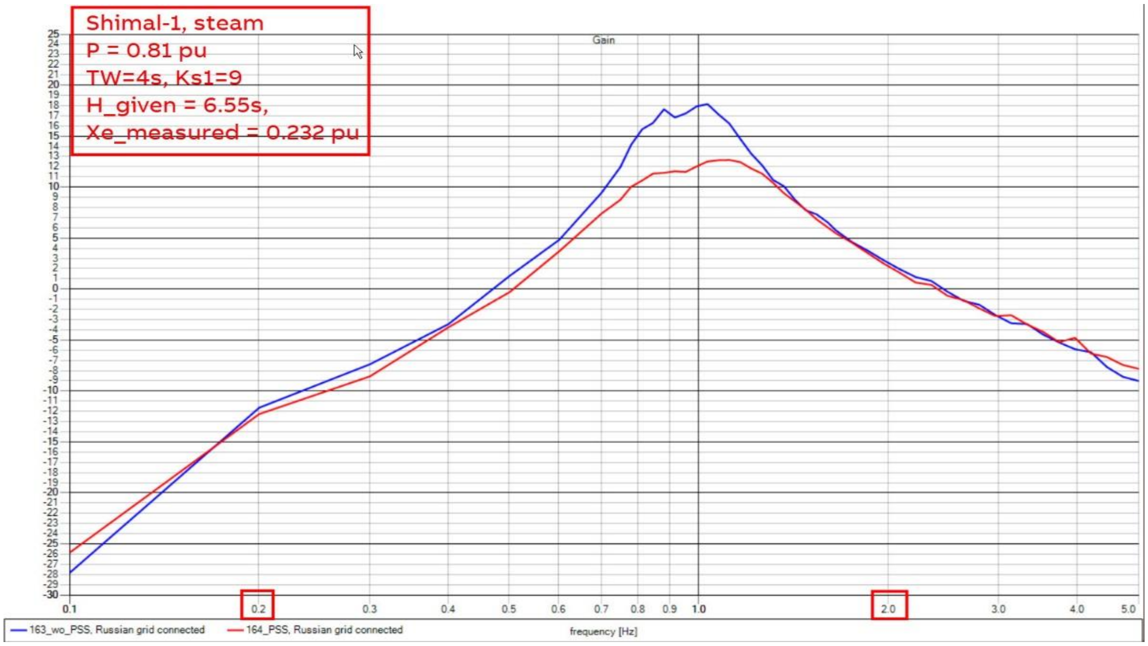


Figure 4.16: Frequency response in situations with and without PSS.

The response of the generation unit observed during the tests was corrected by intervening in the parameter values at the necessary points.

Speed Controller Test Results:

- The current parameters for SGG-1 were tested and improvements were made.
- As a result of the parameters applied after the Generation Unit Regulation System tests, the generator is ready to participate in frequency regulation.
- The connection of the generation unit with the AGC system via SCADA was ensured and the ability to receive parameters was activated.
- After the above-mentioned studies, the first and second frequency regulation system support can be continuously received from SGG.

Impulse System Test Results:

- First of all, improvements were made to the impulse system parameters based on the FSNL test results.
- It was found that the existing PSS parameters were standard values, new PSS parameters were calculated based on the test results and included in the Regulation systems.
- The behavior of the new PSS parameters in both local oscillations and their performance in various oscillation regimes were tested, and it was determined that they responded appropriately to all oscillations in the range of 0.2 Hz - 4 Hz.

4.4.2.3 Frequency Response Tests at Sumgait Power Plant.

The system parameters required to control the active power with AGC instructions through the central SCADA system of the generating unit are organized both at the plant and at the AGC side.

The parameters determined during this adjustment will be reviewed for the purpose of studying the AGC system and optimizing the behavior of the overall system.

An AGC system has been established to regulate the load flow on the 330 kV Derbent line and gas turbines have been connected to the AGC system. The total generation value arriving at the power plant during the corresponding time, the total generation of the power plant and the generation of each turbine are given separately in Figure 4.17

As can be seen from the figure, the power plant is able to execute the instructions given by the AGC system without any problems. At this point, it is possible to see that the "ramp rate" value determined in the AGC system is selected slightly higher than the response speed of the generating unit. This value will be taken into account when adjusting the overall AGC parameters.

