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Title:

ANALYSIS OF FREQUENCY RESPONSE OF THE ALGERIAN POWER SYSTEM.

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I. Abstract:

The frequency response of a power system is a key parameter that reflects its stability and ability to maintain a consistent supply of power. This project presents an analysis of the frequency response characteristics of the Algerian power system, with a focus on frequency control techniques, reserve capacity, flywheel battery and battery energy storage system (BESS) integration. Furthermore, this analysis explores the role of reserve capacity in frequency regulation. Reserve capacity is spare generation capacity that stands by to deal with sudden frequency excursions or imbalances between supply and demand. The assessment focuses on the adequacy of reserve capacity in the Algerian grid and its impact on frequency stability. Finally, the project considers the integration of Battery Energy Storage Systems (BESS) and flywheel battery as a potential solution to improve frequency response capability.

II. Dedication:

I dedicate this work to my loving parents, whose unwavering support, sacrifices, and belief in me have been the driving force behind my accomplishments. Your unconditional love and encouragement have been the pillars of my success. I am forever grateful for your guidance and for instilling in me the values of hard work and perseverance.

To my two brothers, Idir and Rayane, thank you for always being there for me. Your constant encouragement, shared laughter, and support have made this journey more meaningful. I am fortunate to have you as my brothers.

To my extended family, thank you for your continuous support, understanding, and belief in me. Your presence and encouragement have provided me with the strength and motivation to overcome challenges and pursue my dreams.

To my dear friends, Rahim and Salah, your friendship has been a constant source of inspiration and support. Thank you for being there through thick and thin, for your unwavering belief in my abilities, and for pushing me to achieve my best. Your friendship is truly cherished.

Finally, to everyone who has touched my life in one way or another, whether through a kind word, a helping hand, or a moment of inspiration, I extend my heartfelt gratitude. Your presence has made a significant impact on my journey, and I am forever thankful for your support.

Hamam Lyes.

Dedication:

I want to dedicate my work to:

My lovely parents who have always inspired and supported me with everything I needed, their unconditional love,care and guidance ,

My brothers: Hichem, Madjid, Amine, Mohamed and my beloved sister who fill our days with joy and laughter,

My grandparents for their care and kindness,

My uncles and their wives,My aunts and their husbands ,

To my Aunt Mahjouba who passed away few months ago "Allah yrhamha"

All of YKHLEF ABDESSEMED and MOUSSA family

My cousins and neighbours,

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All my former teachers in the different levels of study with their contribution in forming me to be the man I am now,

To power option promotion,

To IGEE members,

Written with love and open heart,

May Allah preserve you all,

Yours ABDOU,

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VI. Definitions and abbreviations :

- **AGC (Automatic Generation Control):** Application allowing the distribution of the production on the groups which are under its control by regulating the frequency as well as the exchange programs on the international interconnection lines.

- **Blackout:** Total or partial absence of voltage on part or the entire electrical network.

- **Black start:** Ability of a production group to start without an external power supply, to couple on a de-energized network, to operate in an isolated network (frequency and voltage adjustment capacity) and to gradually replenish network users.

- **IEC:** International Electro-technical Commission

- **Load:** Any installation that consumes active and/or reactive power.

- **Connection circuit:** All the equipment that makes up the connection between the User's installation delivery station and the network.

- **Customer:** End customer, Distributor or commercial agent.

- **Cogeneration:** Combined production of electricity and heat.

- **Regulatory Commission:** Commission for the Regulation of Electricity and Gaz (CREG), an organization responsible for ensuring compliancewith technical, economic and environmental regulations, consumer protection, transaction transparency and non-discrimination between operators.

- **Metering:** Recording by measuring equipment, per period of time, of the quantity of active or reactive energy injected or taken from thenetwork.

- **Congestion:** State of saturation of an electrical work of the network notallowing carrying out the transport or the distribution of all the quantities injected or withdrawn, taking into accounting the characteristics and the performances of the equipment of the network.

- **Distributor:** Any natural or legal person ensuring the distribution ofelectricity or gas with the possibility of sale.

- **Renewable energies:** Form of electrical energy obtained from the transformation of solar radiation, wind energy, geothermal energy, organic waste, hydraulic energy and biomass utilization techniques.

- **ENS (Energy Not Supplied):** Energy not supplied over a given period.

- **Measurement equipment:** Any equipment intended for metering and/or measurement, such as meters, measuring devices, measurement transformers or related telecommunications equipment in order to enable the manager of the Electricity Transmission Network to fulfill its missions.

- **Manager of the electrical system concerned:** Operator in charge of coordination between the production facilities and the electrical network. In particular, it monitors the permanent balance between consumption andproduction, the security, reliability and efficiency of the electricity supply.

- **Electricity production group:** Physical unit comprising one (or more)generator(s) which produces electricity.

- **IEEE (Institute of Electrical and Electronic Engineers):** Institute of Electrical and Electronic Engineers. Organization which aims to promote knowledge in the field of electrical engineering.

- **Islanding:** Situation in which a production group, after a sudden disconnectionfrom the network, continues to supply its auxiliaries so that it can be available for reconnection to the network.

- **Production installation:** Equipment intended for the production of electricalenergy which includes one or more production groups as well as auxiliary equipment (evacuation station, production auxiliaries, etc.).
- This equipment is grouped together on the same site and operated by the same Producer.

- **Non-synchronous production installation**: Installation for the production of electrical energy using one or more current converter production units or asynchronous machines (including double-fed asynchronous machines, synchronous or asynchronous machines connected to the network by a powerconverter).

- **Synchronous production facility**: Installation for the production of electricalenergy using one or more synchronous generators directly connected to the electrical network (without current converter).

- **Interconnection**: Set of links between two or more networks.

- **LOLE (Loss Of Load Expectation):** Number of hours over a period of oneyear for which peak demand cannot be covered.

- **LOLP (Loss Of Load Probability):** Probability of not being able to coverthe annual peak load demand of the electrical system.

- **Adjustment Mechanism**: Mechanism put in place by the System Operatorin order to:
- Ensuring the production-consumption balance in real time;
- Resolve congestion in the Electricity Transmission Network.

- **Production fleet:** All the electricity production groups connected tothe network.

- **Losses:** Active energy consumption caused by the use of theElectricity Transport Network.

- **Reconstruction plan of an Electricity Transmission Network:**Process of reconstitution, in stages, of the entire Electricity Transmission Network after a total or partial blackout.

- **Producer:** Any natural or legal person who produces electricity.

- **PSS (Power system stabilizer):** Equipment that controls the output of the exciter via the voltage regulator in order to dampen the power oscillations of synchronous machines.

- **Active power:** Electrical power that can be transformed into other forms ofpower such as mechanical, thermal, acoustic.

- **Maximum continuous power (Pm):** Maximum power that an installationcan provide continuously.

- **Minimum technical power (Pi):** Minimum power that an installation canprovide continuously in automatic mode.

- **Nominal power (Pnom):** Power developed by a production facility operating under nominal site conditions.

- **Primary adjustment:** Adjustment ensured by the speed regulation loops ofthe Production Units allowing automatic and rapid (in a few seconds) and decentralized correction of the differences between production andconsumption.

- **Secondary regulation:** Centralized regulation located at the national controlcenter (dispatching) which allows the frequency of the electrical system to bebrought back to its nominal value and the inter-zone power flows to their programmed values.

- **Tertiary adjustment:** Any manual change of the operating point of the production Units constituting the tertiary reserve (minute reserve) with the aimof restoring the secondary reserve in due time (less than 15 minutes).

- **Electricity network:** Infrastructure made up of all the works of the Electricity transport network and the Electricity distribution network.

- **Isolated electrical network:** Small network not electrically synchronized to alarge interconnected network. This definition excludes the Adrar network.

- **Marginal reserve:** Additional Electricity production capacity installed in relationto the peak load for the year, it is expressed as a percentage of the peak load.

- **Primary reserve:** Power reserve active upwards or downwards on the generation facilities taking part in the Primary Frequency/Power Adjustmentand allowing the latter to be implemented.

- **Secondary reserve:** Power reserve active upwards or downwards on theproduction facilities participating in the Secondary Frequency/Power Adjustment and allowing the latter to be implemented.

- **Tertiary reserve:** Power reserve that can be mobilized in less than 15 minutes.The tertiary reserve provides the contribution to the secondary frequency control service in order to cope with the failure of the largest electricity production group connected to the electricity transport network.

- **Black start service:** Service ensuring the availability of means of production capable of starting and delivering active power without havingenergy from a network.

- **Droop:** One of the parameters of the speed regulator of a production group. It is equal to the quotient of the relative value of the quasi-stationaryfrequency difference of the network on the relative variation of the power of the group following the action of the primary speed regulator. This quotient is dimension less and is usually expressed in %.

- **Electrical system:** All of the electricity production, electricity transmission anduser facilities interconnected to the electricity transmission network.

- **Remote control:** Automatic Frequency-Power control system to ensure the production-consumption balance as well as compliance with the exchange programon international interconnections.

- **Control zone:** Zone in which the operator of the electricity production-transmission system controls the permanent balance between electricity supply and demand, taking into account the exchanges of active power with neighboring control zones.

- **Duration of supply:** The Primary Control Power must be supplied until the Power Difference is completely offset by the Secondary Reserve of the Control Zone in which the Power Difference has occurred.

- **Accuracy of Frequency Measurements:** For Primary Control, the accuracy of frequency measurements used in the Primary Regulators must be at least 10 mHz.

- **Insensitivity of the regulators:** The insensitivity range of the Primary Regulators should not exceed ±10 mHz. When deadbands exist on specific controllers, they should be reduced as much as possible.

- **Automatic tuning:** In order to maintain the Zone Adjustment Deviation (ACE) near zero, the tuning must be automatic. Each control area operator must use a device such as the Automatic Production Control (AGC function) to automatically request control reserves. The remote-control system (AGC function) is used to limit the amplitude of the Zone Adjustment Deviation (ACE).

- **Manual adjustment:** In the event of failure of the AGC, the operator of the affected adjustment area will have to use manual adjustment to adjust the production in order to maintain the scheduled exchanges.

- **BESS:** Battery energy storage system.

- **FESS:** Flywheel energy storage system.

VII. Content:

VIII. Introduction:

The Algerian power system plays a vital role in meeting the energy needs of the country's industries, businesses, and households. It consists of a complex network of power generation sources, transmission lines, and distribution networks that work together to ensure the reliable supply of electricity. Maintaining a stable frequency is crucial for the efficient operation of this interconnected system.

Frequency is a fundamental parameter in an electrical power system, representing the number of cycles per second of alternating current. In a synchronized system, such as the Algerian power system, maintaining a stable frequency is essential for maintaining grid stability and preventing cascading failures. Any significant deviation from the nominal frequency can result in disruptions, equipment damage, and even blackouts.

The main objective of this thesis is studying and analyzing the frequency response of the Algerian power system., which is a crucial aspect of assessing the stability and reliability of the country's electrical grid. The frequency response analysis provides valuable insights into how the system behaves under varying power demand conditions, disturbances, and potential contingencies.

The analysis of the frequency response involves examining the system's behavior in terms of its ability to maintain a stable frequency under different operating conditions. This analysis typically includes studying the system's response to changes in load demand, generation imbalances, and potential disturbances caused by faults or sudden changes in generation.

The frequency response analysis helps identify the system's stability limits, potential vulnerabilities, and areas for improvement. It enables power system operators and engineers to assess the adequacy of generation resources, control strategies, and protection schemes. By understanding the system's frequency response characteristics, appropriate measures can be implemented to enhance the system's resilience and ensure reliable operation.

In the context of the Algerian power system, frequency response analysis plays a vital role in the ongoing efforts to modernize and optimize the grid infrastructure. As the demand for electricity continues to grow and renewable energy integration expands, understanding and managing frequency stability becomes even more critical.

The main objectives of this study are providing the analysis of the frequency response of the Algerian power system. In addition to presenting implementation control methods of frequency response and the different configurations that affect the frequency stability of the system. Then, analyzing the limitation of the current implementation methods and suggesting a modern control techniques to improve frequency stability control. Finally, the investigation on the energy storage systems with simulating the flywheel energy storage system, and analyzing the penetration of this technique in the modern power system.

The thesis is presented as the following:

Chapter one:

This chapter focuses on providing an overview about Sonelgaz power system at its different levels and the different statistics of the company.

The different power plant owned by the Algerian company has been reviewed providing the needed background knowledge needed for the second chapter.

Chapter two:

In this chapter, frequency control methods were studied, in addition to the implementation methods of the primary frequency response by explaining their principle of working, their different characteristics. The different types of power reserves are investigated as well in this chapter.

Chapter three:

In this chapter, the fundamental elements of implementation were studied. Then, we did investigate the challenges associated with the implementation. In addition to the emerging methods for primary frequency response. Finally, potential solutions to the challenges and limitations of primary frequency response implementation are evaluated, in addition to the feasibility of these solutions.

Chapter four:

In this chapter, the simulation of flywheel energy storage system (FESS), and battery energy storage system (BESS) are covered. In addition to the effect of these energy storage system on the stability of frequency in the electrical system. Finally, a MATLAB script which will help in analyzing the frequency of the power system is presented.

Chapter1: Presentation of the Algerian power system.

1.1. Introduction

Sonelgaz is a state-owned corporation in Algeria that engages in the energy industry. The firm was established in 1969 and is based in Algiers, Algeria. Its primary business is the generation, transmission, and distribution of electricity and natural gas throughout the country. [1]

Sonelgaz is a significant contributor to the Algerian economy, supplying power and natural gas to millions of people around the country. The firm operates a huge network of power plants, transmission lines, and distribution networks to guarantee that its users have access to dependable and economical electricity.

In recent years, Sonelgaz has made major investments in renewable energy sources like solar and wind energy to reduce the country's dependency on fossil fuels. Sonelgaz's renewable energy projects have helped diversify Algeria's energy mix and positioned the company as a leader in developing clean energy solutions.

Sonelgaz is devoted to corporate social responsibility and supports a variety of activities aimed at fostering sustainable development and social welfare throughout Algeria, in addition to its energy operations.

Sonelgaz is a prominent player in Algeria's energy industry, committed to offering its consumers trustworthy and sustainable energy solutions. Because of its emphasis on renewable energy and commitment to social responsibility, the company is crucial to Algeria's economic development and sustainability.

1.2. Sonelgaz biography

Sonelgaz runs 26 power plants in Algeria, with a total capacity of around 18,500 MW [1]. The company's portfolio includes both thermal and renewable power-producing plants. Thermal power stations use natural gas, oil, and coal, whereas renewable power plants use solar and wind energy.

1.2.1. Electric Power Transmission

Sonelgaz has a transmission network that spans more than 14,500 kilometers across Algeria. [1] The organization has a strong and dependable transmission infrastructure that aids in the effective delivery of power to its clients.

1.2.2. Electric Power Distribution

Sonelgaz operates an electric power distribution network that serves approximately 1,500 villages and cities throughout Algeria. The corporation has about 10 million clients, including both residential and commercial users. [1] To guarantee that its consumers have access to dependable and inexpensive power, the firm has invested considerably in its distribution infrastructure.

Statistics [1]:

• Sonelgaz operates 26 power plants with a total installed capacity of roughly 18,500 MW.

• The corporation has a 14,500-kilometer transmission network.

• Sonelgaz has a distribution network in approximately 1,500 Algerian towns and cities.

• The company's client base includes over 10 million people.

• Sonelgaz has spent about DZD 1,500 billion in infrastructure for power generation, transmission, and distribution.

1.3. Classification of power plants

A power plant is a facility that converts primary energy sources such as coal, natural gas, nuclear energy, or renewable energy sources such as solar or wind into electrical power. In a power plant, the energy from a primary source is converted into mechanical energy, which is subsequently converted into electrical energy via a generator. A power plant's electrical energy is later transported to customers via an electrical grid, where it is utilized for lighting, heating, cooling, and powering numerous gadgets and machinery. Power plants are critical to contemporary society, supplying electricity to homes, companies, and industries.

There are two forms of electric energy generation: conventional and non-conventional energy generation.

Power plants are classed into numerous groups depending on various characteristics such as the kind of fuel used, the technology used to create energy, and the plant's size. The most popular method to categorize power plants is by the fuel they utilize, which can include fossil fuels such as coal, natural gas, and oil, as well as renewable sources such as solar, wind, hydro, and biomass.

Another approach to categorizing power plants is according to the technology used, which might include thermal power plants, renewable energy power plants, and nuclear power plants. Thermal power plants create heat from fossil fuels or biomass, which is then used to generate steam, which powers a turbine to generate electricity. Renewable energy power plants create electricity without the need for fossil fuels by using renewable energy sources such as sun, wind, and hydro. Nuclear power plants create heat from nuclear processes, which is then utilized to drive turbines and generate electricity.

1.3.1. Non-Conventional Sources of Energy

Non-conventional energy sources are those that are not sourced from typical fossil fuels such as coal, oil, and natural gas. They rely instead on renewable energy sources including solar, wind, hydro, geothermal, tidal, and biomass. These energy sources are referred to be unconventional since they are not the principal energy sources that have historically been used to power human activities. Non-traditional energy sources are becoming more essential as the globe strives to move to more sustainable and ecologically acceptable types of energy generation. They have various benefits over traditional energy sources, including lower greenhouse gas emissions, less reliance on foreign oil, and increased energy security.

1.3.1.1. Solar Energy

Algeria has one of the greatest levels of solar radiation in the world, particularly in the south. As a result, the country has enormous potential for solar energy growth. Algeria has created many large-scale solar power plants, including the Hassi R'Mel integrated solar combined-cycle power plant and the Djelfa photovoltaic power plant.

Figure1.1: Batna photovoltaic power plant. **[1]**

1.3.1.2. Wind Energy

Wind energy is produced by harnessing the wind's energy to turn turbines and generate electricity. Wind moves wind turbine blades, which in turn rotate a shaft attached to a generator. The mechanical energy from the rotating shaft is subsequently converted into electrical energy by the generator. Wind energy is an ecologically acceptable alternative to traditional fossil fuels since it is a clean and renewable source of energy that does not create damaging pollutants or greenhouse gases. Wind energy can be captured onshore, offshore, or in isolated places where the wind resource is continuous and powerful.

Figure 1.2: Kabertene wind power plant in Algeria. **[1]**

Algeria has abundant wind resources, notably along its coastline. The Algerian wind power station has a capacity of 10.2 MW. By 2030, the government hopes to have installed 4,500 MW of wind generating capacity. The country is actively developing many wind powers projects, including the Adrar wind farm and the Boughezoul wind farm.

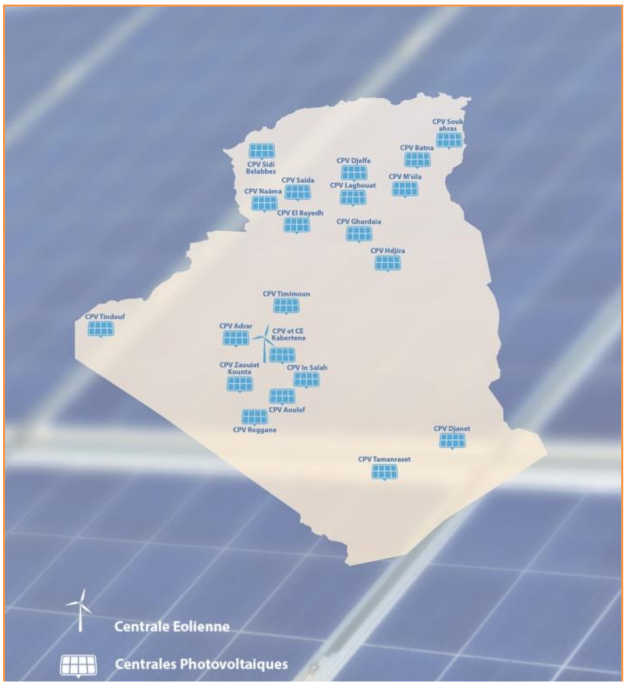


Figure 1.3: photovoltaic and wind power plants. **[1]**

This energy is produced by the following types of plants [**1**]:

- Photovoltaic power plant: 356.1 MW.
- Wind power plant : 10.2 MW.

1.3.2. Conventional Sources of Energy

Conventional power plants are large-scale facilities that generate electricity from fossil fuels like coal, oil, or natural gas. Steam turbines are often utilized in these plants to transform the energy created by the combustion of fossil fuels into mechanical energy, which is subsequently used to generate electricity.

The Algerian Company of Electricity and Gas - Production of Electricity is the country's longest-running electricity producer.

The company is responsible for the maintenance and operation of its power stations, which represent Algeria's largest production park, with a current installed power of more than 18 GW, to reach around 24 GW by 2030, [**1**] consisting of four devices of varying power levels: steam turbines, gas turbines, hydraulic and combined cycles.

1.3.2.1. **Thermal power plants**

Thermal power plants are a form of conventional power plant that creates electricity by the combustion of fossil fuels such as coal, oil, or natural gas. Steam turbines are utilized in these plants to transform the energy created by the combustion of fossil fuels into mechanical energy, which is subsequently used to generate electricity. Thermal power plants are frequently utilized because of their great capacity and efficiency, making them one of the most common types of power plants in the world.

Thermal power plants are classified as coal-fired, oil-fired, or gas-fired. Natural gas-fired thermal power stations are Algeria's principal source of energy generation. These power plants use natural gas to heat water and generate steam, which powers turbines and generates electricity. Natural gas-fired thermal power plants are noted for their high efficiency and low emissions when compared to coal and oil-fired power plants.

Thermal power plants need a large quantity of fuel to create electricity, which can result in high operational costs as well as greenhouse gas and other pollution emissions. They are, however, dependable and may generate enough electricity to power entire cities or areas.

1.3.2.2. Combined cycle power plants

A combined cycle power plant uses both a gas turbine and a steam turbine to generate energy. This facility is more efficient and emits less pollutants than standard thermal power plants.

Natural gas is used in a gas turbine to create mechanical energy, which is then utilized to drive a generator and generate electricity in a combined cycle power plant. The gas turbine exhaust gas is then transported via a heat recovery steam generator (HRSG), which warms the water to make steam. The steam is then utilized to power a steam turbine, which generates more energy.

The major benefit of combined cycle power plants over typical thermal power plants is their better efficiency. They may attain efficiencies of up to 60%, allowing them to produce more power from the same quantity of fuel. Furthermore, combined cycle power plants emit fewer greenhouse gases and other pollutants than standard thermal power plants.

Algeria has many combined cycle power plants, notably the Hassi R'Mel integrated solar combined-cycle power plant, which is one of Africa's largest. This plant, which has an installed capacity of 1,350 MW, [1] generates electricity using both natural gas and solar energy.

Combined cycle power plants are becoming more common as countries aim to reduce their dependency on fossil fuels and switch to cleaner energy sources.