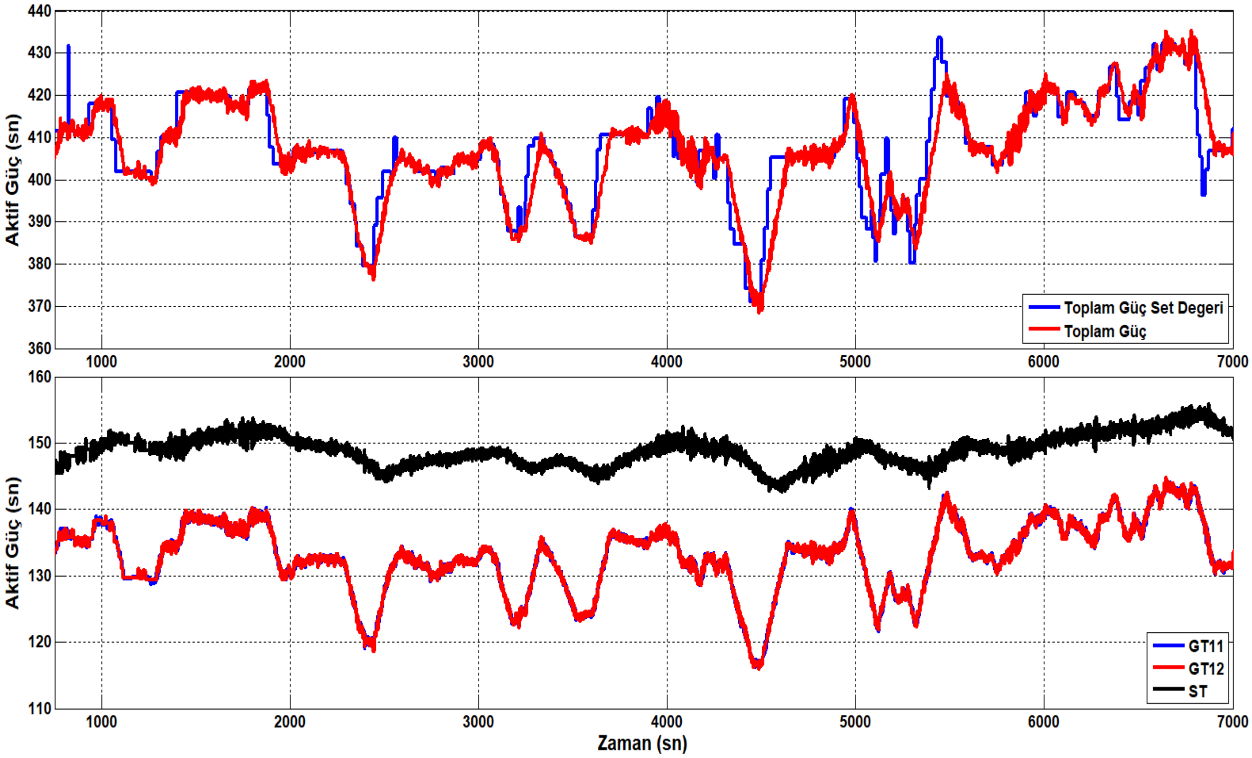


Figure 4.17: AGC related test results at Sumgait Power Plant , Gas Turnine Generators 1 and 2

Additionally, it appears that the load command from AGCE to the power plant is shared equally by the gas turbines and that the units execute the given commands at the same speed.

As a result of these tests, the AGC connection and the overall response of the generating unit are working as expected.

4.4.2.4 Test Results in Isolated Island Mode at Sumagait Power Plant.

In addition to all tests, a short-term isolated island mode test was organized. The purpose of this test is to verify the operation of the control system in isolated island mode (after disconnection to the Russian grid).

For this purpose:

- The 330 kV Derbent line was disconnected from the grid,
- The gas turbines were switched to the frequency speed regulator mode,
- The response of the generation unit to changes in the grid frequency was investigated,
- The frequency speed regulator was turned off and the connection to the Russian grid was restored.