1.3.2.3. Hydraulic:

Hydraulic energy, commonly referred to as hydroelectric power, is a type of renewable energy produced by the movement of water. Typically, this energy is captured by building dams or other structures across rivers and streams to form a reservoir of water. The rushing water's force is then employed to drive turbines and create power.

Hydraulic energy is a significant form of electricity generation in Algeria. There are numerous big hydroelectric power facilities in the nation, notably the Djorf Torba and Tichy Haf dams, which have a combined capacity of over 3,000 MW. [1] These power facilities supply an important share of Algeria's electricity, particularly during peak demand periods.

1.3.3. Sonelgaz power plants [1]:

- Electrification rate: 98%
- Installed capacity: 24,561 MW
- Transmission network: 32,720 km
- Distribution Network: 367,573 km
- Length of the electricity network: 400,293 km
- Number of customers: 10,983,538.

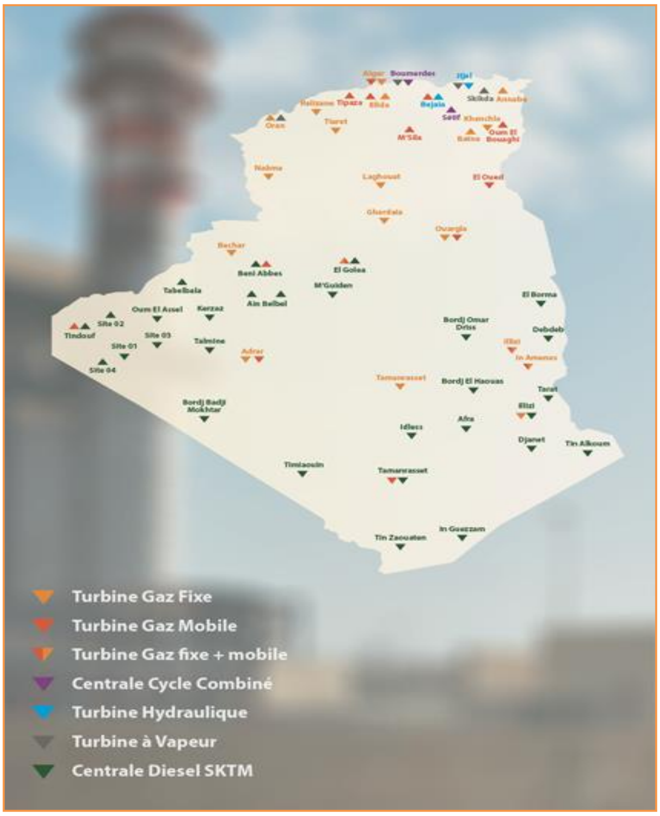


Figure 1.4: Map of power plants. [1]

In 2022, Sonelgaz - Production of electricity operates and maintains 59 power plants of different types of electricity production [1]:

- ❖ 05 Steam Thermal Power Plants (TV), 14 TV generators;
- ❖ 30 Gas Thermal Power Plants (GTP), 83 fixed GTP units;
- ❖ 14 Mobile Gas Turbine Plants (TGM), 50 mobile TG units;
- ❖ 02 Combined Cycle (CC) single shaft plants (01TV+01TG), six (06) CC units;
- ❖ 04 Combined Cycle Power Plants (CC) multi-shaft (02TG+01TV), eight (08) CC units;
- ❖ 04 Hydraulic Turbine (TH) plants, 09 TH units.

In addition to these plants, our company has been operating and maintaining the HassiBerkine gas turbine plant (4 x 110 MW) for Sonatrach since 2001.

The company has a production park with different technologies such as [1]:

- ❖ Gas Turbines Technology General Electric Type Frame 5 (20 units), Frame 6 (6 units), Frame 9 (18 units), 9FA (38 units);
- ❖ Steam Turbines General Electric Technology Type A10 (14 units);
- ❖ Gas Turbines ALSTOM GT13E2 Technology (05 units);
- ❖ Gas Turbines Siemens Technology Type V94.2 (13 units) and V94.3 (15 units);
- ❖ Steam Turbines Siemens Technology Type SST5 (06 units);
- ❖ Mobile Gas Turbines (54 units) General Electric Technology Type TM 2500+ and PWPS Type FT8.

1.4. The structure of the power system

The power system of Sonelgaz is organized into three main components: generation, transmission, and distribution.

1.4.1. Generation

The generation component of Sonelgaz's power system includes the power plants that produce electricity. Sonelgaz operates a diverse range of power plants, including thermal, renewable energy, and hydropower plants, to meet the energy demands of Algeria. These power plants generate electricity that is sent to the transmission network for distribution to customers.

1.4.2. Transmission

The transmission component of Sonelgaz's power system includes the high-voltage power lines that transport electricity over long distances from the power plants to the distribution networks. The transmission network is responsible for ensuring that the electricity is delivered to the distribution networks with minimal loss of energy. Sonelgaz operates a vast network of transmission lines that spans the country and connects the various power plants to the distribution networks.

1.4.3. Distribution

The distribution component of Sonelgaz's power system includes the low-voltage power lines that deliver electricity from the transmission network to customers. The distribution networks are responsible for ensuring that the electricity is delivered to customers safely and reliably. Sonelgaz operates a vast network of distribution lines that spans the country and delivers electricity to millions of customers.

Sonelgaz's power system is designed to ensure that energy is generated, transmitted, and supplied to customers across Algeria in a safe and reliable manner.

1.5. The main structures for electric power systems

There are three main structures for electric power systems:

1.5.1. Radial Structure

A radial power system is the simplest and most common structure for power systems. It consists of a single power source (such as a power plant) that sends electricity out in one direction along a single path to the load (such as homes or businesses). The disadvantage of this structure is that it is vulnerable to power interruptions, as any fault or outage in the transmission line can disrupt power delivery to all downstream loads.

1.5.2. Loop Structure

A loop power system is a more complex structure than the radial structure. It has multiple power sources and multiple paths for power transmission. In a loop system, there are two or more paths for electricity transmission, which can provide a degree of redundancy and fault tolerance. However, the loop structure is more expensive to build and maintain than the radial structure.

1.5.3. Mesh Structure

A mesh power system is the most complex structure for power systems. It has multiple power sources and multiple transmission paths, creating a highly redundant network. A mesh structure can provide high levels of reliability and fault tolerance, as electricity can be rerouted through multiple paths if there is a fault or outage in one of the transmission lines. However, the mesh structure is the most expensive to build and maintain of the three structures.

1.6. Conclusion

In conclusion, Sonelgaz's power system is a critical component of Algeria's energy infrastructure, providing reliable and affordable electricity to millions of customers while promoting sustainable development. The company's focus on renewable energy and commitment to reducing its carbon footprint make it a key player in the country's efforts to transition to a more sustainable energy system.

One crucial aspect of power system operation is frequency response control, which refers to the ability of the power system to maintain a stable frequency in the face of changes in supply and demand. Frequency response control is essential to ensuring that the power system remains stable and reliable and that disruptions are minimized.

The next chapter will delve into frequency response control in more detail, exploring the various strategies used to achieve it, such as deploying energy storage systems, controlling power plant output, and managing demand response programs. We will also examine the challenges and opportunities presented by frequency response control and how Sonelgaz is addressing them to ensure the continued stability and reliability of its power system.

Chapter2: Primary frequency response analysis.

2.1. Introduction

The frequency of the power system is a critical parameter that must be maintained within a narrow range to ensure the stable and reliable operation of the power system. In Algeria, the power system frequency is maintained at 50 Hz, and any deviations from this value can have significant impacts on the power system.

If the frequency of the power system drops below 50 Hz, it indicates that there is more demand for electricity than there is supply, which can result in blackouts or load shedding to prevent system collapse. On the other hand, if the frequency increases above 50 Hz, it indicates that there is more supply than demand, which can damage equipment and result in a loss of generation.

Maintaining a stable frequency on the power system is crucial for the safety and reliability of the power grid. It ensures that the system is operating within its limits and prevents damage to the equipment. Therefore, Sonelgaz, the Algerian power company, has established several strategies to maintain frequency regulation on their power system. These strategies are critical in ensuring that the power system operates smoothly and reliably, providing a steady supply of electricity to meet the needs of customers.

2.2. Frequency control methods

Frequency control is essential in power systems to ensure stable and reliable operation. Primary frequency control, also known as governor control, is the first line of defense against frequency deviations caused by sudden changes in load or generation. Secondary frequency control, also known as automatic generation control (AGC), provides more precise frequency regulation by adjusting the output of individual generators in response to frequency deviations. Tertiary frequency control involves more advanced control techniques, such as economic dispatch and load shedding, to ensure long-term stability of the power system.

The sequential actions and impacts of these three frequency control methods on the system frequency can be summarized as follows **[2]**:

2.2.1. **Primary frequency control** When there is a sudden change in load or generation, the system frequency will deviate from its nominal value. Primary frequency control, which is implemented through governor control, responds quickly to this deviation by adjusting the output of the generators to bring the frequency back to its nominal value. The response time of primary frequency control is typically in the range of seconds.

2.2.2. **Secondary frequency control** Once the system frequency has been brought back to its nominal value by primary frequency control, secondary frequency control takes over to provide more precise frequency regulation. AGC adjusts the output of individual generators based on their frequency bias settings, which reflect their ability to respond to frequency deviations. AGC responds more slowly than primary frequency control, with response times in the range of minutes.

2.2.3. **Tertiary frequency control** In the long term, frequency stability is maintained through advanced control techniques such as economic dispatch and load shedding. Economic dispatch ensures that the most cost-effective combination of generators is used to meet the system's load, while load shedding reduces the system load in the event of a severe frequency deviation. These methods have even slower response times than secondary frequency control, with response times in the range of tens of minutes to hours.

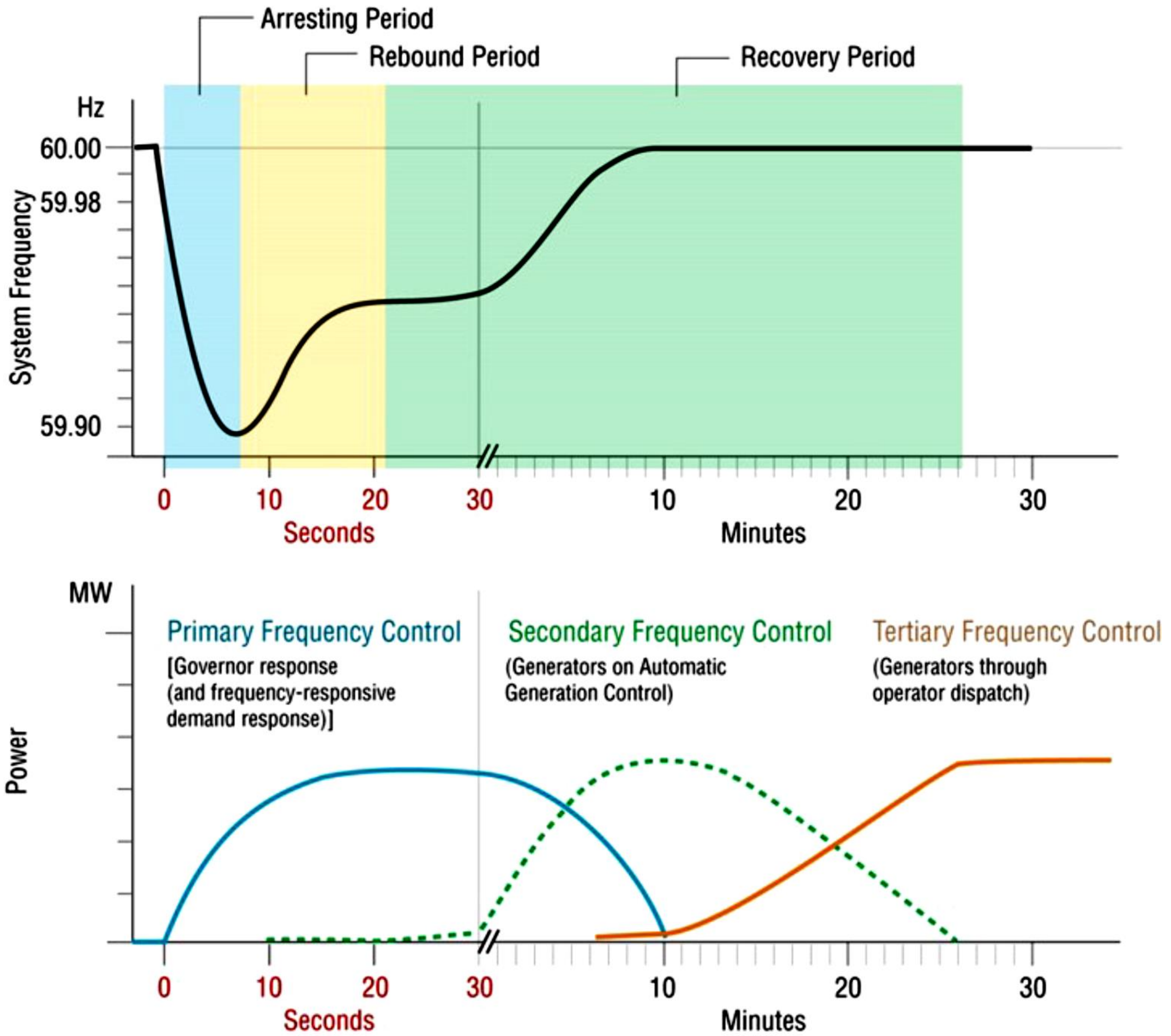


Figure 2. 1: The Sequential Actions and Impacts on System Frequency of Primary, Secondary, and Tertiary Frequency Control. [2]

2.2.4. Load and Generation Balance

The balance between the total load and total generation in a power system is crucial for maintaining frequency stability. Any sudden imbalance between the two can cause frequency deviations. Therefore, it is important to continuously monitor and adjust generation output to match the load demand.

2.2.5. Frequency Deviation

This refers to the difference between the actual frequency and the nominal frequency of the power system. Frequency deviations can occur due to sudden changes in load or generation and can lead to instability if not addressed quickly.

2.3. Implementation methods of the primary frequency response

The nominal frequency of Algeria's power system is 50 Hz, and the allowable frequency deviation is ±1%. [1] In the event of a frequency deviation, Sonelgaz has procedures in place to address the issue and restore frequency stability as quickly as possible.

The frequency regulation is an important part of Algeria's electric power system, and Sonelgaz works diligently to ensure that the system remains stable and reliable at all times.

There are several methods used to implement primary frequency response in power systems. Among the most frequent approaches are:

2.3.1. Governor droop control

- **Definition:**

  Governor droop control is a method used in power systems to adjust the speed of generators in response to changes in system frequency. It is based on the "droop" principle, in which generators are intended to slow down gradually when the system frequency declines to avoid a serious load imbalance.

  In governor droop control, the output frequency of the generators is monitored, and when the frequency drops below a certain threshold, the speed of the generators is adjusted to increase the output frequency. This is achieved by adjusting the fuel supply to the generator's prime mover, such as a turbine or engine.

- **The procedure for implementing governor droop control:**

  The process involves setting the droop characteristic of the generator. This is typically expressed as a percentage and represents the amount of droop that occurs for a given change in frequency. For example, a droop setting of 5% means that the generator's speed will decrease by 5% for every 1 Hz drop in frequency.

- **Example:**

  The RADJE400AGROU3MES.P generator (cap Djnat power plant) has a nominal speed of 3000 RPM and a droop setting of 5%. The turbine torque constant is 13 N-m/RPM, and the generator voltage is 400 V.
  If the system frequency drops from 50.007999 Hz to 49.412998 Hz.

  First, we need to calculate the frequency deviation, which is the difference between the nominal frequency and the actual frequency:

  $$\text{Frequency deviation} = 50.007999 \text{ Hz} - 49.412998 \text{ Hz} = 0.59 \text{ Hz} \qquad (1.1)$$

  Next, we can calculate the new generator speed using the droop setting and frequency deviation:

$$Generator\ speed = Nominal\ speed - (Droop\ setting\ x\ Frequency\ deviation)\ Generator\ speed$$

$$= 3000\ RPM - (0.05\ x\ 0.59\ Hz). \quad (1.2)$$

Generator speed = 2989.38 RPM

Finally, we can calculate the power produced using the generator speed, turbine torque constant, and generator voltage:

$$Power\ produced = Generator\ speed\ x\ Turbine\ torque\ constant\ x\ Generator\ voltage. \quad (1.3)$$

Power produced = 2989.38 RPM x 13 N-m/RPM x 400 V
Power produced = 15544776 W (or 15.54 MW)

Comment: in this example, a 0.59 Hz drop in frequency caused the generator speed to decrease by 10.62 RPM and the power produced to decrease by 15.54 MW. By adjusting the droop setting, power system operators can control the frequency response of their generators and maintain stability under changing operating conditions.

The droop characteristic is set using a governor control law, which is a mathematical equation that determines the amount of fuel to be supplied to the generator's prime mover based on the system frequency and the desired droop setting. The control law typically takes into account factors such as the inertia of the generator and the response time of the governor.
The specific form of the governor control law depends on the type of governor being used, but a general form of the control law is **[3]**:

$$Valve\ position = Kp\ x\ Frequency\ deviation + Ki\ x\ Integral\ of\ frequency\ deviation + Kd\ x\ Derivative\ of\ frequency\ deviation \quad (1.4)$$

where:

- *Kp is the proportional gain, which determines the responsiveness of the governor to changes in frequency deviation.*
- *Ki is the integral gain, which determines how much the governor integrates the error signal over time.*
- *Kd is the derivative gain, which determines how much the governor responds to changes in the rate of change of the error signal.*

The integral and derivative terms are often used to improve the performance of the governor by reducing steady-state errors and damping oscillations. The values of Kp, Ki, and Kd are typically determined through a process of tuning or optimization, using a combination of simulation and experimental testing.

It is important to note that the specific form of the governor control law can vary depending on the type of governor and the specific requirements of the power system. The control law may also be modified or adapted in response to changes in operating conditions or system requirements.

2.3.2. Under-frequency load shedding

- **Definition:**

Under-frequency load shedding (UFLS) is a technique used to maintain the stability of the power system by shedding or disconnecting a portion of the load when the frequency of the system falls below a certain threshold. The principle of UFLS is based on the fact that a sudden drop in frequency indicates a mismatch between the supply and demand of power in the system, which can lead to instability and even blackouts [4].

- **The UFLS technique:**

The UFLS approach entails classifying power system loads based on their criticality. When the frequency falls below a specific level, the UFLS system will disconnect non-critical loads in order to minimize power demand and stabilize the system frequency. The quantity of load shed is determined on the severity of the frequency drop and the UFLS system's capability.

The system is typically designed to meet certain performance requirements, such as shedding enough load to maintain a stable frequency in the system.

- **Example of UFLS**:

A power system with a UFLS system that is designed to shed 10% of the load when the frequency falls below 49.5 Hz. If the frequency falls below this threshold, the UFLS system will automatically disconnect 10% of the non-critical load to reduce the demand for power and stabilize the frequency [4].

- **The parameters of UFLS:**

It includes the frequency threshold, the percentage of load to be shed, and the criticality of the different loads. The UFLS system is typically designed to meet certain performance requirements, such as shedding enough load to maintain a stable frequency in the system.

In terms of analysis, UFLS is an important technique for maintaining the stability and reliability of the power system. However, UFLS alone may not be sufficient to prevent blackouts in all cases, and other control strategies such as governor control and automatic generation control may also be needed.

- **Numerical example:** a power system with a total load of 1000 MW and a UFLS system that is designed to shed 10% of the load when the frequency falls below 49.5 Hz. If the frequency drops to 49 Hz, the UFLS system will disconnect 100 MW of non-critical load to reduce the demand for power and stabilize the frequency.

2.3.3. **Automatic generation control**

- **Definition:**

  Automatic generation control (AGC) is a technique used to automatically adjust the power output of generators in the power system to match the changing demand for power. The principle of AGC is based on the fact that the power system needs to maintain a balance between the supply and demand of power to maintain a stable frequency and voltage **[4]**.

- The procedure for AGC involves measuring the frequency and power output of the generators in the power system and comparing them to the setpoint values. If there is a deviation from the setpoint values, the AGC system will automatically adjust the power output of the generators to bring the frequency and power output back to the desired levels.

- **Example**:

  A power system with two generators that are connected to the grid. The AGC system is designed to maintain a frequency of 50 Hz and a power output of 500 MW. If the demand for power increases, the AGC system will automatically adjust the power output of the generators to meet the increased demand and maintain the desired frequency and power output.

- **The parameters of AGC**: include the setpoint values for frequency and power output, the gain of the AGC system, and the response time of the generators. The AGC system is typically designed to meet certain performance requirements, such as maintaining a stable frequency and voltage in the system.

  Simplified model for the work of the AGC is implemented in the figure.

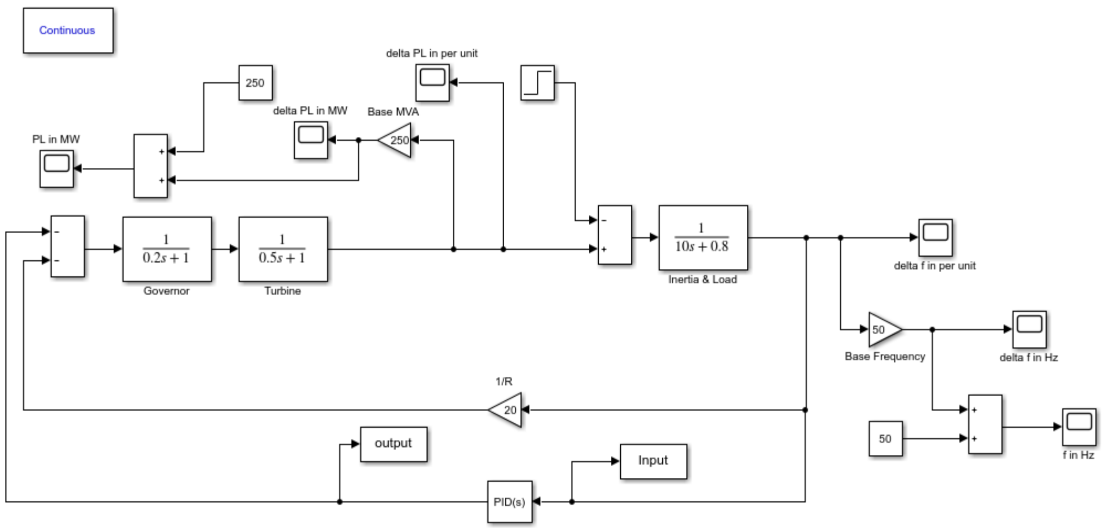


Figure 2. 2: simplified mole of the AGC using MATLAB-Simulink **[17]**.