During the tests, the grid frequency varied within the range of +/- 200 mHz. The variation of the active output power of the QT-12 with the expected active output power from the gas turbines during this time is shown in Figure 4.18. As can be seen from the figure, the responses to grid frequency changes are in line with expectations.

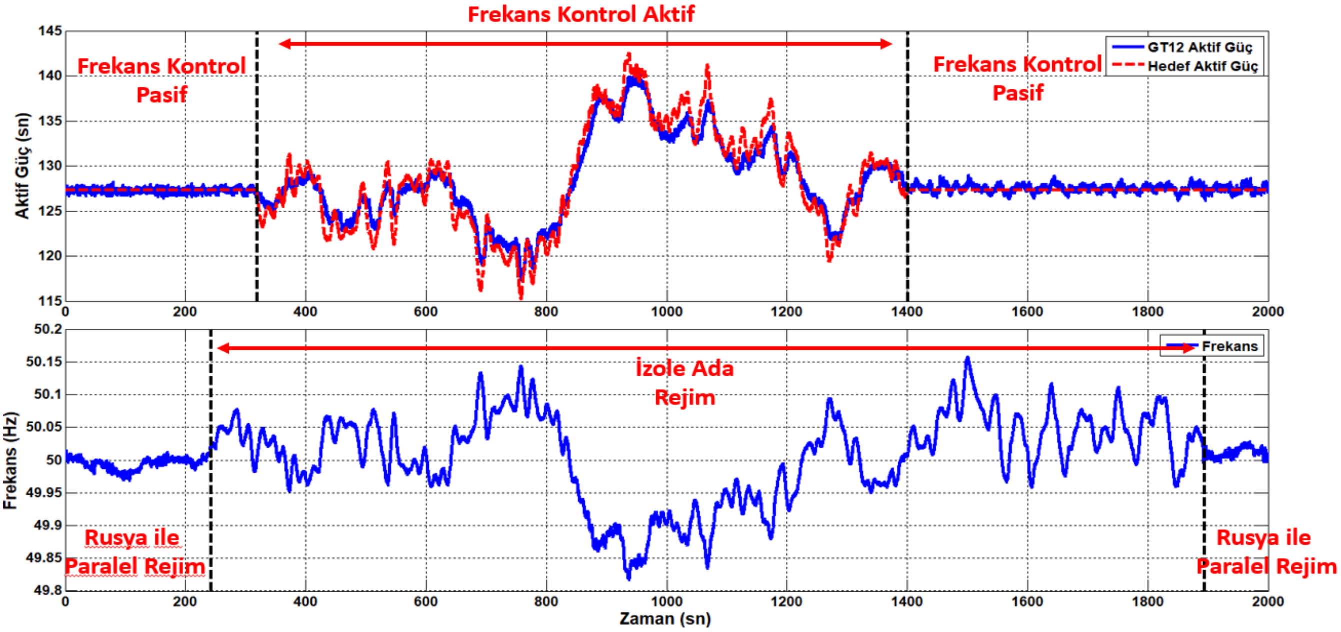


Figure 4.18: Grid frequency and generation unit response results in isolated island mode.

CHAPTER FIVE

DISCUSSION AND CONCLUSION

The integration of renewable energy sources such as wind and solar energy into the power grids of Azerbaijan poses very serious problems in frequency regulation. This master thesis provides detailed information about renewable energy systems, as well as the problems that arise after their integration into the system, their real simulations and partial solutions**.**

Impact of Renewable Integration on Frequency Stability: The simulations show that the introduction of 480 MW of renewable energy into the grid causes significant fluctuations in frequency stability, which reduces the reliability of the system. This instability is due to the temperature-dependent factors and unpredictability inherent in renewable sources, as well as their lack of physical inertia compared to other power plants. For example, simulations of a short circuit in the second unit of the Shimal Power Plant and the shutdown of 2 generators due to a technological process failure at the Sumgait power plant revealed obvious frequency deviations, which highlight the vulnerability of the grid in the presence of renewable energy sources.

Additionally, during large-scale accidents, overloading of the Derbent Power Line can be a very serious problem. The line often experiences sharp load increases to compensate for system failures, but its structural limitations and dependence on external systems such as the Russian grid make new solutions inevitable to increase self-reliance.