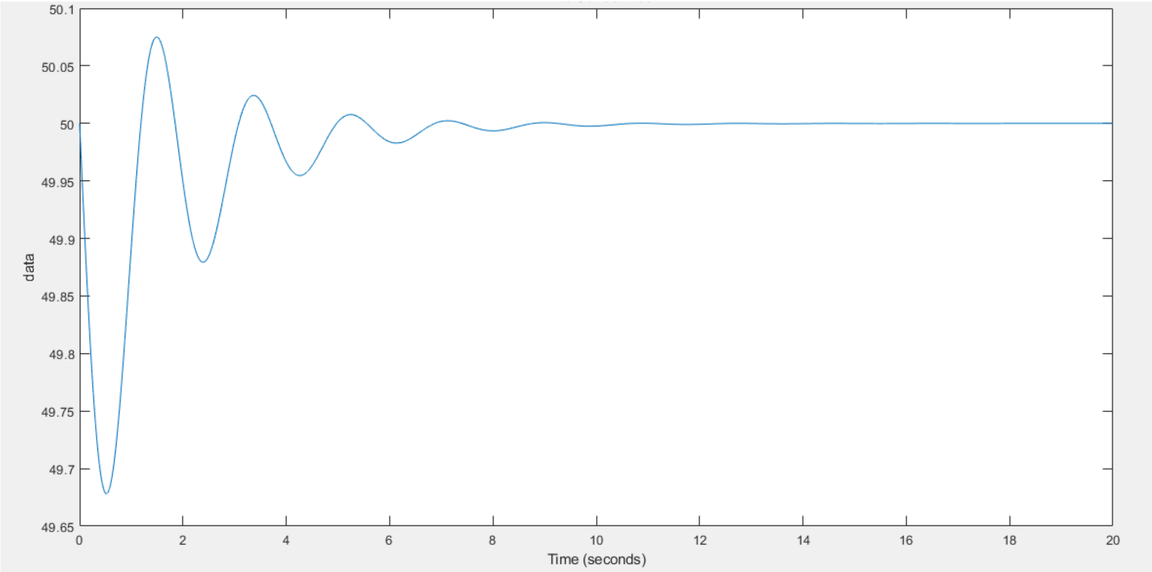


Figure 2. 3: The frequency response of the AGC system.

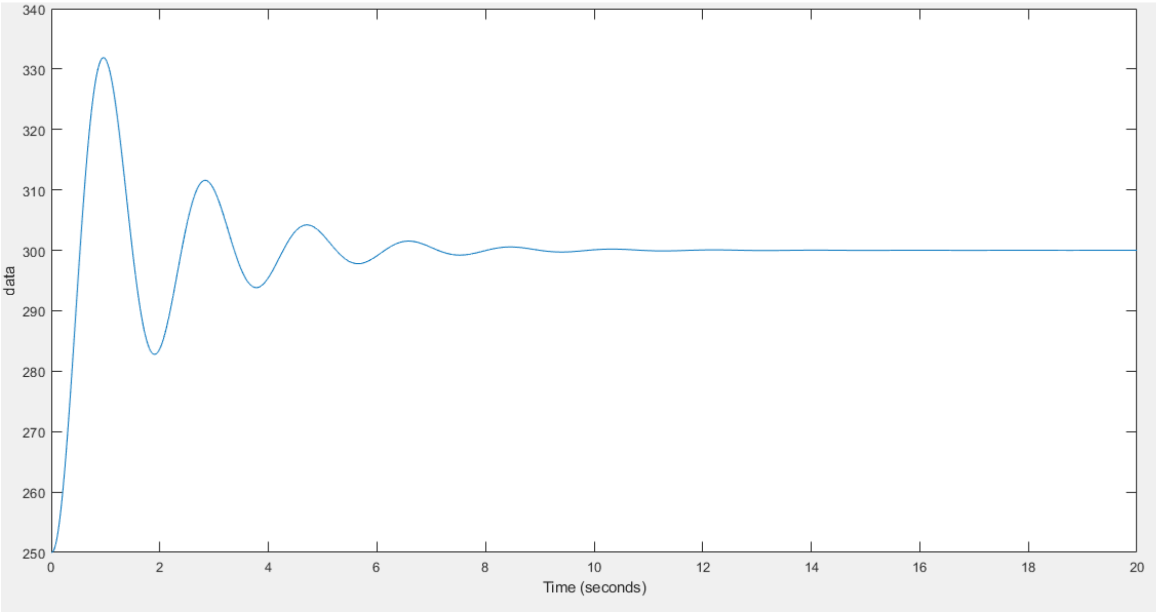


Figure 2. 4: The power fluctuation of the system.

As the results show in the figure2.3 and figure2.4 when there is a fluctuation in the system frequency the AGC will sense this disturbance caused by the imbalance energy between the generation side and consummation side so the AGC will response by increasing or decreasing the power in the system until it achieves the stability.

2.3.4. Fast frequency response

- **Definition:**

Fast frequency response (FFR) is a technique used to quickly adjust the power output of generators in the power system to counteract the rapid changes in frequency caused by sudden disturbances or faults in the system. The principle of FFR is based on the fact that the power system needs to respond quickly to maintain a stable frequency and prevent cascading failures [5].

- **The procedure:**

  The process for FFR involves the use of fast-acting devices such as battery energy storage systems, flywheels, and supercapacitors to quickly inject or absorb power into the system to stabilize the frequency. The FFR system typically operates on a timescale of seconds to minutes, compared to the governor control and AGC systems which operate on a timescale of minutes to hours [5].

- **Example:** FFR is a power system that experiences a sudden loss of generation due to a fault in one of the generators. The FFR system can quickly inject power into the system using a battery energy storage system to stabilize the frequency and prevent cascading failures.

- **The parameters of FFR:**

include the capacity and response time of the fast-acting devices, the gain of the FFR system, and the frequency response characteristics of the power system. The FFR system is typically designed to meet certain performance requirements, such as providing a fast response time and minimizing the impact on the power system.

2.3.5. Dynamic Demand Control (DDC)

- **Definition:**

Dynamic Demand Control is a technique used to manage the demand for electricity in real-time by adjusting the demand based on the available supply. The principle of DDC is to provide a mechanism for reducing the demand for electricity during periods of high demand or low supply, while maintaining the required level of service.
The procedure for DDC involves the use of smart meters and other devices to monitor the demand for electricity in real-time. The demand is then adjusted by either reducing or shifting the load to periods of lower demand. The adjustment can be done automatically or through manual intervention [6].

- **The parameters:**

The parameters of DDC include the demand response programs, the characteristics of the load, and the communication and control infrastructure. The DDC system is typically designed to meet certain performance requirements, such as reducing the demand during periods of high demand or low supply and maintaining the required level of service.

2.3.6. Reserve power

- **Definition:**

Reserve power is a technique used to ensure that there is sufficient capacity in the power system to meet the load demand even during unexpected contingencies or emergencies. The principle of reserve power is based on the fact that the power system needs to have sufficient reserve capacity to respond to unexpected events and maintain the stability of the system.

- **The process:**

The procedure for reserve power involves the allocation of a certain amount of generating capacity that is kept in reserve to meet unexpected increases in demand or to provide backup power in case of unexpected outages. The amount of reserve power is typically expressed as a percentage of the total generating capacity and is based on the reliability requirements of the system.

- **The parameters:**

The parameters of reserve power include the reserve capacity requirement, the reliability standards of the power system, the generating capacity of the system, and the characteristics of the generating units. The reserve power system is typically designed to meet certain performance requirements, such as providing sufficient backup power in case of unexpected outages and maintaining the stability of the system during contingencies.

2.4. **Various types of power reserves**

In the electric power system, there are several types of power reserves, such that:

2.4.1. **Spinning Reserve**

Spinning reserve is the extra generating capacity that is available at all times to quickly respond to sudden changes in demand or unexpected disturbances. This reserve is typically provided by generators that are already online and spinning at less than full capacity, allowing them to quickly increase their power output when needed. Spinning reserve is typically measured in megawatts (MW) and is often required by grid operators to maintain system stability.

The Algerian national grid code specifies that the spinning reserve requirement for the Algerian power system should be equal to at least 8% of the total installed capacity. This means that the power system in Algeria must maintain a spinning reserve of at least 8% of its total installed capacity to ensure that there is enough reserve power available to cover sudden changes in demand or generation **[4]**.

To calculate the required amount of spinning reserve for a specific power system in Algeria, the total installed capacity of the system would be multiplied by the spinning reserve requirement percentage. For example, if a power system in Algeria has a total installed capacity of 9000 MW, the required amount of spinning reserve would be:

$$Spinning\ Reserve\ =\ 9000\ MW\ x\ 0.08\ =\ 720\ MW \tag{1.5}$$

This means that the power system in Algeria would need to maintain a spinning reserve of at least 720 MW to ensure that there is enough reserve power available to cover sudden changes in demand or generation. If there is a sudden increase in demand or a sudden loss of generation, the spinning reserve can be quickly dispatched to increase power output and maintain system stability.

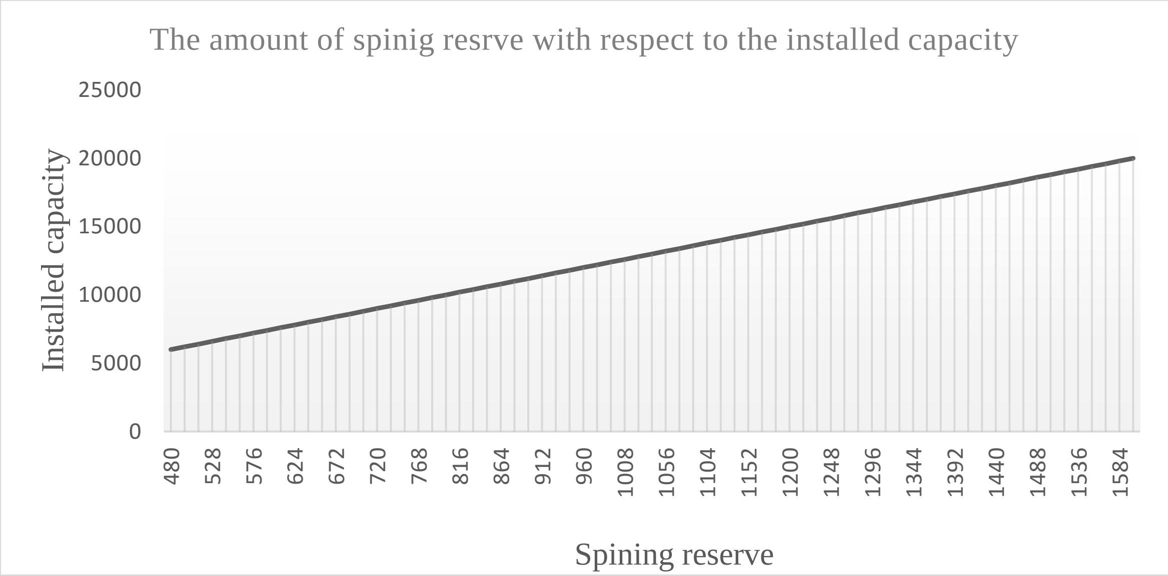


Figure 2. 5: The amount of the spinning reserve with respect to the installed capacity.

2.4.2. Non-Spinning Reserve

Non-spinning reserve is the extra generating capacity that is available but not already spinning. This type of reserve is typically provided by generators that are offline but can be started quickly when needed. The non-spinning reserve is often used as a backup to spinning reserve and is also measured in megawatts (MW).

2.4.3. Responsive Reserve

Responsive reserve is a type of reserve that can quickly respond to changes in demand or disturbances on the power grid. This reserve is typically provided by energy storage systems or other sources of flexible capacity that can ramp up or down quickly to provide additional power when needed.

2.4.4. Regulation Reserve

Regulation reserve is a type of reserve that is used to maintain the frequency of the power grid at its nominal value of 50 Hz. This reserve is provided by generators that can quickly ramp up or down to provide additional power or reduce power output as needed to maintain grid frequency. The regulation reserve is typically measured in megawatts per minute (MW/min).

According to the Algerian national grid code, the regulation reserve requirement is currently set at 2% of the total installed capacity of the power system. **[4]** This means that the power system in Algeria must maintain a regulation reserve of at least 2% of its total installed capacity to ensure that there is enough reserve power available to regulate the system frequency and voltage over longer periods.

To calculate the required amount of regulation reserve for a specific power system in Algeria, the total installed capacity of the system would be multiplied by the regulation reserve requirement percentage. For example, if a power system in Algeria has a total installed capacity of 15 000 MW, the required amount of regulation reserve would be:

$$Regulation\ Reserve\ =\ 15\ 000\ MW\ x\ 0.02\ =\ 300\ MW \qquad (1.6)$$

This means that the power system in Algeria would need to maintain a regulation reserve of at least 300 MW to ensure that there is enough reserve power available to regulate the system frequency and voltage over longer periods. If there are long-term changes in demand or generation, the regulation reserve can be dispatched to adjust power output and maintain system stability.

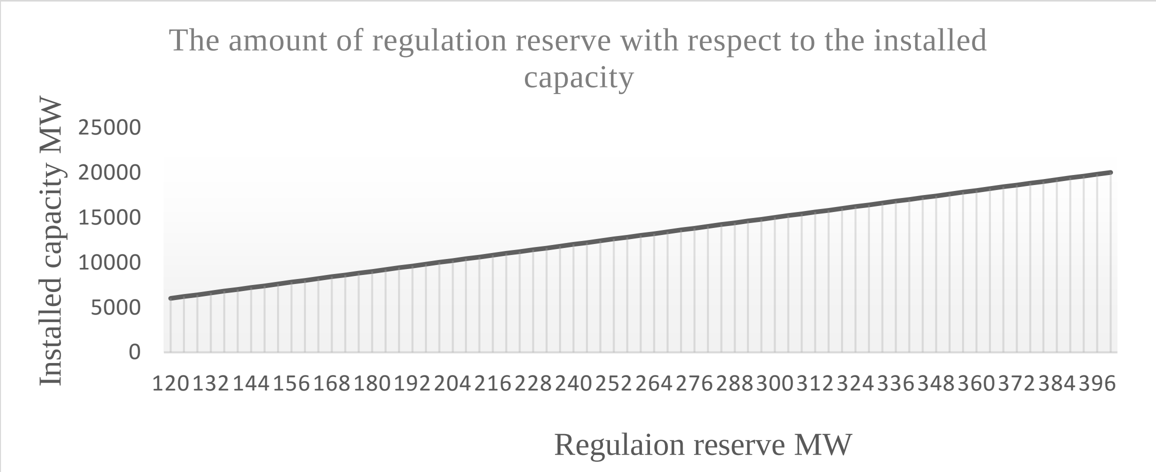


Figure 2. 6: The amount of regulation reserve with respect to the installed capacity.

2.4.5. Black Start Reserve

Black start reserve is a type of reserve that is used to restart the power grid in the event of a complete blackout. This reserve is typically provided by generators that are capable of starting up without external power and can provide enough power to start other generators and restore power to the grid.

2.4.6. The primary reserve

also known as frequency control reserve (FCR), is a type of reserve that is used to maintain the frequency of the power system during normal operation. The frequency of the power system is a measure of the balance between the total power demand and the total power generation at any given moment. If the frequency deviates too far from the nominal value, it can lead to instability and potentially cause blackouts.

The primary reserve is typically provided by generators that are already online and spinning at full capacity, but with some extra headroom to increase their power output if needed. The amount of primary reserve required is typically calculated based on the maximum output of the largest generator in the system, multiplied by a factor that accounts for the likelihood of a sudden loss of generation.

The primary reserve is dispatched automatically by the control system when there is a sudden change in power demand or generation. If the frequency drops below the nominal value, the primary reserve is dispatched to increase power output and restore the frequency. If the frequency rises above the nominal value, the primary reserve is dispatched to decrease power output and reduce the frequency.
The value of primary reserve in Algeria may be determined by the Algerian Energy Regulatory Commission (CREG), which regulates the electricity sector in the country. The primary reserve requirement in Algeria may depend on the size and characteristics of the power system, the types of generators used, and the regulatory requirements for maintaining system stability.

According to the Algerian national grid code, the primary reserve requirement is currently set at 5% of the total installed capacity of the power system. **[4]** This means that the power system in Algeria must maintain a primary reserve of at least 5% of its total installed capacity to ensure system stability during normal operation.

To calculate the required amount of primary reserve for a specific power system in Algeria, the total installed capacity of the system would be multiplied by the primary reserve requirement percentage. For instance, if a power system in Algeria has a total installed capacity of 15 000 MW, the required amount of primary reserve would be:

$$Primary\ Reserve\ =\ 15\ 000\ MW\ x\ 0.05\ =\ 750\ MW \tag{1.7}$$

This means that the power system in Algeria would need to maintain a primary reserve of at least 750 MW to ensure system stability during normal operation. If the frequency deviates too far from the nominal value, the primary reserve can be dispatched to increase or decrease power output and restore the frequency to its nominal value.

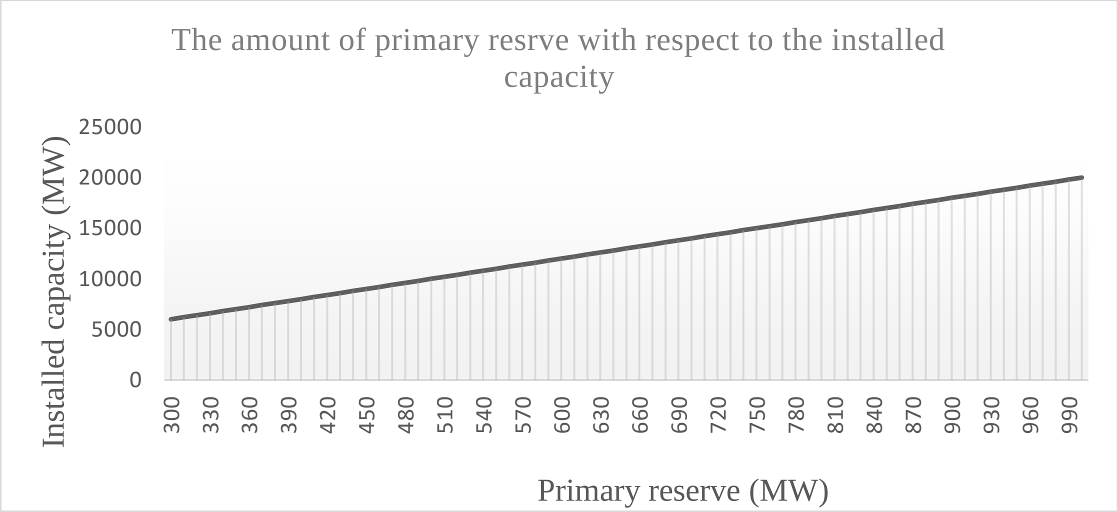


Figure 2. 7: The amount of primary reserve with respect to the installed capacity.

When a disturbance occurs in the power system, these different types of reserves can be used to help maintain system stability and prevent blackouts. For example, if a generator suddenly goes offline, spinning reserve can be quickly dispatched to make up the difference and maintain system balance. Similarly, if there is a sudden increase in demand, responsive reserve can be used to quickly provide additional power and prevent a voltage collapse.

2.5. General advantages and disadvantages of each frequency control strategy

Frequency control strategy	***Advantages***	***Disadvantages***
Governor Droop Control	• Simple and widely used control method. • Allows for stable operation of generators in parallel. • Provides a level of frequency stability during transient conditions.	• Droop setting may not be optimized for all operating conditions. • Limited response time to frequency deviations.
Under-Frequency Load Shedding	• Response time to frequency variations is quick. • Can contribute in the prevention of cascading outages. • It is simple to implement in most power systems.	• Inefficient utilization of producing capacity. • Due to the lack of electricity, customers may be dissatisfied. • Strategy may turn out that it will not be successful in preventing major system breakdowns.
Automatic Generation Control	• Power production is continuously adjusted to fit demand. • Quick response to frequency variations. • Multiple generators can be coordinated.	• Accurate modeling of the power system is required. • It is possible that it will be useless in harsh operating circumstances. • Increases the damage that occurs on generating equipment.

Fast Frequency Response	• Quick response to frequency variations. • Can help prevent cascading outages. • Can be simply implemented in the majority electric power systems	• Enormous funding for specialist equipment is required. • It may happen that it will not be successful in preventing significant system breakdowns. • Coordination among many generators might be challenging.
Dynamic Demand Control	• Can assist in reducing the general demand during peak periods. • Smart grid technology offers simple implementation.	• Considerable investment in new technologies may be essential. • It may be challenging to execute in particular locations or with specific consumer groups. • Extreme working circumstances can make it ineffective.
Reserve Power	• Provides a reserve of accessible power to respond to unexpected variations in demand. • Can be easily implemented in most power systems.	• Inefficient use of generating capacity during normal operating conditions. • May not be effective in preventing major system failures. • Can be expensive to maintain and operate

Table 2. 1: General advantages and disadvantages of each frequency control strategy [4].

2.6. Regulating energy

- **Definition:**

 Regulating energy, also known as regulation capacity, refers to a reserve capacity that can be used to help balance supply and demand on the electric grid. It is a type of power reserve that can be dispatched quickly to adjust the output of generators and other resources in response to changes in system demand or unexpected changes in generation output.

Regulating energy is typically used to maintain the stability of the grid and prevent frequency deviations, which can lead to power outages and other disruptions. This reserve capacity can be provided by a variety of resources, including generators, energy storage systems, and demand response programs.

To calculate the required amount of regulating energy for a specific power system in Algeria, you would need to know the total installed capacity of the system and the value of regulating energy expressed in units of MW/Hz.

The formula to calculate the required amount of regulating energy is [4]:

$$Regulating\ Energy\ =\ Installed\ Capacity\ (MW) x\ Regulating\ Energy\ Value\ \left(\frac{MW}{Hz}\right)$$

The total installed capacity of the Algerian power system is 18,500 MW and the regulating energy value is 0.1 MW/Hz. To calculate the required amount of regulating energy, we would use the following formula:

Regulating Energy = 18,500 MW x 0.1 MW/Hz= 1,850 MW/Hz = 185 MW/0.1Hz.

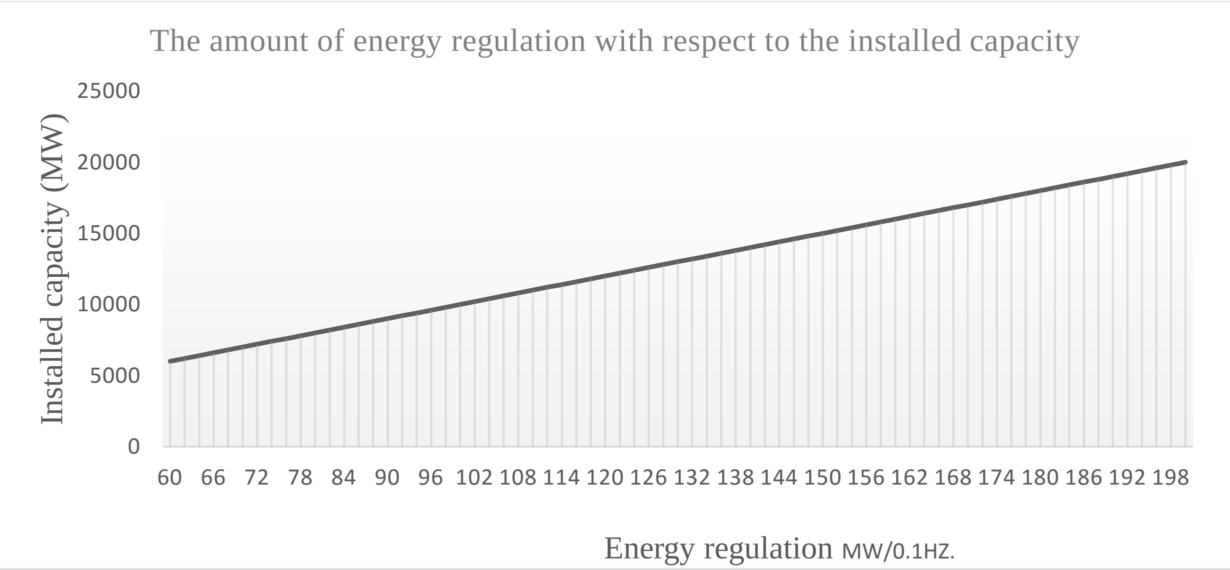


Figure 2. 8: The amount of energy regulation with respect to the installed capacity.

It's important to note that the required amount of regulating energy can vary depending on the size and characteristics of the power system, the types of generators used, and the regulatory requirements for maintaining system stability. The regulating energy value may also change over time as the power system evolves and new technologies are implemented.

2.7. Comparison between the UCTE criteria and NERC criteria

Here is a table that outlines the types of frequency response control according to UCTE and NERC, along with their timelines and a brief analysis of each:

Type of Frequency	UCTE Criteria	Timeline	NERC Criteria	Timeline	Analysis

Response Control					
Primary Frequency Response (PFR)	Must achieve at least 80% of the required response within 30 seconds	2008 - present	Must achieve at least 90% of the required response within 10 minutes	2013 - present	PFR is the fastest and most important form of frequency response, as it occurs within seconds of a disturbance. The UCTE criterion is more stringent than the NERC criterion.
Secondary Frequency Response (SFR)	Must achieve the remaining 20% of the required response within 5 minutes	2008 - present	Must achieve the remaining 10% of the required response within 10 minutes	2013 - present	SFR provides additional frequency control after PFR, and it is slower than PFR. The time frame for achieving the required response is longer than that of PFR.
Tertiary Frequency Response (TFR)	None specified	N/A	Must achieve the remaining 10% of the required response within 30 minutes	2013 - present	TFR provides longer-term frequency control and is the slowest of the three types. The UCTE criteria do not specify TFR requirements, while the NERC criteria do.

- **Analysis:**

Table 2. 2: Comparison between the UCTE criteria and NERC criteria **[7] [8]**.

The table2.2 shows that there are three types of frequency response control: primary, secondary, and tertiary. The primary response is the fastest and most important, as it provides the initial response to a disturbance. The secondary response provides additional frequency control and is slower than the primary response, while the tertiary response is the slowest and provides longer-term frequency control.

The UCTE and NERC criteria for frequency response control have some similarities and differences. The UCTE criteria are more stringent than the NERC criteria, with a requirement of achieving at least 80% of the required response within 30 seconds for PFR compared to NERC's requirement of achieving at least 90% of the required response within 10 minutes.

2.7.1. **Frequency configurations and parameters used by UCTE and NERC**

Comparing all the different frequency configurations and parameters used by UCTE and NERC is a complex task, as there are many different factors to consider. However, here are some key points of comparison **[7] [8]**:

1. Criteria for frequency response: Both UCTE and NERC use RoCoF and maximum deviation as the criteria for calculating frequency response requirements. RoCoF refers to the rate of change of frequency, while maximum deviation refers to the maximum amount that frequency can deviate from its nominal value.

2. Timeframes for frequency response: UCTE specifies different timeframes for primary and secondary frequency response, with primary response required within 30 seconds and secondary response required within 5 minutes. NERC specifies primary, secondary, and tertiary frequency response, with primary response required within 10 minutes, secondary response required within 10 minutes, and tertiary response required within 30 minutes.

3. Methods of frequency control: Both UCTE and NERC allow for a range of methods of frequency control, including governor control, load shedding, energy storage systems, and demand response. UCTE also allows for fast reserve and voltage control as methods of frequency control.

4. UCTE's formula for calculating frequency response requirements is simpler and based on the size of the power system, while NERC's formula is more complex and based on the available generation and load as well as the probability of disturbance. However, both formulas are designed to ensure that the power system has enough frequency response to maintain stability and reliability in the event of a disturbance.

2.7.2. Comparison between the primary frequency response requirements for UCTE and NERC

Component	***UCTE***	***NERC***
Nominal Frequency	50 Hz	60 Hz
Frequency Deviation	±200 mHz	±0.3 Hz
Primary Reserve	3% of system demand or 3000 MW, whichever is greater	3% of system demand or 2600 MW, whichever is greater

Response Time	30 seconds or less	10 minutes or less
Spinning Reserve	0.7% of system demand or 700 MW, whichever is greater	2% of system demand or 1750 MW, whichever is greater

Table 2. 3: Comparison between the primary frequency response requirements for UCTE and NERC **[7] [8].**

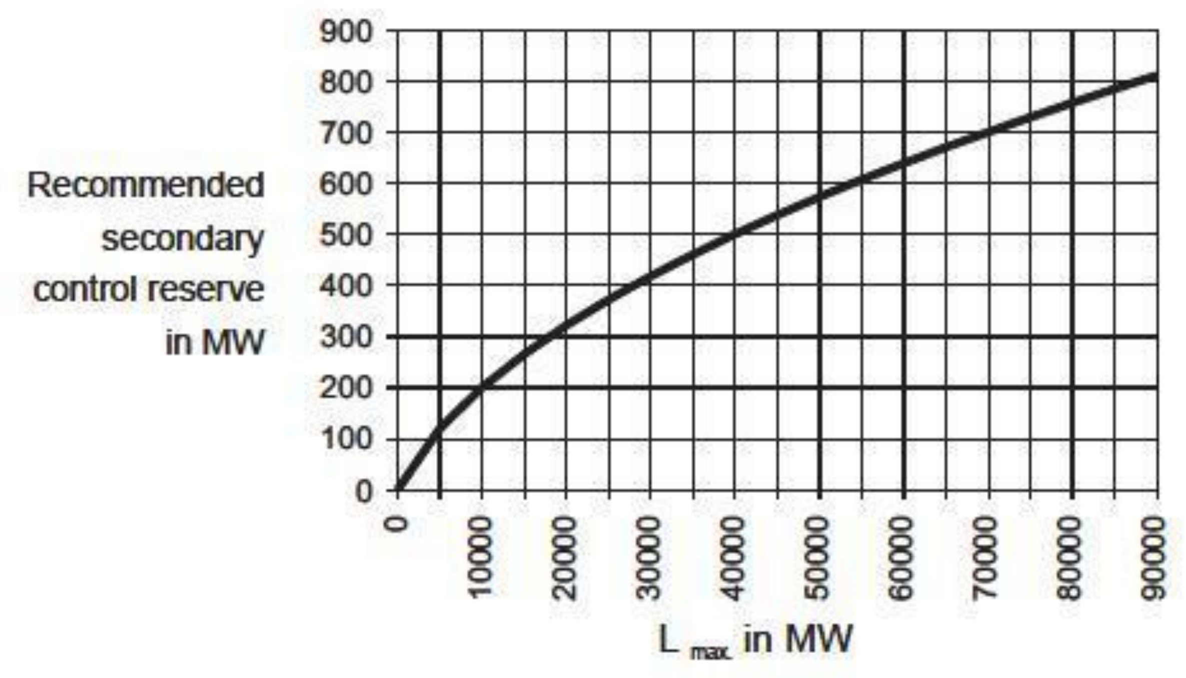


Figure 2. 9: The UCTE recommended secondary control reserve with respect to maximum power of the load.**[8]**

- **Analysis:**

As we can see, there are some notable differences between the primary frequency response requirements for UCTE and NERC. One of the most significant differences is the nominal frequency, with UCTE using 50 Hz and NERC using 60 Hz. This affects the frequency deviation tolerance, with UCTE allowing for a maximum deviation of ±200 mHz and NERC allowing for a maximum deviation of ±0.3 Hz.

In terms of reserves, both requirements necessitate the availability of primary reserves to resp ond to unexpected changes in generation or load.
UCTE needs 3% of system demand or 3000 MW, whichever is greater, whereas NERC requir es 3% of system demand or 2600 MW, whichever is greater.
Primary reserve response times varies as well, with UCTE requiring a response time of 30 sec onds or fewer and NERC needing a response time of 10 minutes or less.
The two requirements necessitate the availability of spinning reserves in order to maintain fre

quency stability. However, the requirements are different, with UCTE requiring a minimum of 0.7% of system demand or 700 MW, whichever is greater, while NERC requires a minimum of 2% of system demand or 1750 MW, whichever is greater.

	Primary control reserve:	Secondary control reserve + minute reserve:	Tertiary reserve;
UCTE	3 000 MW (two times the largest generator)	Lmax | | result 40000 | 422500 | 500	no recommendation.
Belgium	around 100 MW	Lmax | | result 11000 | 132500 | 214.0054945	460 MW by generators + 200 MW with interruptible loads.
France	around 700 MW	recommendation of the UCTE or more conservative during peak hours	1 500 MW (in order to compensate the loss of the French largest unit)
Spain	1.5% of the nominal capacity of any generator Pn | result 750 | 11.25	when the load variation is fast, 782.3042886 otherwise . 391.1521443 This reserve is calculated for each hour every day Lmax 17000	capacity of the biggest unit + 2% of the expected load on the considered period. Lmax | result 8500 | 170
Pennsylvania New Jersey Maryland interconnection in the United States.	spinning reserve should represent more than 75% of the primary reserve PR | SR 609 | 456.75	1.1% of the expected peak load during the off- or on-peak period	calculated probabilistically for a given period

Table 2. 4 : Comparison of the control types between Spain, France, Belguim, UCTE and USA.**[7] [8]**

In general, while there are some notable differences between the primary frequency response requirements for UCTE and NERC, both criteria aim to maintain frequency stability by ensuring that adequate reserves are available to respond to sudden changes in generation or load.

2.8. The availability of resources and level of risk tolerance of the Algerian frequency power system

In terms of resources, Algeria has significant reserves of natural gas, which is the primary fuel used to generate electricity in the country. In addition, the country has been investing in renewable energy sources, such as solar and wind power, to diversify its energy mix and reduce dependence on fossil fuels.

As for risk tolerance, the Algerian frequency power system operates within a narrow frequency range of ±1%, which is typical of most power systems around the world. This means that any deviation outside of this range can have significant impacts on the stability and reliability of the system. To mitigate these risks, Sonelgaz has established robust procedures and contingency plans to address frequency deviations and restore stability as quickly as possible.

2.8.1. **Sonelgaz contingency plans and risk mitigation strategies**

Sonelgaz has established several contingency plans and risk mitigation strategies to address frequency deviations and ensure the stability and reliability of the Algerian frequency power system. Among the most frequent approaches are:

1. Contingency Planning: Sonelgaz has established robust contingency plans to address various scenarios, such as the loss of a major power plant or transmission line. These plans include procedures for quickly restoring power to affected areas and mitigating the impacts of any disruptions.

2. Monitoring and Control: Finally, Sonelgaz closely monitors and controls the frequency of the power system to ensure that it remains within acceptable limits. This includes using sophisticated control systems and real-time monitoring to quickly detect and respond to any frequency deviations.

3. In addition to, maintaining primary and secondary reserves, load shedding as a last resort measure, and implementing demand response programs to reduce overall demand during periods of high demand. By having these contingency plans and risk mitigation strategies in place, Sonelgaz can effectively manage and balance the load and generation on their power system, ensuring a stable and reliable power supply for their customers.

2.9. Analysis of the frequency response for the event of Bellarat

In 3 February2023, Sonelgaz had loss in the generation because of collapse of the generator of Bellarat, which produce a fluctuation in the system frequency. This part represents the study and the analysis of the frequency response of Algerian power system, in addition to different configuration and parameters used in the regulation of the frequency to ensure the stability of the system.

The figure displays the frequency response curve in (Hz) with respect to the time (the real time in hours).

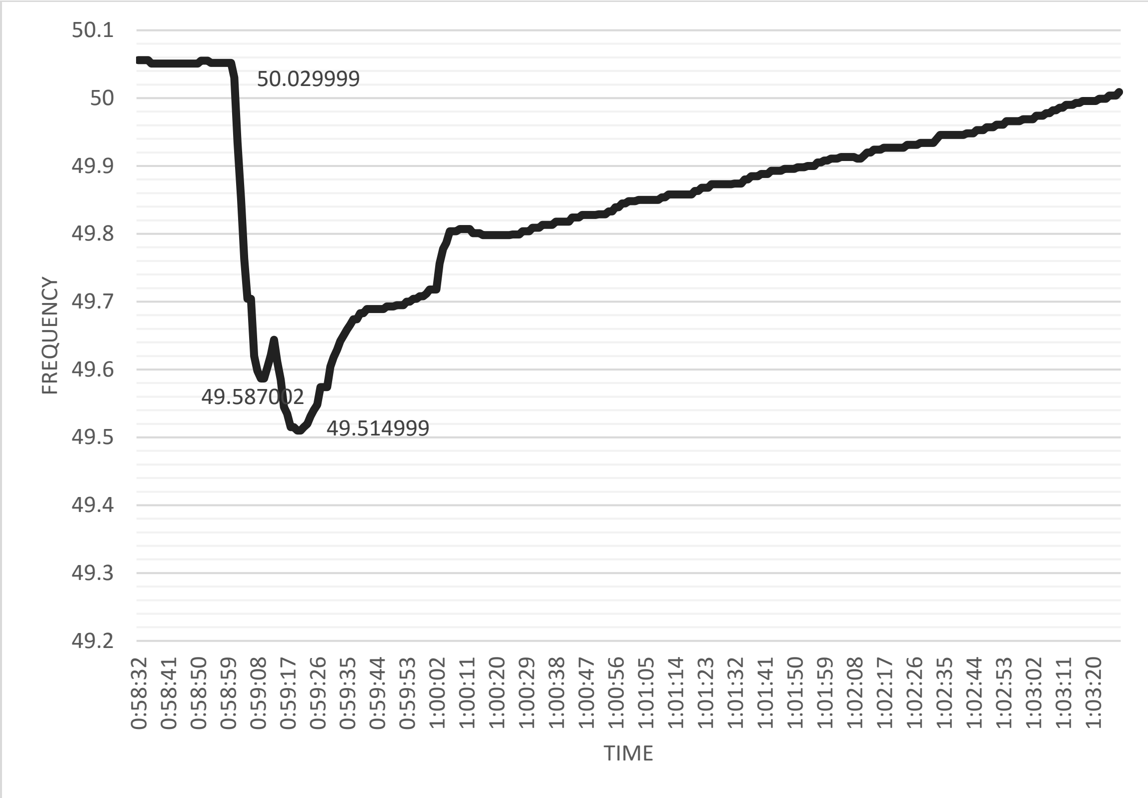
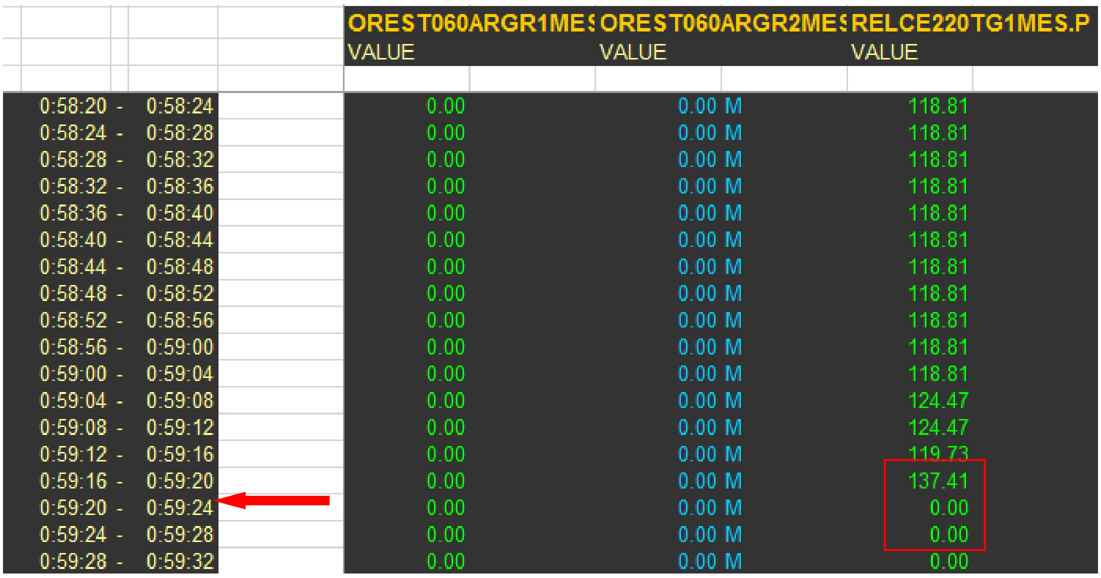


Figure 2. 10: The frequency response during the event of Bellarat.

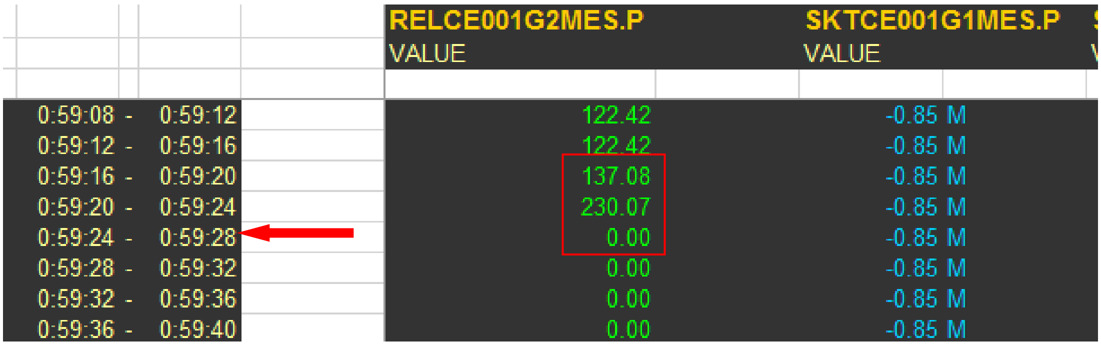
	BELLA001CC2MES.P VALUE	BELLA001G11MES.P VALUE	BELLA001G12MES.P VALUE	BELLA001G20MES.P VALUE	BELLA001G21MES.P VALUE	BELLA001G22MES.P VALUE
0:58:20	731.49	0.00 M	0.00 M	247.34	242.46	243.02
0:58:24	731.49	0.00 M	0.00 M	247.34	242.46	243.02
0:58:28	731.49	0.00 M	0.00 M	247.34	242.46	243.02
0:58:32	731.49	0.00 M	0.00 M	247.34	242.46	243.02
0:58:36	731.49	0.00 M	0.00 M	247.34	242.46	243.02
0:58:40	731.49	0.00 M	0.00 M	247.34	242.46	243.02
0:58:44	731.49	0.00 M	0.00 M	247.34	242.46	243.02
0:58:48	731.49	0.00 M	0.00 M	247.34	242.46	243.02
0:58:52	731.49	0.00 M	0.00 M	247.34	242.46	243.02
0:58:56	731.49	0.00 M	0.00 M	247.34	242.46	243.02
0:59:00	731.49	0.00 M	0.00 M	247.34	242.46	243.02
0:59:04	126.06	0.00 M	0.00 M	50.24	-25.00	0.00
0:59:08	20.36	0.00 M	0.00 M	26.14	-11.83	0.00
0:59:12	20.36	0.00 M	0.00 M	12.84	0.00	0.00
0:59:16	20.36	0.00 M	0.00 M	12.84	0.00	0.00
0:59:20	20.36	0.00 M	0.00 M	12.84	0.00	0.00

Figure 2. 11: The power generation of Bellarat generators during the event.



	OREST060ARGR1ME VALUE	OREST060ARGR2ME VALUE	RELCE220TG1MES.P VALUE
0:58:20 - 0:58:24	0.00	0.00 M	118.81
0:58:24 - 0:58:28	0.00	0.00 M	118.81
0:58:28 - 0:58:32	0.00	0.00 M	118.81
0:58:32 - 0:58:36	0.00	0.00 M	118.81
0:58:36 - 0:58:40	0.00	0.00 M	118.81
0:58:40 - 0:58:44	0.00	0.00 M	118.81
0:58:44 - 0:58:48	0.00	0.00 M	118.81
0:58:48 - 0:58:52	0.00	0.00 M	118.81
0:58:52 - 0:58:56	0.00	0.00 M	118.81
0:58:56 - 0:59:00	0.00	0.00 M	118.81
0:59:00 - 0:59:04	0.00	0.00 M	118.81
0:59:04 - 0:59:08	0.00	0.00 M	124.47
0:59:08 - 0:59:12	0.00	0.00 M	124.47
0:59:12 - 0:59:16	0.00	0.00 M	119.73
0:59:16 - 0:59:20	0.00	0.00 M	137.41
0:59:20 - 0:59:24	0.00	0.00 M	0.00
0:59:24 - 0:59:28	0.00	0.00 M	0.00
0:59:28 - 0:59:32	0.00	0.00 M	0.00

Figure 2. 12: The RELCE220TG1MES.P power generarion during the event of Bellarat.



	RELCE001G2MES.P VALUE	SKTCE001G1MES.P VALUE
0:59:08 - 0:59:12	122.42	-0.85 M
0:59:12 - 0:59:16	122.42	-0.85 M
0:59:16 - 0:59:20	137.08	-0.85 M
0:59:20 - 0:59:24	230.07	-0.85 M
0:59:24 - 0:59:28	0.00	-0.85 M
0:59:28 - 0:59:32	0.00	-0.85 M
0:59:32 - 0:59:36	0.00	-0.85 M
0:59:36 - 0:59:40	0.00	-0.85 M

Figure 2. 13: The RELCE001G2MES.P power generation during the event of Bellarat.