Role of Advanced Frequency Regulation Systems: Modern frequency control devices have achieved great results in addressing such problems. New frequency control techniques such as synthetic inertia, fast frequency response (FFR) systems, and battery energy storage systems (BESS) completely fill the gaps left by traditional methods. The simulation results show that the BESS can react quickly to sudden changes in frequency when activated. In addition, changes made to the AGC systems at Sumgait and Shimal Power Plants and additions to their input parameters can accelerate the effective response of the system.

Challenges Identified:

1. **Inertia deficit:** The main disadvantage of renewable energy sources is the lack of natural inertia. In wind and solar power plants, special devices are needed to create inertia. Although these are built with electronic systems, they are not as effective as traditional methods in maintaining a stable frequency**.**

2. **Risks of network overload:** Overloading of power transmission lines because of accidents has a negative impact on the energy system of our country and neighboring countries, especially Russia. An example of this is the Derbent power transmission line.

3. **Limited AGC and PSS Tuning:** Although the use of AGC and PSS systems used in large power plants is very useful, their lack of modification depending on the load and production creates many problems.

4. **Delayed SPS Activation**: Although the use of special protection systems (SPS) and the time they take to turn on and turn on the power transmission lines is very short; it is very important to find and develop devices that work faster than this

Proposed Solutions:

1. Battery Energy Storage Systems (BESS)

Installing BESS systems and its installation at one of the nationally important Absheron and Yashma substations can solve the problems of the Azerbaijani energy system and its frequency regulation, reducing our country's dependence on neighboring countries in this matter. Therefore, the installation of this system is an invaluable proposal. If this project is implemented, it will directly support the operation of AGC and PSS systems.

2. AGC and PSS Reconfiguration

Reconfiguration of AGC and PSS systems is mandatory in large power plants. Simulation results of Sumgait and Shimal power plants show that optimized regulation increases the ability of the network to respond to disturbances. Conducting comprehensive regulation studies and applying adaptive algorithms can further improve the stability of the system. These regulations should not be limited to Sumgait and Shimal Power Plants. It is important to carry out these works in the newly commissioned Jenub Power Plant and obtain real results.

Future Considerations:

1. **Policy and Regulatory Frameworks:** Policymakers should develop regulations that incentivize investments in advanced frequency regulation technologies and renewable integration.
2. **Capacity Building:** Training programs for system operators and engineers should focus on managing hybrid grids with significant renewable contributions.
3. **Research and Development:** Further research is required to explore emerging technologies such as adaptive neuro-fuzzy inference systems (ANFIS) and artificial neural networks (ANN) for dynamic frequency control.
4. **Scenario Planning:** Extensive scenario-based simulations will help anticipate potential disruptions and prepare for diverse operational conditions, including extreme weather events.

Conclusion:

When we look at the development of this Master thesis, we see that many complex problems and many cases that have a negative impact on the frequency of the energy system have been investigated and solutions have been given. In the literature review section of the Master thesis, deep and detailed information has been provided, starting from traditional frequency regulation methods to more modern fuzzy logic systems. In addition, general information has been provided about the current energy system in Azerbaijan, and the protection and automation equipment that play a role in maintaining a stable frequency has been discussed. The principles of operation of SPS systems and the input parameters of these protection systems are shown in the tables. The DigSILENT Powerfactory simulation program, which organizes the management of the Azerenergy system and its projects, was used as a simulation tool. The main goal of the simulation is to determine the frequency deviations in the system because of the integration of renewable energy sources into the system from 2025, and as a result, to monitor the changes occurring in the system's base stations and power transmission lines. As a result of research and simulations, it has become clear how important the Derbent power transmission line is for our system. As a main goal, new proposals have been given in this master thesis to eliminate the dependence of the country's energy system on foreign countries. For example, the installation of new battery systems, the reconfiguration of AGC and PSS systems can be cited. In the coming years, increasing production capacity to meet the energy demands of the growing industrial enterprises in the country will be one of the main issues, and at the same time, the high-quality indicators of the energy delivered to the users should be the main target.

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