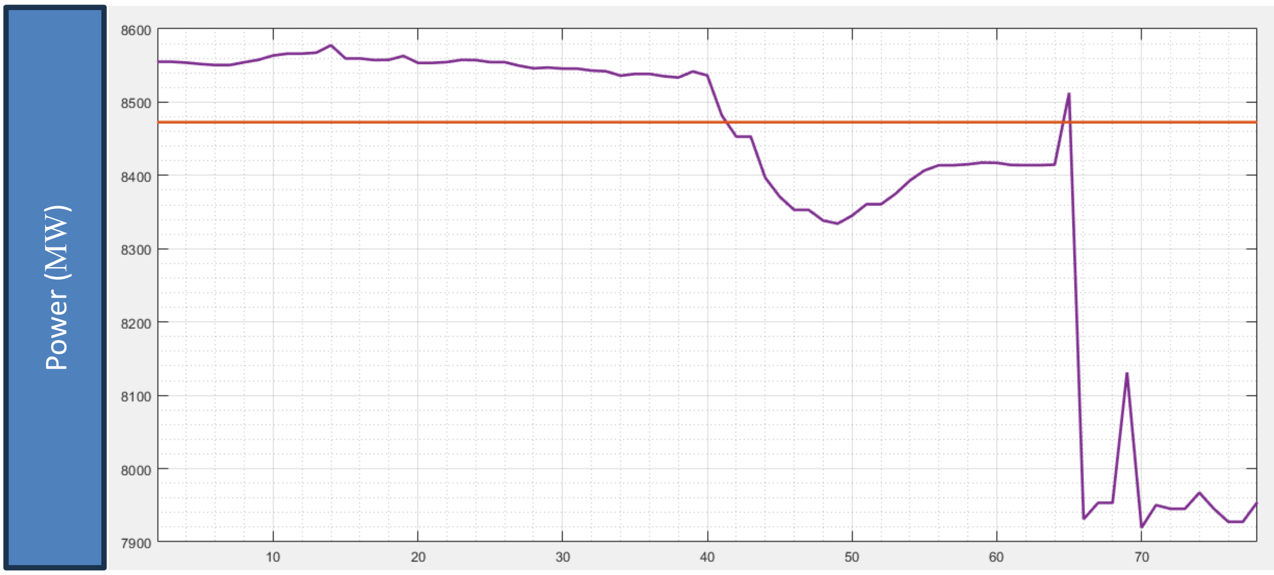


Figure 2. 14: The purple curve is total power generation and the red curve is total load demand (MW) with respect to the time (s).

Discussion and analysis:

The figure2.10 shows the frequency curve with respect to time.

- Before the (0:59:01) the frequency of the system was stable in the range of toleration +- 100 mHz from the main frequency 50 Hz.
- From (0:59:01) to (0:59:09) the system suffers from loss of Bellarat generator. The loss is estimated to be 582 MW. Which leads to frequency fluctuation in the system, the frequency decrease until 49.587 HZ.
- From (0:59:09) to (0:59:13) the power system reacts to the system frequency fluctuation so the using the droop control method which is the sharing of the other generator so they increase the amount of the power programed of the production to maintain the stability of the system. The frequency of the system starts recovering and it increase to 49.64 Hz.
- From (0:59:13) to (0:59:21) the system had another loss of the generation. This time because of the RELCE001G2MES.P and RELCE220TG1MES.P the loss of those two generators was in the same time. The amount of the power losses are 137.08 MW and 137.41 MW, so in total of 212 MW. So, this secondary loss in power caused another frequency disturbance this time it decreased to 49.51499 Hz.
- From (0:59:13) to (1:01:54): the system starts recovering by using the different control methods and different reserves. This leads to recovering in the system frequency and at (1:01:54) the frequency reaches the range of stability 49.9 Hz.

Units	type	nominal power	power programmed	power measured	power max	power 12 s from (59:04 to 59:16)	dP
BERRO220GROUP2MES.P		245	201	214	238	201	0
HAMMC002G3MES.P		200	179.7	189.2	222.02	222.02	42.32
BOUFC220AGRP3MES.P		230	108.690819	114.333031	168.655411	149.292831	40.602012
RADJE400AGROU3MES.P		380	279.388672	309.980591	309.980591	279.388672	0
SKHCE400TG1MES.P		400	426.18	437.74	437.74	425.09	-1.09
SKHCE400TG3MES.P		400	384.07	400.36	410.57	400.36	16.29
SKSCE400TG1MES.P		240	234	245	253	245	11
SKSCE400TG2MES.P		180	134	145	145	145	11
SKSCE400TG3MES.P		240	245	262	262	262	17
SKSCE400TG4MES.P		180	171	182	182	182	11
SKDCE400TG2MES.P		400	371	412	412	398	27
NAAMC400MECHP1MES.P		750	138	146	146	137	-1
NAAMC400MECHP2MES.P		750	155	157	157	154	-1
SKTCE001G2MES.P		380	402	408	408	408	6
SKTCE001G3MES.P		380	371	379	379	379	8
AARCE400AGROU1MES.P		380	287.65	322.62	322.62	287.65	0
AARCE400AGROU2MES.P		380	171.58	205.87	205.87	205.87	34.29

AARCE400AGROU3MES.P	380	320.44	355.41	355.41	320.44	0
MSILA001G1MES.P	225	157.57	163.92	163.92	157.87	0.3
MSILA001G2MES.P	225	187.47	191.67	237.87	191.67	4.2
BELLA001CC2MES.P	750	754.83	20.01		13.55	-741.28
BELLA001G20MES.P	250	255.03	28.82		0.16	-254.87
BELLA001G21MES.P	250	250.03	42.92		11.46	-238.57
BELLA001G22MES.P	250	249.44	0		0	-249.44
HAMEO220TG1MES.P	110	88	108	108	108	20
HAMEO220SHGTLMES.P	100	14	61	104	93	79
TILGC003G3MES.P	230	191	205	237	219	28

Table 2. 5: List of the generators during the event and their response.

Discussion:

The table2.5 shows the list of the generator during the event of Bellarat with nominal power of each generator and power generation response for the frequency fluctuation. In addition to power deviation as known also as the power contribution of the generator in regulating the system frequency.

Units		Fn	F measured	dF	time to sense	time to reach the max	Regulating energy	K	generation rate
BERRO220GROUP2MES.P		50.007999	49.412998	0.595001	16 s	196 s	59.83	8%	82.04%
HAMMC002G3MES.P		50.007999	49.412998	0.595001	4 s	12 s	59.83	7%	89.85%
BOUFC220AGRP3MES.P		50.007999	49.412998	0.595001	4 s	16 s	59.83	8%	47.26%
RADJE400AGROU3MES.P		50.007999	49.412998	0.595001	36 s	36 s	59.83	13%	73.52%
SKHCE400TG1MES.P		50.007999	49.412998	0.595001	4 s	4 s	59.83	13%	106.55%
SKHCE400TG3MES.P		50.007999	49.412998	0.595001	4 s	32 s	59.83	13%	96.02%
SKSCE400TG1MES.P		50.007999	49.412998	0.595001	12 s	28 s	59.83	8%	97.50%
SKSCE400TG2MES.P		50.007999	49.412998	0.595001	12 s	12 s	59.83	6%	74.44%
SKSCE400TG3MES.P		50.007999	49.412998	0.595001	12 s	12 s	59.83	8%	102.08%
SKSCE400TG4MES.P		50.007999	49.412998	0.595001	12 s	12 s	59.83	6%	95.00%
SKDCE400TG2MES.P		50.007999	49.412998	0.595001	8 s	8 s	59.83	13%	92.75%
NAAMC400MECHP1MES.P		50.007999	49.412998	0.595001	8 s	8 s	59.83	25%	18.40%
NAAMC400MECHP2MES.P		50.007999	49.412998	0.595001	8 s	8 s	59.83	25%	20.67%

SKTCE001G2MES.P	50.007999	49.412998	0.595001	8 s	8 s	59.83	13%	105.79%
SKTCE001G3MES.P	50.007999	49.412998	0.595001	12 s	12 s	59.83	13%	97.63%
AARCE400AGROU1MES.P	50.007999	49.412998	0.595001	24 s	24 s	59.83	13%	75.70%
AARCE400AGROU2MES.P	50.007999	49.412998	0.595001	8 s	8 s	59.83	13%	45.15%
AARCE400AGROU3MES.P	50.007999	49.412998	0.595001	24 s	24 s	59.83	13%	84.33%
MSILA001G1MES.P	50.007999	49.412998	0.595001	8 s	8 s	59.83	8%	70.03%
MSILA001G2MES.P	50.007999	49.412998	0.595001	8 s	168 s	59.83	8%	83.32%
BELLA001CC2MES.P	50.007999	49.412998	0.595001	4 s				
BELLA001G20MES.P	50.007999	49.412998	0.595001	4 s				
BELLA001G21MES.P	50.007999	49.412998	0.595001	4 s				
BELLA001G22MES.P	50.007999	49.412998	0.595001	4 s				
HAMEO220TG1MES.P	50.007999	49.412998	0.595001	12 s	12 s	59.83	4%	80.00%
HAMEO220SHGTLMES.P	50.007999	49.412998	0.595001	8 s	24 s	59.83	3%	14.00%
TILGC003G3MES.P	50.007999	49.412998	0.595001	4 s	16 s	59.83	8%	83.04%

Table 2. 6: List of the generators during the event and their different parameters.

- **Discussion:**

The table2.6 shows the list of the generator of the event of Bellarat and the frequency before the event and after it and its deviation. In addition to the time response of each generator and the static drop of the power plant. Finally, it shows also the amount of the energy regulation and the rate of generation of each generator.

type of the unites	number of the unites	number of the unites reacted	reserve contribution	All unites average	contributed unites avrage
all unites	23	16	356.01	15.48	22.25
TG unites	8	7	113.29	14.16	16.18
CC unites	14	8	163.71	11.69	20.46
HAMEO220SHGTLMES.P	1	1	79	79	79

Table 2. 7: The average contribution of the combined cycle and gas turbine during the event of Bellarat.

This table2.7 shows the average contribution of gas turbine unites and combined cycle unites in addition to their total contribution during the event of Bellarat.

2.10. Conclusion

This chapter has examined a various aspects of frequency control methods and implementation strategies, along with an analysis of reserve power and primary reserve. We have highlighted the benefits and disadvantages of various frequency control strategies emphasizing their individual strengths and limitations.

In addition, a comparison of the UCTE and NERC criteria has been provided, highlighting the differences in the frequency configurations and other criteria employed by the two organizations. Furthermore, the major frequency response specifications for NERC and UCTE have been compared, illustrating the similarities and contrasts between the two sets of standards.

The Algerian frequency power system's resource availability and level of risk tolerance are important considerations for choosing the best frequency control solutions. Sonelgaz, the Algerian electricity company, has put in place certain risk-reduction measures and backup plans that are essential to maintaining the system's dependability and stability.

In the next chapter, we will delve deeper into these topics, providing an in-depth analysis of reserve power, a comprehensive comparison of frequency control strategies, and an exploration of the specific considerations for the Algerian frequency power system. Through these analyses, we aim to enhance the knowledge and effectiveness of frequency control mechanisms in maintaining power system stability.

In general, an efficient frequency control plan necessitates a thorough comprehension of various techniques and execution strategies. It is crucial to take into account the precise specifications and standards specified by pertinent organizations like UCTE and NERC. To preserve the stability and dependability of the system, appropriate contingency plans and risk mitigation techniques must be created and implemented in practice. In addition, the availability of resources and the level of risk tolerance of the power system should be taken into consideration.

Chapter 3: Primary Frequency Response Implementation methods.

3.1. Introduction

Primary frequency response is a power system control mechanism that helps maintain the balance between electricity generation and consumption by automatically adjusting the output of generators when there is a deviation in system frequency. In simple terms, primary frequency response is an automatic way of adjusting power generation to keep the power grid stable when there is a sudden change in demand. It is an essential feature of power systems that helps ensure a reliable and stable supply of electricity to consumers. In this chapter, the primary frequency response implementation will be analyzed, including its challenges and limitations, to evaluate its effectiveness in maintaining power system stability.

The purpose of the analysis section is to provide a comprehensive evaluation of the primary frequency response implementation, including its challenges and limitations. This analysis aims to provide insights into the effectiveness of the current methods of primary frequency response implementation and identify potential solutions to address the challenges and limitations. The analysis also includes case studies of real-world implementations of primary frequency response to help illustrate the practical applications of the mechanism. Ultimately, the goal of this analysis is to provide a better understanding of primary frequency response and its role in maintaining power system stability.

3.2. Primary Frequency Response Implementation Overview

Primary frequency response is a mechanism that helps maintain power system stability by automatically adjusting the output of power generators in response to changes in system frequency. In Algeria, primary frequency response is likely to be implemented in a similar way as in other power systems, where generators are equipped with control systems that can detect frequency deviations and automatically adjust the output of the generator to bring the system frequency back to its nominal value.

To implement primary frequency response, power system operators typically establish agreements with power generators to provide a certain amount of frequency response in exchange for compensation. The frequency response capability of a power plant depends on various factors, such as the type of generator, its operating conditions, and its control system.

In Algeria, the primary frequency response implementation may be governed by local regulations or standards, and may involve coordination between power system operators and power generators to ensure that the system frequency is maintained within acceptable limits.

3.3. The fundamental elements of implementation

The key components of primary frequency response implementation typically include the following [4]:

1. **Frequency Measurement:** Frequency measurement is essential to primary frequency response implementation as it provides a means of detecting frequency deviations from the nominal frequency. Typically, frequency measurements are taken at multiple points in the power grid to ensure that frequency deviations are detected as soon as possible.

2. **Control Systems:** Power generators must be equipped with control systems that can detect frequency deviations and automatically adjust the output of the generator to bring the system frequency back to its nominal value. These control systems can be based on various technologies, such as analog or digital controllers, and can include various types of control algorithms.

3. **Communication Systems:** Communication systems are essential for coordinating the primary frequency response across the power grid. Typically, power system operators need to communicate with power generators to provide instructions and to monitor the status of the generators. Communication systems can be based on various technologies, such as wired or wireless networks.

4. **Agreements and Compensation:** Power system operators typically establish agreements with power generators to provide a certain amount of frequency response in exchange for compensation. These agreements specify the terms of the frequency response, such as the amount of response required, the duration of the response, and the compensation offered to the generator.

5. **Monitoring and Control Centers:** Monitoring and control centers are responsible for monitoring the power grid and coordinating the primary frequency response. These centers typically use advanced monitoring and control systems to detect frequency deviations and to provide instructions to power generators.

Overall, the key components of primary frequency response implementation are designed to detect frequency deviations and to automatically adjust the output of power generators to bring the system frequency back to its nominal value. These components work together to ensure that the power grid remains stable and that the supply of electricity to consumers is reliable.

3.4. Challenges Associated with the Implementation

- The challenges that arise when implementing primary frequency response:

  Implementing primary frequency response can pose several challenges, some of which include:

1. **Control System Design:** Designing control systems for power generators that can detect frequency deviations and adjust the output of the generator accordingly can be complex and challenging. The control system must be fast and accurate to respond to changes in frequency, and it must be robust enough to operate under a variety of operating conditions.

2. **Communication Delays:** Communication delays between power system operators and power generators can delay the implementation of primary frequency response, reducing its effectiveness in maintaining power system stability.

3. **Grid Integration:** Integrating primary frequency response into the power grid can be challenging, particularly in large, complex power systems. The implementation of primary frequency response must be coordinated across the entire power grid to ensure that frequency deviations are detected and corrected quickly.

4. **Cost:** Implementing primary frequency response can be costly, particularly for smaller power generators. The cost of implementing frequency response capabilities can be a significant barrier to entry for smaller generators, limiting the number of generators that can provide primary frequency response.

5. **System Inertia:** The effectiveness of primary frequency response can be limited by the amount of system inertia in the power grid. Inertia is a measure of the energy stored in the rotating masses of generators and motors, and it plays an important role in maintaining system stability. Power systems with low levels of inertia may require additional frequency response capabilities to maintain stability.

6. **Policy and Regulatory Barriers:** Policies and regulations can pose barriers to the implementation of primary frequency response. Regulations may impose technical or economic constraints that limit the ability of power generators to provide frequency response capabilities.

Addressing these challenges requires careful planning and coordination among power system operators, power generators, and policymakers. Effective primary frequency response implementation must take into account the specific technical, economic, and regulatory conditions of the power system.

3.5.1. Challenges in Primary Frequency Response Implementation (Causes and Impacts)

The table3.1 summarizes the challenges, causes, and impacts of primary frequency response implementation:

Challenge	Cause	Impact
Control System Design	Complexity and accuracy requirements	Reduced effectiveness of primary frequency response
Communication Delays	Delays in communication between operators and generators	Reduced effectiveness of primary frequency response
Grid Integration	Challenges in coordinating implementation across the power grid	Reduced effectiveness of primary frequency response

Cost	High implementation costs, particularly for smaller generators	Limited availability of primary frequency response
System Inertia	Low levels of system inertia	Reduced effectiveness of primary frequency response
Policy and Regulatory Barriers	Technical and economic constraints imposed by policies and regulations	Limited availability of primary frequency response

Table 3. 1: list of challenges, causes, and impacts of primary frequency response implementation.

3.5.2. The limitations of the current methods for primary frequency response

The current methods for primary frequency response, such as the use of governor droop control and load shedding, have several limitations. Some of these limitations include:

1. **Slow Response Time:** Governor Droop control and load shedding can be slow to respond to frequency deviations. This can result in a loss of power system stability and the potential for cascading failures.

2. **Limited Range of Response:** Governor Droop control and load shedding have a limited range of response. They can only provide frequency response within a narrow frequency range, which can limit their effectiveness in maintaining power system stability.

3. **System Inertia Dependence:** Governor Droop control and load shedding rely on the system inertia to maintain stability. Power systems with low levels of inertia may require additional frequency response capabilities to maintain stability.

4. **Limited Flexibility:** Governor Droop control and load shedding can be inflexible in their response. Once triggered, they provide a fixed amount of frequency response, regardless of the severity of the frequency deviation or the availability of other resources.

5. **Lack of Coordination**: The current methods for primary frequency response are often not well-coordinated across the power grid. This can result in redundant or conflicting responses that can further destabilize the power system.

6. **Limited Participation:** The current methods for primary frequency response are typically limited to large generators and are not widely available to smaller generators. This limits the number of resources that can contribute to frequency response and can increase the risk of power system instability.

In general, these limitations highlight the need for new and more effective methods for primary frequency response that can address the challenges and limitations of the current methods.

3.5.3. The impact of the limitation methods

These limitations impact the effectiveness of the primary frequency response implementation by reducing the ability of the power grid to maintain stability during frequency deviations, increasing the risk of cascading failures, limiting the participation of smaller generators, and reducing the flexibility and coordination of frequency response. This highlights the need for new and more effective methods for primary frequency response.

3.6. Emerging methods for primary frequency response

There are several new and emerging methods for primary frequency response that can address the challenges and limitations of the current methods. Some of these methods include:

1 **Virtual Synchronous Generators (VSGs):** VSGs use power electronics to emulate the behavior of synchronous generators, allowing them to provide fast and flexible frequency response. VSGs can be installed on smaller generators, which can increase the number of resources available for frequency response.

2. **Battery Energy Storage Systems (BESS):** BESS can provide fast and flexible frequency response by charging and discharging their stored energy in response to frequency deviations.

BESS can be installed at various points in the power grid, which can improve the coordination and flexibility of frequency response.

3. **Power System Stabilizers (PSS):** PSS can improve the stability of the power grid by adjusting the output of generators in response to frequency deviations. PSS can be integrated into the control systems of generators, allowing for coordinated and flexible frequency response.

4. **Demand Response (DR):** DR allows for the reduction of electricity demand during periods of high frequency deviation. DR can be implemented through smart grid technologies and can provide a flexible and scalable solution for frequency response.

5. **Flexible AC Transmission Systems (FACTS):** FACTS use power electronics to improve the control and stability of the power grid. FACTS can provide fast and flexible frequency response and can be installed at various points in the power grid.

6. **Flywheel energy storage system (FESS):** Flywheel energy storage systems help to maintain frequency stability by providing quick reaction times, high power density, cycle capabilities, and environmental advantages. Given their capacity to fast store and release energy, they are a useful option for reducing frequency variations and maintaining the dependable functioning of electric power networks.

In general, these new and emerging methods for primary frequency response can provide fast, flexible, and coordinated solutions to the challenges and limitations of the current methods. However, these methods may require additional investments in infrastructure, technology, and regulatory frameworks, which can pose challenges to their implementation.

3.7. Potential solutions to the challenges and limitations of primary frequency response implementation

These potential solutions can help address the challenges and limitations of primary frequency response implementation and improve the stability, reliability, and efficiency of the power grid.

Potential Solutions to Primary Frequency Response Challenges and Limitations
1. Increase the use of new and emerging methods, such as VSGs, BESS, PSS, DR, and FACTS.
2. Improve the coordination and communication between different stakeholders in the power grid.
3. Invest in research and development to improve the performance and efficiency of existing frequency response methods.

4. Implement regulatory frameworks that incentivize the use of frequency response resources and promote the development of new and innovative frequency response technologies.

Table 3. 2: Potential Solutions to Primary Frequency Response Challenges and Limitations.

3.8. Evaluate the feasibility of these solutions

The feasibility of the potential solutions to primary frequency response challenges and limitations depends on various factors, including technical, economic, and regulatory considerations. Here is a brief evaluation of the feasibility of each solution:

1. Increasing the use of new and emerging methods: This solution is feasible and already being implemented in some power systems. However, it may require significant investments in new technologies and infrastructure.

2. Improving coordination and communication: This solution is feasible and can be implemented through improved protocols and standards for data sharing and communication. However, it may require significant changes to the organizational and regulatory structure of the power system.

3. Investing in research and development: This solution is feasible and can lead to significant improvements in the performance and efficiency of existing frequency response methods. However, it may require significant funding and long-term commitment.

4. Implementing regulatory frameworks: This solution is feasible and can incentivize the use of frequency response resources and promote innovation. However, it may require significant changes to the regulatory framework and coordination between different regulatory bodies.

In general, while these potential solutions are feasible, their implementation will require a significant amount of planning, investment, and coordination among various stakeholders in the power system.

3.9. Energy Storage System (ESS)

An energy storage system is a technology or equipment that saves excess energy for later use. It is essential in modern energy systems because it addresses the difficulty of balancing energy supply and demand. Energy storage systems allow power to be captured and stored when it is abundant or cheap and then released when it is most required, such as during peak demand hours or when renewable energy sources are not providing power. Batteries, flywheels, compressed air, pumped hydroelectric storage, and thermal energy storage are all examples of these systems. They provide various advantages, including improved grid stability, intermittent renewable energy sources integration, and backup power during outages. The development and adoption of energy storage systems are essential for achieving a more sustainable and resilient energy future.

This project will focus more on the batteries and flywheel energy storage systems.

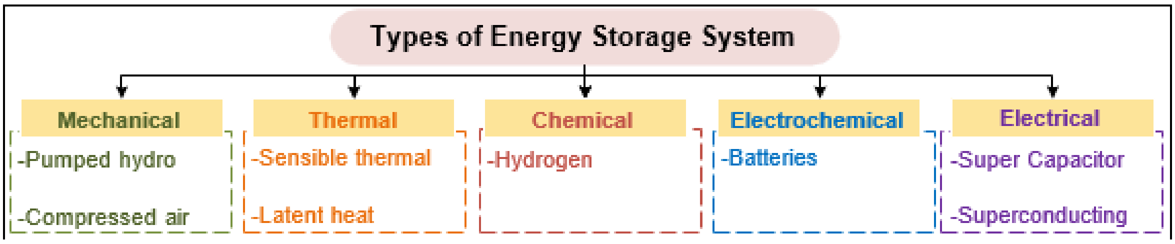


Figure 3. 1: Types of energy storage systems used in the power system **[9].**

Summary tables were made to show a brief description of different types of ESSs which reached the commercial or early commercial stage. In addition to presents a simple comparison between different ESSs. Figure3.2 shows briefly the capital cost of different ESSs.

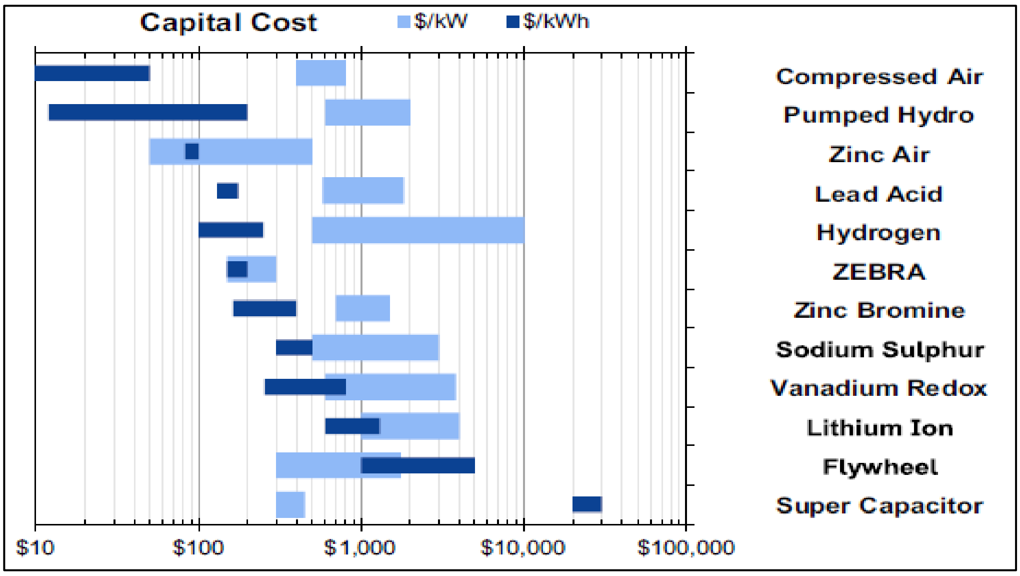


Figure 3. 2: A brief comparison of the power in kW and the energy in kWh costs in US dollars for various types of energy storage systems (Zinc Air, Lead Acid, ZEBRA, Zinc Bromine, Sodium Sulphur and Lithium Ion are types of batteries) **[9].**

Type	Structure	Advantage/disadvantage
Flywheel Energy Storage System (FESS)	The system stores energy mechanically be rotating a flywheel coupled with an electrical machine. By accelerating the velocity of the machine, the electrical energy is converted to mechanical energy. The electrical energy is retrieved by decelerating the velocity.	**The system has a long life, i.e. regarding the number of charging and discharging cycles, and a fast response. The high self-discharge is the main disadvantage of FESS.**

Lithium-Ion Battery Energy Storage System (BESS)	**The most conventional structure of Lithium-Ion battery contains a graphite anode, a cathode made of a Lithium metal oxide and an electrolyte consisting of a solution of a Lithium salt in a mixed organic solvent embedded in a separator felt.**	**The Li-Ion batteries have high power, high permissible depth of discharge, yet a high cost. However, the cost declined rapidly in the last years.**

Table 3. 3: flywheel and battery energy storage systems [9].

	Parameters / Type of ESS	Response time [70]	Discharge time [70]	Rated capacity (MW) [64]	Depth of discharge % [61]	Efficiency % [61]	Cycle lifetime [61, 64]
	Pumped hydro	min	hours	100-5000	100	70-80	**(30-60Y)**
	Compressed air	min	hours	50-300	70-90	70-89	**(20-40Y)**
	Flywheel	ms	sec to min	0.4-20	70-90	95	**(15-20Y)**
	Hydrogen	sec to min	hours	10-200	100	30-40	**(5-20Y)**
	Lead-Acid	ms	sec to hours	0-40	30-80	85	**(5- 20Y)**
Batteries	**Lithium-Ion**	ms	ms to hours	1-100	70-95	85-95	**(5-15Y)**
	Redox flow	sec	sec to hours	0.03-3	100	80	**(5-30+Y)**
	Sodium-Sulfur	**sec**	**sec to hours**	**0.05-34**	**92**	**70 -95**	**(5-15Y)**

Table 3. 4: Comparison between energy storage systems **[9]**.

3.9.1. The flywheel energy storage system (FESS)

The flywheel energy storage system (FESS) consists primarily of two main components: the electrical machine and the AC/DC power electronic converters. These components are essential for connecting the machine, which operates at variable speeds, to the power system.

In a commercial FESS, as depicted in Figure 2.6 **[2]**, the flywheel is enclosed within a vacuum chamber to enable it to rotate at high tangential speeds, thereby storing a greater amount of energy. However, it's important to note that as the velocity, density, and pressure of the gas surrounding the flywheel increase, so does the aerodynamic drag **[9]**.

To overcome the challenge of extracting heat from the rotor within a vacuum environment, a Permanent Magnet Synchronous Machine (PMSG) is utilized **[2]**. PMSGs offer higher efficiency and a smaller physical footprint compared to other types of motor/generator systems with similar ratings **[2]**. This choice of motor/generator type helps to optimize the performance and efficiency of the flywheel energy storage system.

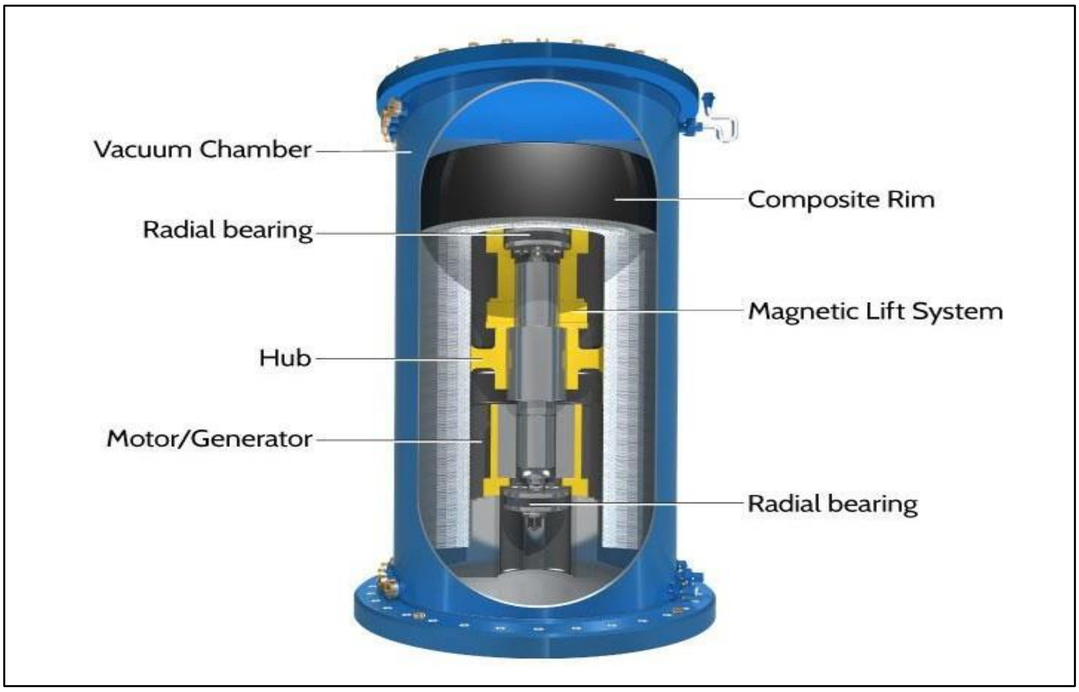


Figure 3. 3: A commercial flywheel energy storage unit by Beacon power co. **[10]**

The energy E (joule) stored in the FESS is **[11]**

$$E = KJ\omega max^2 \qquad 3.1$$

where K is the flywheel shape factor (K=0.93 for a constant stress disc and K=0.5 for a thin rim), J (kg.m^2) is flywheel moment of inertia which is determined by the mass and the shape of the flywheel and ω_{max} (rad) is the maximum velocity.
For a flywheel with a radius of r (m) and a mass concentrated in the rim mF (kg) with a concentration factor K=0.5, the energy stored can be calculated using equation (3.2) as:

$$E = 0.5 \times r^2 \times mF \times \omega_{\max}^{2} \quad (3.2)$$

The energy density stored, Evol, can be expressed per unit volume (Joule/m^3) using equation (3.3):

$$Evol = 0.5 \times \rho \times r^2 \times \omega_{\max}^{2} \quad (3.3)$$

Here, ρ (kg/m^3) represents the mass density.

The tensile stress, σ (N/m), in the rim is given by equation (3.4):

$$\sigma = \rho \times \omega_{\max}^{2} \times r^2 \quad (3.4)$$

The maximum velocity depends on the density and strength of the flywheel material [83]. Therefore, the maximum kinetic energy stored per unit volume (joule/m^3) can be calculated using equation (3.5):

$$Evol_{\max} = 0.5 \times \sigma max \quad (3.5)$$

A composite material made from a combination of carbon fiber and fiberglass was used in the commercial FESS **[10].** The New York system operator uses this 20 MW/6 MWh commercial FESS as a frequency control device. The system comprises of 200 flywheels, each of which has a 100 kW/30 kWh storage capacity **[12].**

Operating Flexibility	▪ **No dispatch restrictions and unlimited daily cycling** ▪ **Ability to instantaneously switch between energy, capacity and all ancillary services products to obtain the highest hourly and sub-hourly intervals and capture the real-time market's price volatility**
No Degradation	▪ No degradation and 30-year design life – eliminates the costs of oversizing systems to meet contracted 9 capacity and replacing depleted battery stack every 7-10 years ▪ No variable Operations & Maintenance (O&M) costs means the FESS will be dispatched more in wholesale markets and will capture more energy

	arbitrages spread
Extreme Temperature Operation	▪ Requires no HVAC and can operate in extreme temperatures (-40 to 50 C) and humidity ▪ Minimal fixed O&M (one maintenance outage every 10 years) make the FESS well-suited for remote environments and renewables + storage under long-term contracts
Safe and Sustainable	▪ No chemicals or hazardous materials, posing far less risk of fire or of environmental liability upon disposal ▪ 98% steel product can be recycled

Table 3. 5: Amber Flywheel Capabilities. [13]

3.9.1.1. Reduce Transmission Congestion and Losses:

To address the increasing congestion in California's transmission systems due to the rise in renewable energy generation, storage systems placed strategically on both sides of the congestion can be utilized. These storage systems can be dispatched during congested periods to alleviate system constraints and reduce transmission congestion costs and losses. Flywheel energy storage systems have demonstrated their ability to respond rapidly to demand signals from the California Independent System Operator (ISO), allowing them to charge and discharge electricity and effectively manage the grid while minimizing expenses.

12 MWh of congestion may be reduced by a 1 MW, 4 MWh flywheel energy storage facility that can cycle up to three times each day. If the average cost of congestion is $40 per megawatt-hour, each project would save California ratepayers $175,000 annually by reducing congestion. IOUs (Investor-Owned Utilities) might save California's customers $17.5 million annually by installing a 100 MW (400 MWh) flywheel energy storage system [13]. In contrast, conventional storage methods like lithium-ion batteries can only be cycled once every day, which yields just a third of the potential savings that flywheel systems may provide.

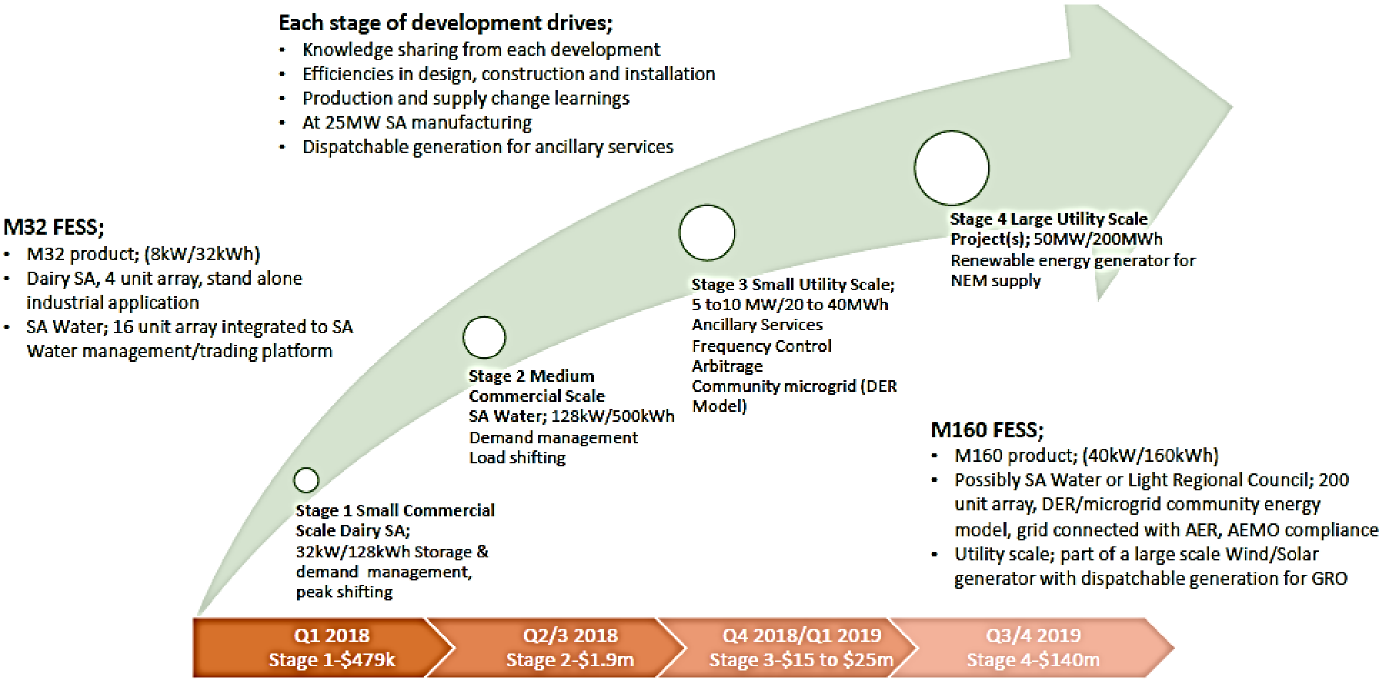


Figure 3. 4: FESS project development [13].

3.9.2. Battery energy storage system (BESS)

In order to reach the necessary voltage and capacity, a battery energy storage system (BESS) connects numerous cells either in series, parallel, or both ways [9]. According to estimates, the installed capacity of BESSs will rise from 1.5 GW in 2015 to over 14 GW by 2020 [9]. Due to the dramatic reduction in price of lithium-ion batteries over time, many of these systems use them as their principal technology. In actuality, Lithium-Ion battery prices have dropped from above $3,000/kWh in 1990 to around $200/kWh in early 2016 [14].

A typical commercial BESS arrangement is shown in Figure 3.5 [9]. A control unit that directs the system's overall functioning is installed in the system. Furthermore, a battery management system is used to continually track important variables including the voltage, temperature, and status of charge of individual battery modules [9]. The BESS operates safely and optimally thanks to these monitoring and control systems.

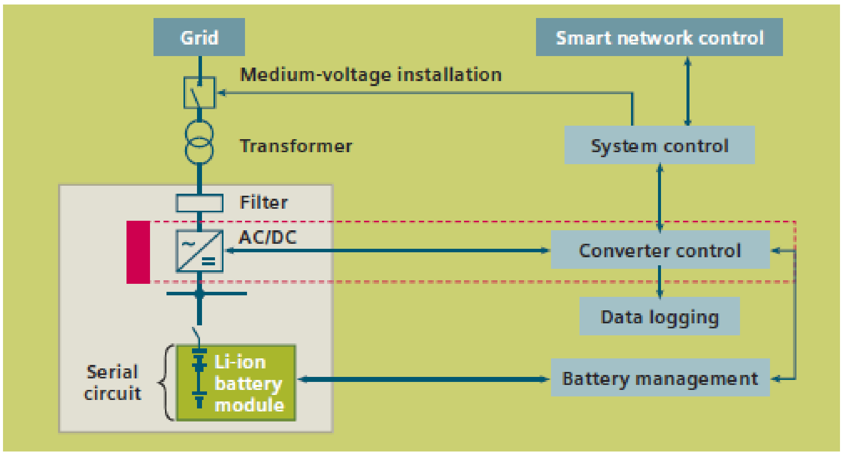


Figure 3. 5: A schematic diagram of a commercial battery energy storage system [9].

3.9.3. Energy storage systems for frequency response

In the Algerian electric power system, frequency response services can be provided in large part by energy storage devices. When the supply-demand balance fluctuates, the power system's capacity to maintain a constant frequency is referred to as frequency responsiveness.

Algeria may improve its capacity for frequency response by incorporating energy storage technologies into the grid in the following ways:

1. Frequency regulation: Power injection or absorption capabilities of energy storage systems allow them to react quickly to variations in system frequency, which helps to stabilize the grid. Energy storage can take in extra power when there is surplus generation, preventing frequency from increasing too much. On the other hand, when there is a lack of generation, stored energy can be released to keep frequency within reasonable bounds.

2. Quick Response Time: Compared to traditional power plants, energy storage systems offer the benefit of nearly immediate response times. They can respond to frequency variances quickly and accurately by offering frequency assistance in milliseconds.

3. Ancillary Services: Energy storage systems can help with ancillary services like main and secondary frequency regulation. In order to keep system frequency at the optimum level, these services constantly monitor and modify power injections.

4. Integration of Renewable Energy: Energy storage devices can help Algeria's expanding solar and wind energy industries. By holding onto extra energy during times of high generation and releasing it during times of low generation, energy storage can lessen the intermittent character of renewable energy sources. This helps to stabilize frequency.

In the Algerian electric power system, implementing energy storage devices for frequency response can improve grid stability, lessen reliance on conventional spinning reserves, and maximize the integration of renewable energy sources. Energy storage can aid in the development of an effective and dependable power system in Algeria by supplying quick and accurate frequency management.

3.10. Conclusion

In conclusion, this chapter has provided an overview of the implementation of primary frequency response, highlighting its fundamental elements. We have explored the challenges associated with its implementation and discussed the limitations of current methods.

To overcome these challenges and address the limitations, several solutions have been proposed. One such solution is the integration of energy storage systems for frequency response. Specifically, the utilization of energy storage systems like the flywheel energy storage system (FESS) and battery energy storage systems (BESS) can significantly enhance the effectiveness and efficiency of primary frequency response. These storage systems have the capability to rapidly inject or absorb power, allowing for quick adjustments to regulate system frequency and ensure stability.

Furthermore, reducing transmission congestion and losses plays a vital role in the successful implementation of primary frequency response. By optimizing transmission infrastructure and minimizing losses, the power system can effectively respond to frequency deviations and maintain stability.

In the next chapter, we will see the simulation of some energy storage system and how the integration of this storage systems affect the frequency stability of the system.

Chapter 4: Simulation of FESS and the modes of load control using BESS.

4.1. Introduction

The simulation chapter of this project focuses on the analysis and studying two energy storage systems the Flywheel Energy Storage System (FESS) and the Battery Energy Storage System (BESS). The simulations are conducted using Simulink, a powerful simulation tool, along with MATLAB scripting to perform a static analysis of the frequency response.

Modern power systems depend largely on energy storage systems because they maintain stability, control power flow, and ensure a steady supply of electricity. Two popular energy storage methods are FESS and BESS. FESS uses the concept of energy storage in a spinning mass, whereas BESS uses chemical processes to store and release energy.

This simulation chapter's main objective is to evaluate the frequency response characteristics of these two methods of energy storage. An essential aspect is frequency response analysis, which evaluates the way the system can manage variations in power demand and preserve grid stability.

4.2. MATLAB

MATALB stands for "MATrix LABoratory" and is known for its extensive matrix manipulation capabilities. The software is a powerful programming language and environment commonly used in scientific and engineering fields to simulate the different scripts and designs.

In addition, MATALB program is easy to use and give very precise results but it provides also very big library full of different designs and scripts some provided by the platform and other provided by the users who want to share their works.

One of the most interesting features is the ability to interface MATALB with other platforms and this will give the user the space and the freedom of designing and realizing the user ideas using the different platforms which can interface with MATALB.

The software is used in different application like mathematics and numerical analysis, signal processing, control system and robotics, machine learning and data analysis, simulation and modeling, and many different other applications.

MATLAB provides powerful tools for visualizing data, including plots, graphs, and charts. In addition to offering a variety of options for customizing the appearance and style of visualization (shape of the graphs, colors, the titles and lot of other options).

In this project, we used two platform provided by MATALB. The first one is MATALB script; we use it to write a script which will help us to do the analysis of the frequency response. The second one is MATALB Simulink; we did use it to simulate the different models.

4.3. Flywheel energy storge system (FESS):

MATALB Simulink is used to design a flywheel energy storage system connected to the utility grid. The purpose of this model is to supply power to the grid and act as buck up reserve for the system to maintain the frequency of the gird stabile.

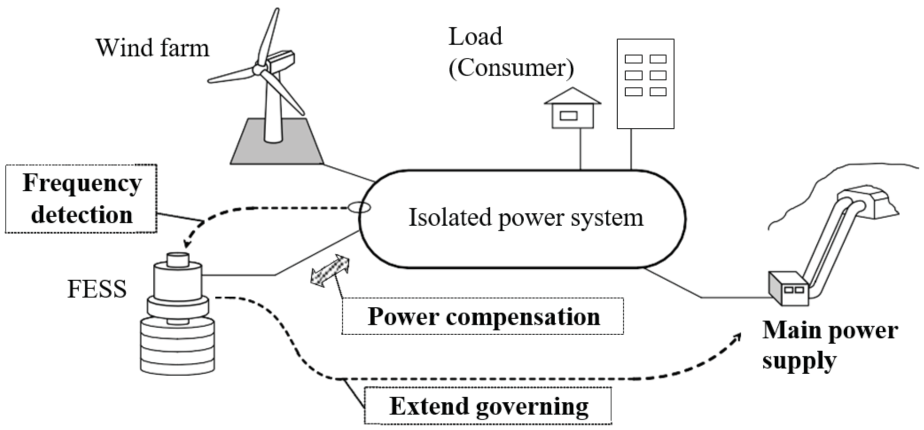


Figure 4. 1: Overview of FESS operation **[15].**

Description

When the load demand exceeds the wind production capability, the system integrates a flywheel technology to produce electricity. To meet the increasing load requirement, the flywheel system works as an energy storage device and enhances wind power. When there is no energy stored in the flywheel or when wind power is inadequate, a diesel generator is employed to provide the extra power needed.

The load is connected to the flywheel system, which is designed to store and release energy as needed. When the load demand exceeds the power provided by the wind turbine, the flywheel mechanism steps in to fill the void. It serves as a buffer, ensuring a constant and consistent power supply to the load.

When the wind power exceeds the load requirement in all-wind mode, the diesel generator may be turned off and the synchronous machine works as a synchronous condenser. The synchronous machine's excitation mechanism regulates the grid voltage to keep it at the nominal value, maintaining system stability.

A secondary load bank is used to control the system frequency. It is made up of eight series-connected sets of three-phase resistors and GTO thyristor switches. The load bank may change the system load in 1.75 kW increments from 0 to 446.25 kW. Excess wind power that exceeds consumer demand is absorbed by the secondary load bank, which aids in system frequency stabilization.

The Discrete Frequency Regulator block is used to regulate the frequency. To assess the system frequency, this controller employs a typical three-phase Phase Locked Loop (PLL) technology. The frequency error is calculated by comparing the observed frequency to the reference frequency (50 Hz), which is then integrated to provide the phase error. The phase error is used by a Proportional-Differential (PD) controller to create an output signal indicating the needed secondary load power. This signal is transformed into an 8-bit digital signal that is used to control the switching of the eight three-phase secondary loads. To reduce voltage disturbances, switching occurs at the zero crossing of voltage.

By introducing the flywheel system into the High-Penetration Wind-Diesel model, the whole system becomes more dependable and efficient, delivering a consistent power supply regardless of whether demand from the load is high or wind power output is low.

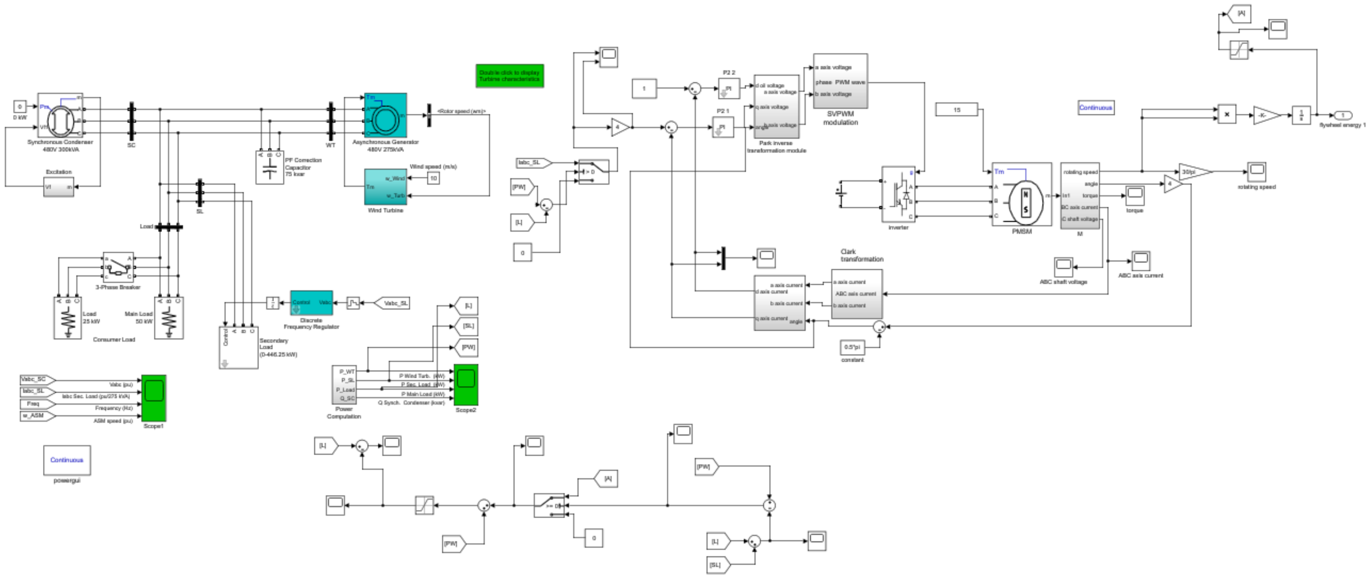


Figure 4. 2: The designed model of an isolated power system with flywheel energy storage system.

The power plant model

The power plant is a wind farm which consist of:

- Wind turbine.
- Asynchronous generator 480 V, 275 KVA.
- Correction capacitor of 75 KVA.

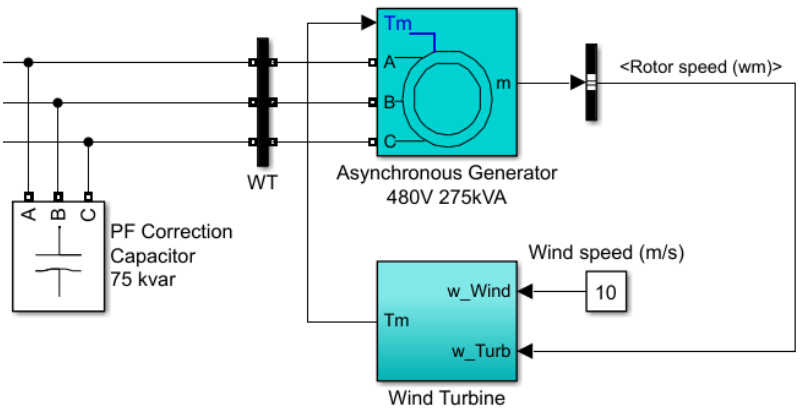


Figure 4. 3: Wind farm model.

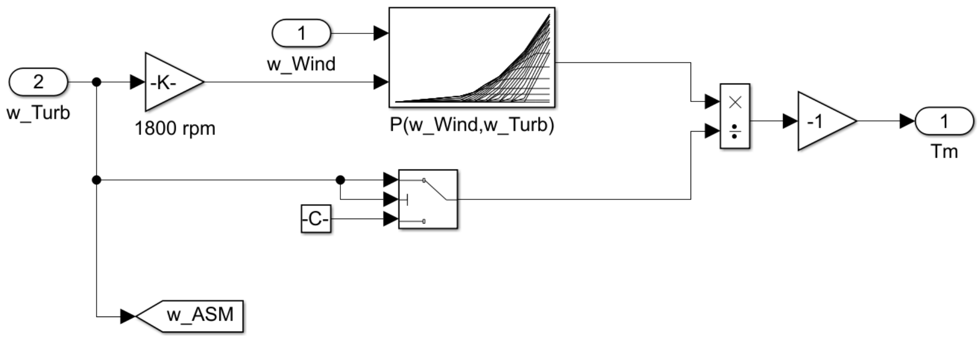


Figure 4. 4: wind turbine model.

Synchronous condenser

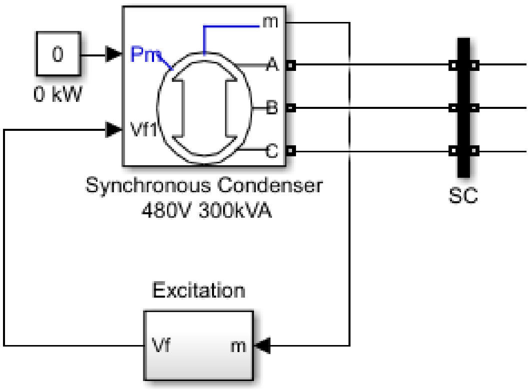


Figure 4. 5: synchronous condenser.

The load model

The model of the consumer load it consists of:

- Main load of 50 KW.
- Load of 25 KW

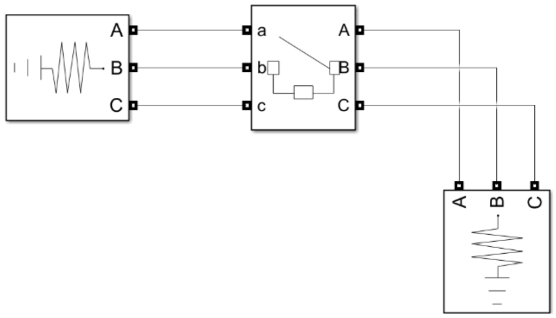


Figure 4. 6: consumer load model.

The secondary load or the damp load

This load has a control system which control the amount of the energy provided to the load, because the purpose of this load is to absorb the excess and the additional energy in the system.

- The capacity of this load is between 0 KW to 446.25 KW.

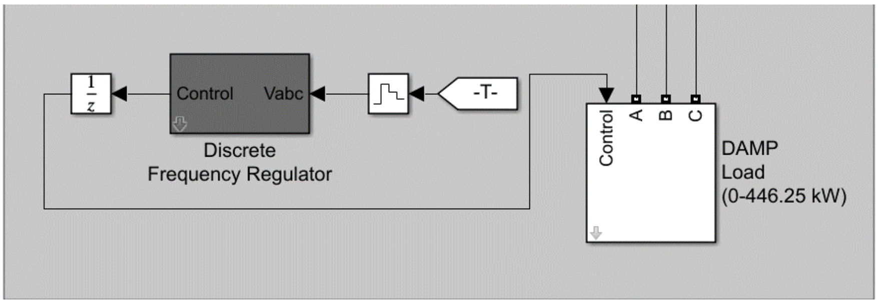


Figure 4. 7: The damp load model.

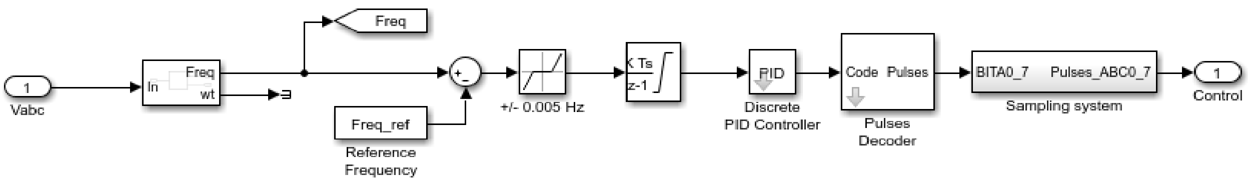


Figure 4. 8: Discrete frequency regulator model.

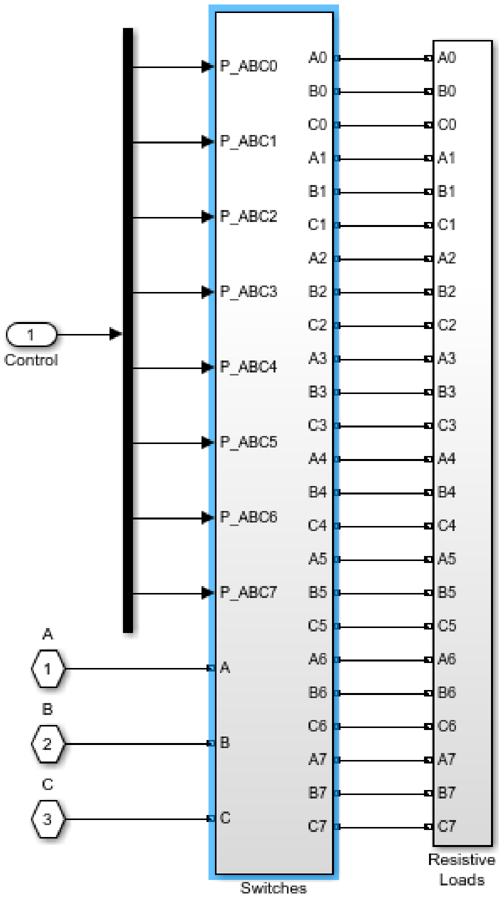


Figure 4. 9: The control system of the damp load.

Flywheel energy storage system

Flywheels are revolving masses that store kinetic energy. It is used as a system energy storage device. Its primary role is to store energy during times of excess energy and release it during times of deficit power. The inertia of the flywheel controls how much energy it can store and how quickly it responds to variations in power demand.

The model it consists of two parts. The first part is the FESS model and the second part is the control system of the flywheel model.

- Flywheel model:
  The flywheel model consists of asynchronous machine, inverter, capacitor, and converter as it shows in the figure below.

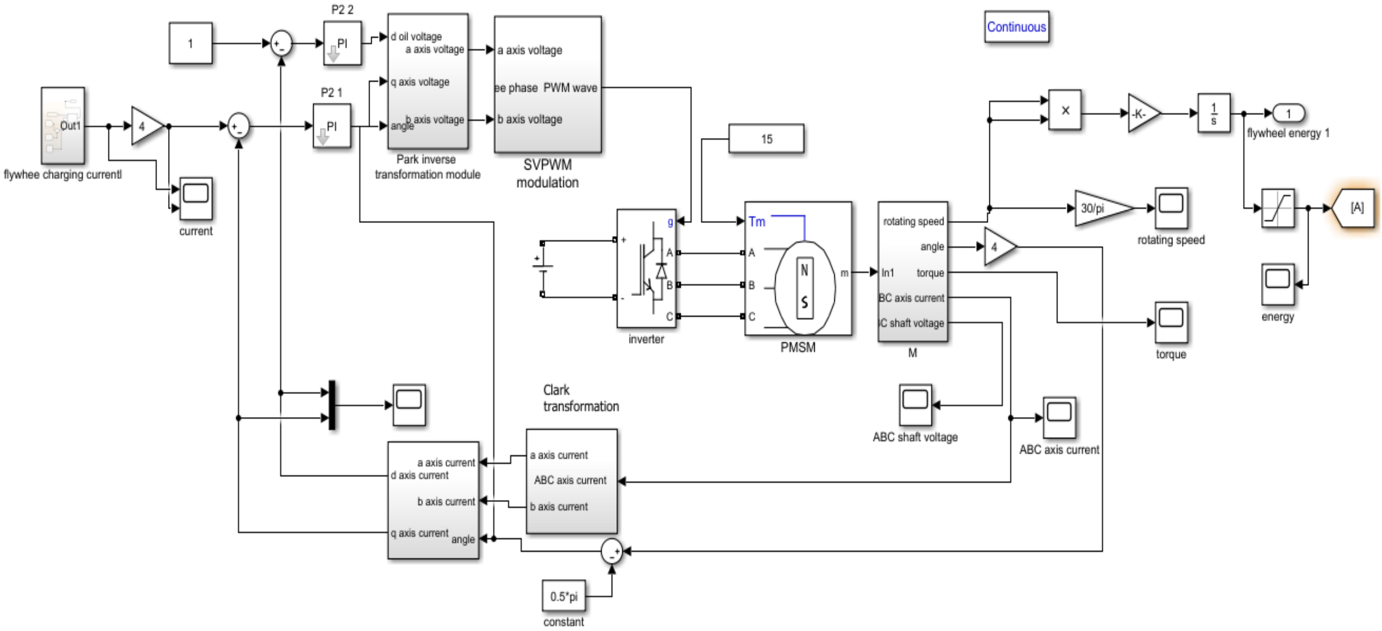


Figure 4. 10: Flywheel energy storage system model using Simulink matlab.

- **The control system model**
  The control system model consists of Clark and Park transformation and then goes to SVM to generate the signal to the inverter.

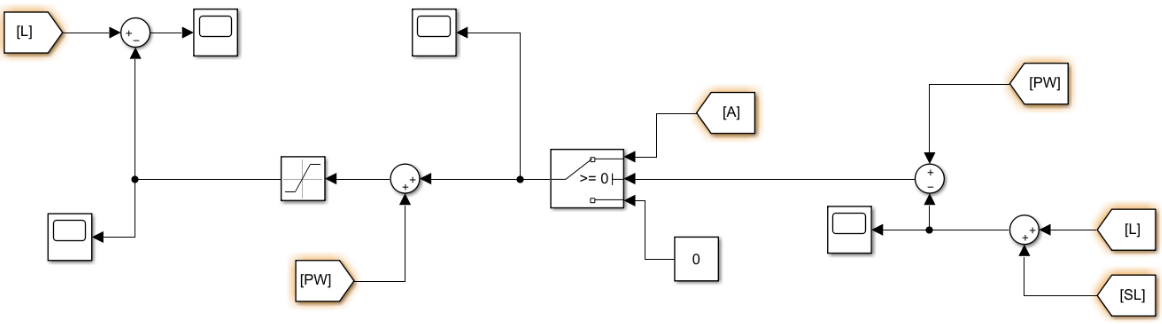


Figure 4. 11: Simplified discharging control model of flywheel using MATLAB-Simulink.

4.3.1. Simulation results

Wind turbine power:

The figure4.12 shows the change of power generated using the wind turbine with respect to the time.

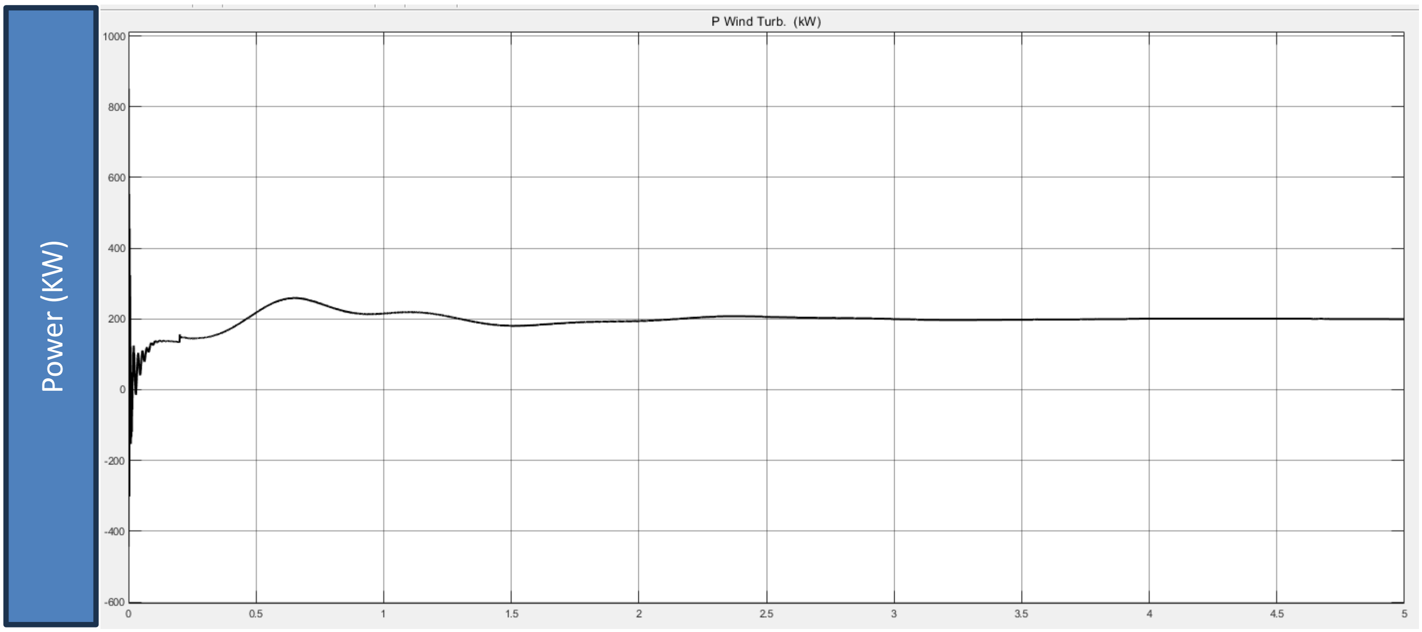


Figure 4. 12: power produced by the wind turbine over a period of 5 seconds.

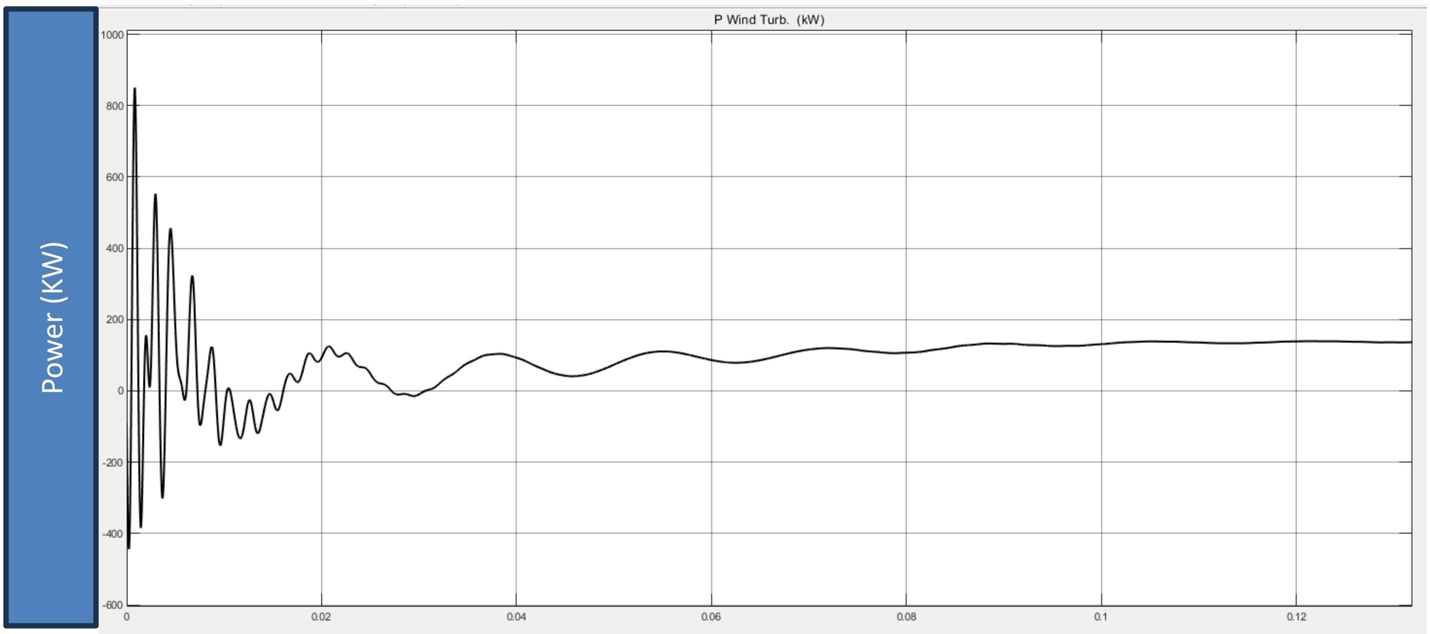


Figure 4. 13: power produced by the wind turbine over a period of 0.12 seconds.

Discussion:

The power produced by the wind generator and its fluctuation as it is displayed in the figure4.13. At the beginning we notice a fluctuation on the power generated by the wind generator and then by the time it stabilized on 170 MW.

The load power:

The curve in the figure shows the change in the power consumed by the main load with respect to the time.

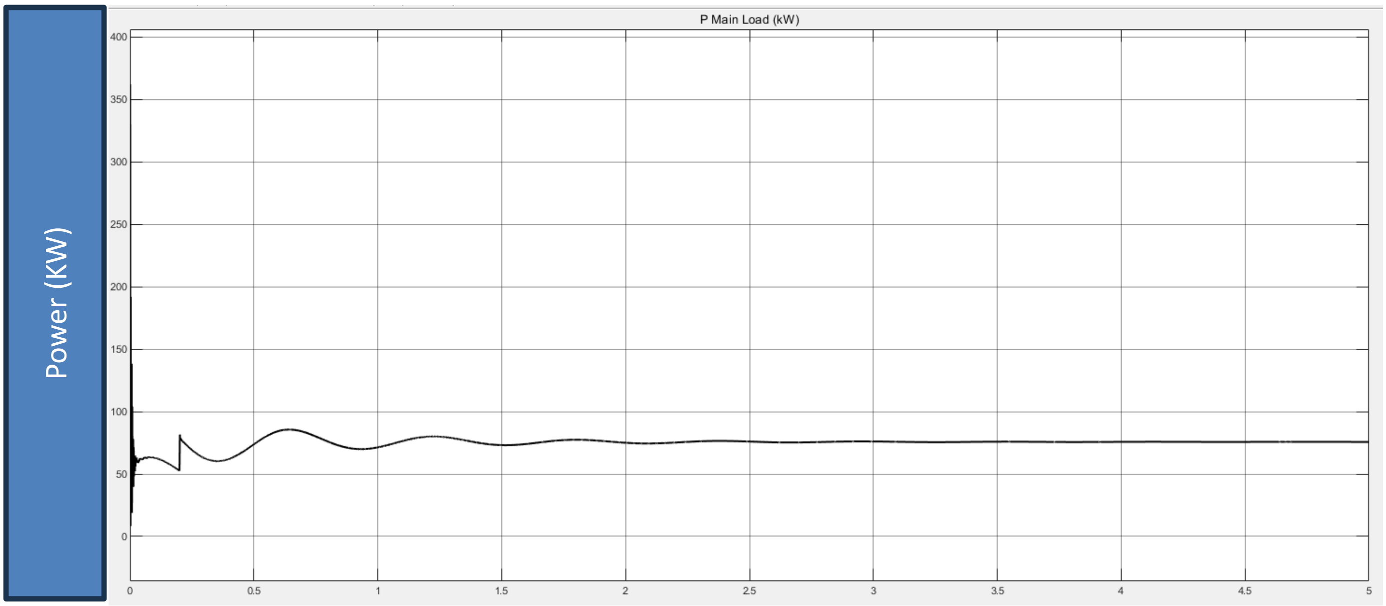


Figure 4. 14: Main load power consumption over a period of 5 seconds.

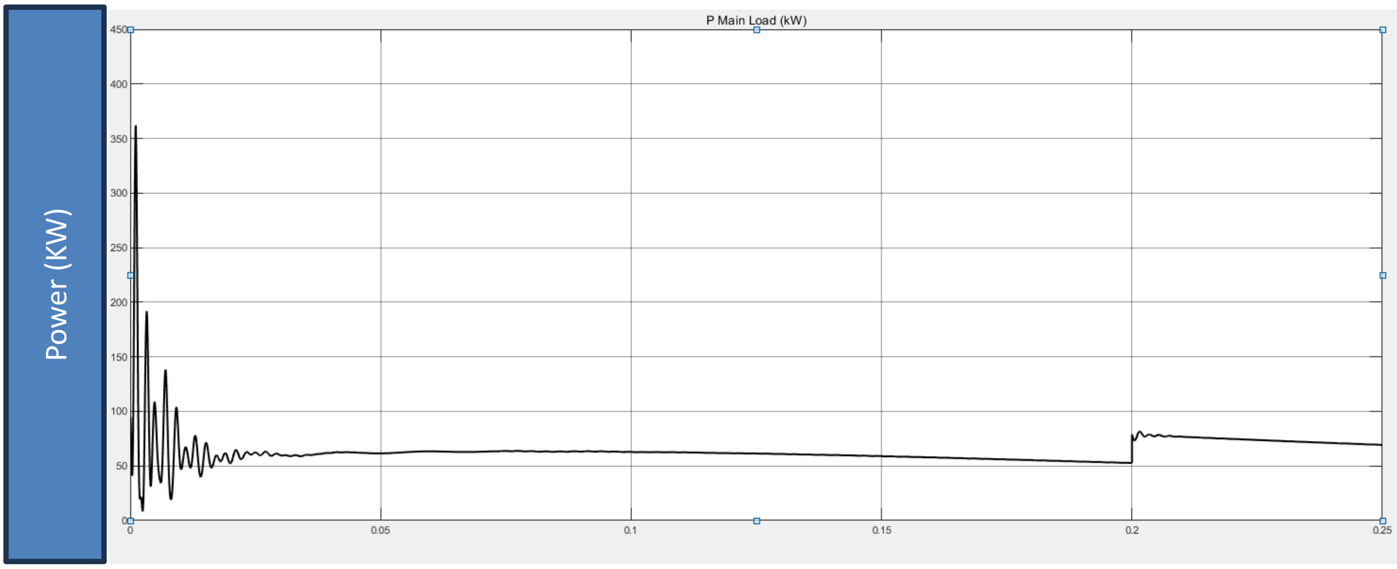


Figure 4. 15: Main load power consumption over a period of 0.25 second.

Discussion:

The figure4.15 shows the main load power consumption as it shows in the beginning there are instability on the power demand and after period the power demand become stable at 75 MW.

The secondary load:

The curve in the figure depicts the change in power utilized by the secondary load over time.

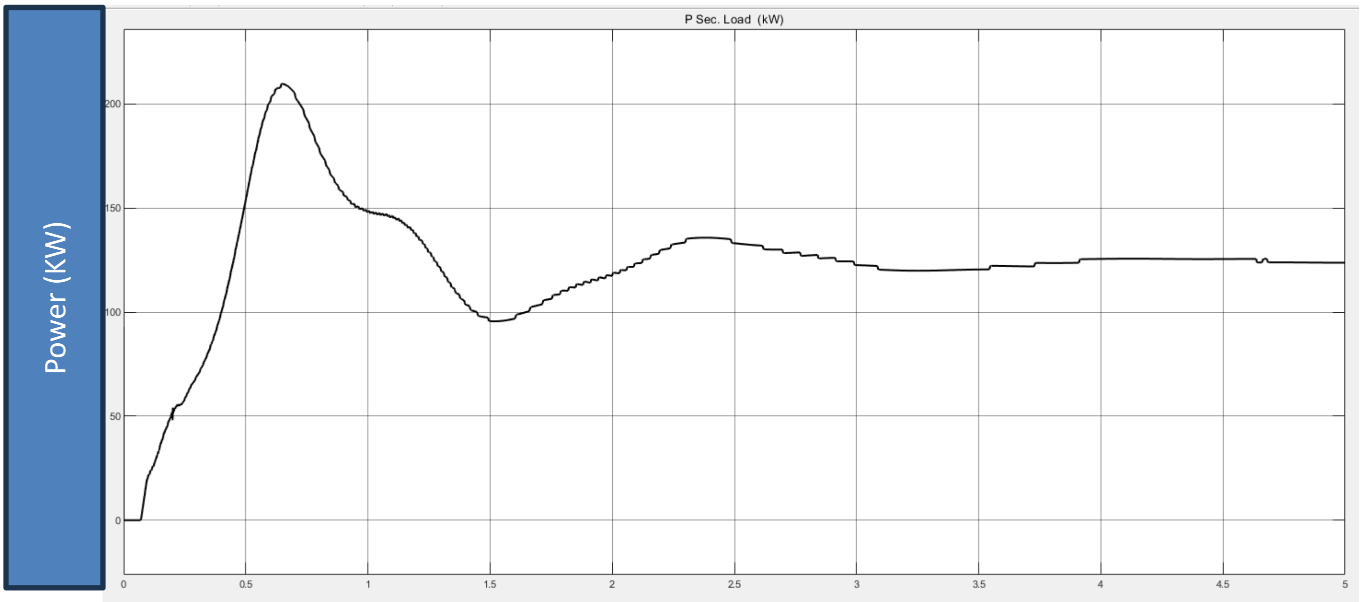


Figure 4. 16: The secondary load (damp load) power consumption.

Discussion:

The secondary load is used as dump load. The main purpose of this load is to consume the extra power produced by the wind turbine after it satisfy both the main load and the flywheel energy storage system (FESS).

In the beginning, the power consumed by this load is zero and it increase very slowly because of the instability of the wind generation and the charging of the flywheel energy system.

When the system is satisfied and the flywheel energy system is fully charged the extra power produced by the load is pumped to this secondary load to maintain the frequency stability of the system.

The flywheel charging current:

The figure4.17 shows the current used to charge the flywheel over the time.

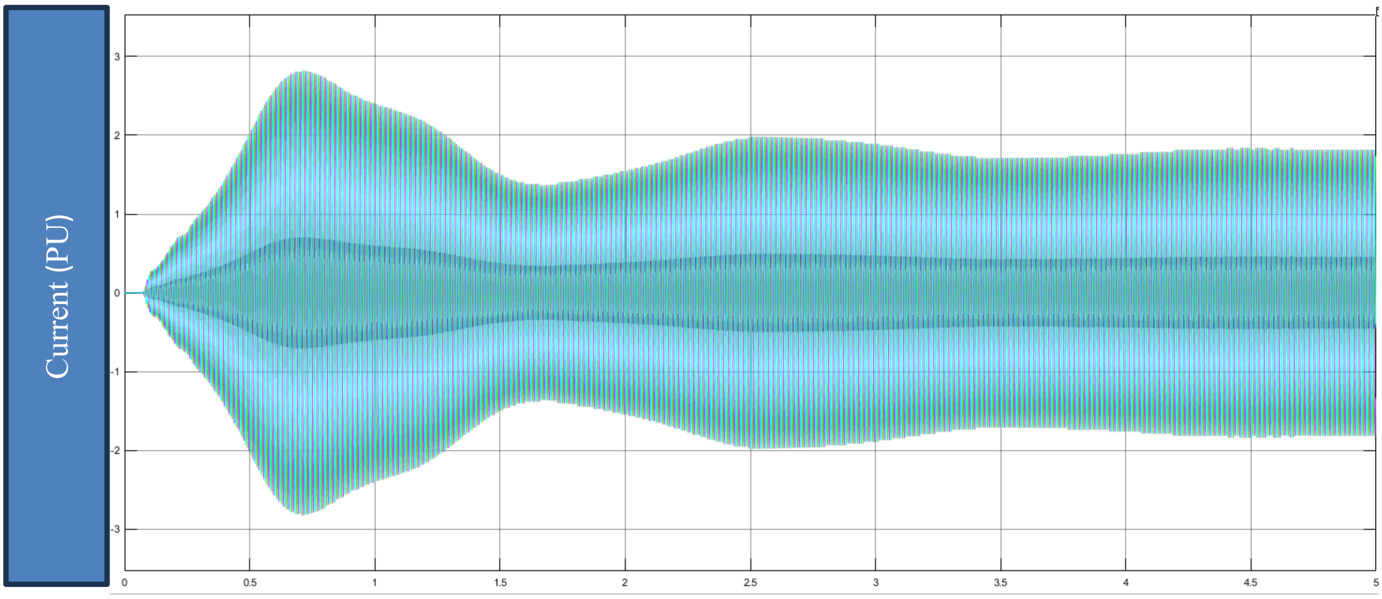


Figure 4. 17: The flywheel charging current.

Discussion:

The figure4.17 displays the current charging the flywheel this current is produced by the wind turbine.

In the first periods the current is at zero because of the wind instability so the power is directed to the main load. After that, the wind is producing and the extra power from the power distained to the main load, so this extra power will be stored in the flywheel and it will be released when it is needed.

The flywheel power charging:

The figure4.18 displays the curve of the flywheel while it is charging.

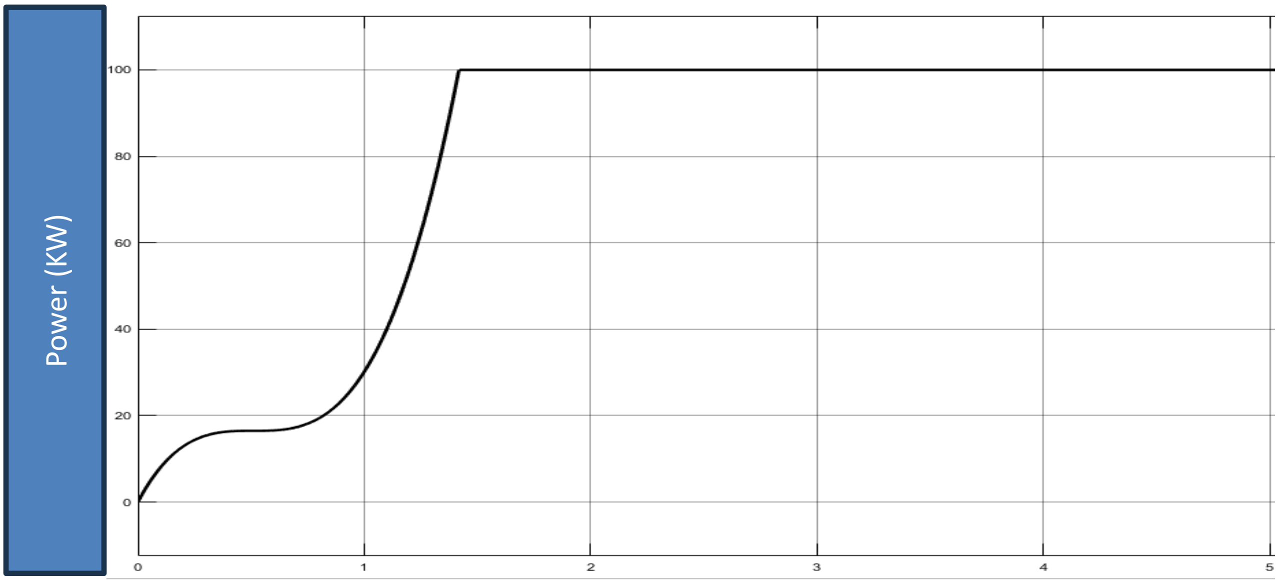


Figure 4. 18: The battery charging energy (KAh).

Discussion:

The figure4.18 displays the curve of the power during the charging period as it shows at the beginning the flywheel start charging very slowly because of the perturbation at the generation side. After that, the when the flywheel is fully charged it stabilized at its nominal charge power which is 100 KW.

The flywheel discharging energy:

The figure4.19 shows the curve of the flywheel energy supplied into the system whenever the power is needed.

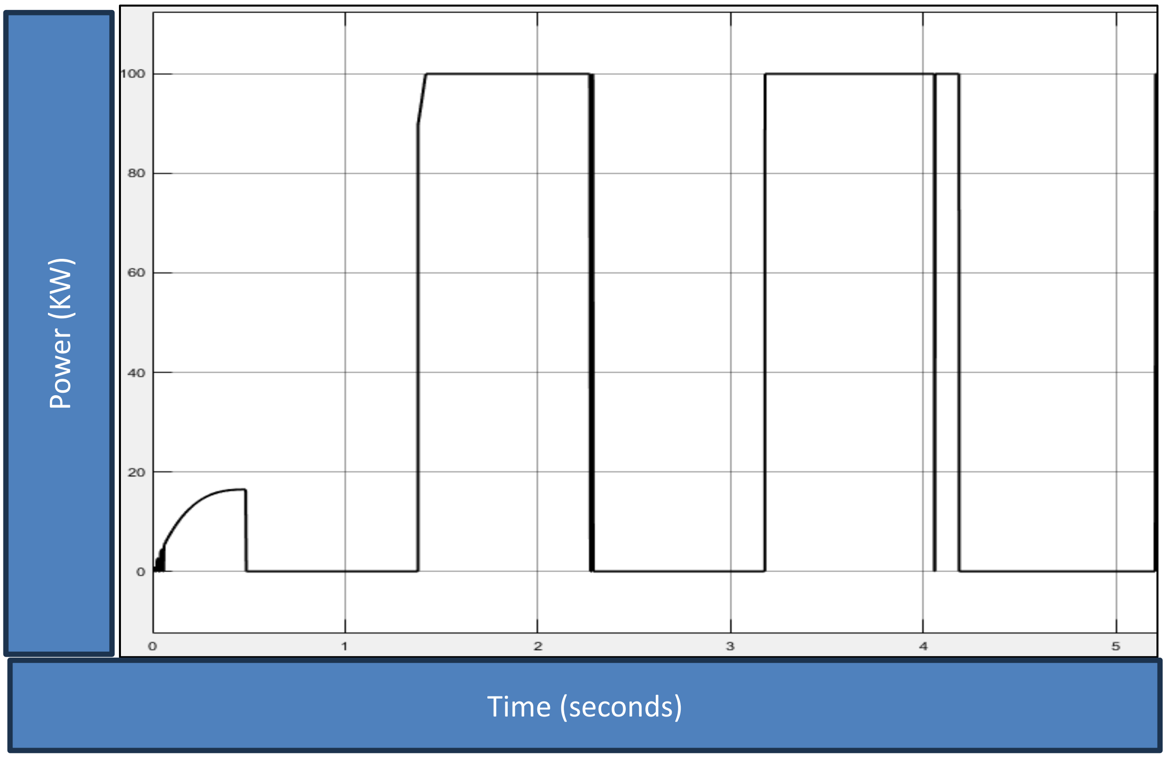


Figure 4. 19: The flywheel power (kw) supplied to the system.

The figure4.19 shows the power released by the flywheel in the system. As it shows in the figure at beginning the system did not response directly to the sudden insatiability on the produced power is due to the state of charge of the flywheel. Then, the soon the flywheel is charged it start contributing on the stability of the system by releasing the energy stored in it.

When the system is satisfied the power contribution is zero as it displayed in the figure.

The frequency response

The figure4.20 displays the frequency response of the system over time.

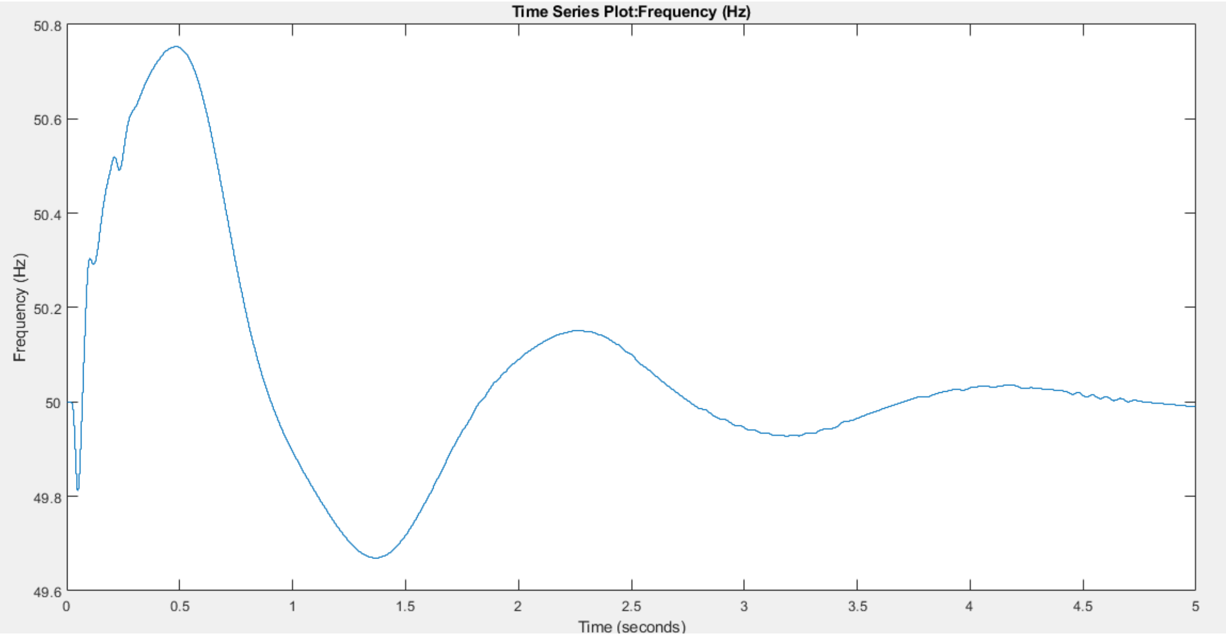


Figure 4. 20: The system's frequency response.

Discussion:

The figure4.20 shows the fluctuation on the frequency after period of time the frequency stabilize at its nominal frequency which is 50 Hz.

Due to fluctuation on the wind power and the main load this leads to instability in the system (power generation = power demand) which leads to the fluctuation in the system frequency.

The storing energy system and the diesel generator contribution are directly involved in the stability of the system. So, when we have extra power is produced by wind turbine, we store it in the flywheel and when it is fully charged, we despite this power in the secondary load.

When the system is in need of the power, we use first the power sored in the flywheel if it is not enough, we use the diesel generator to produce the power needed by the system.

4.4.1. Battery energy system storage BESS model

Battery Energy Storage networks (BESS) are critical components in modern power networks, providing benefits such as grid stabilization, peak shaving, load shifting, and renewable energy integration. MATLAB/Simulink is a popular tool for modeling and simulating complex systems, including BESS.

Implementing a BESS model using Simulink in MATLAB allows engineers and researchers to design and analyze the behavior of battery systems in a simulated environment. **[16]** Simulink provides a graphical interface where users can create a block diagram representation of the BESS system, incorporating battery models, power converters, control algorithms, and load profiles.

Users may simply construct and specify the components of a BESS system using Simulink's wide library of pre-built blocks. Battery behavior, including as charge and discharge characteristics, efficiency, and state-of-charge, may be predicted using mathematical formula.

Simulink also allows for the incorporation of control techniques to optimize the operation of the BESS. Control algorithms can be programmed to monitor power flow, maintain battery state-of-charge, and adapt to grid circumstances or specialized applications like peak shaving or load balancing.

The battery energy storage networks (BESS) MATLAB-Simulink model is presented below:

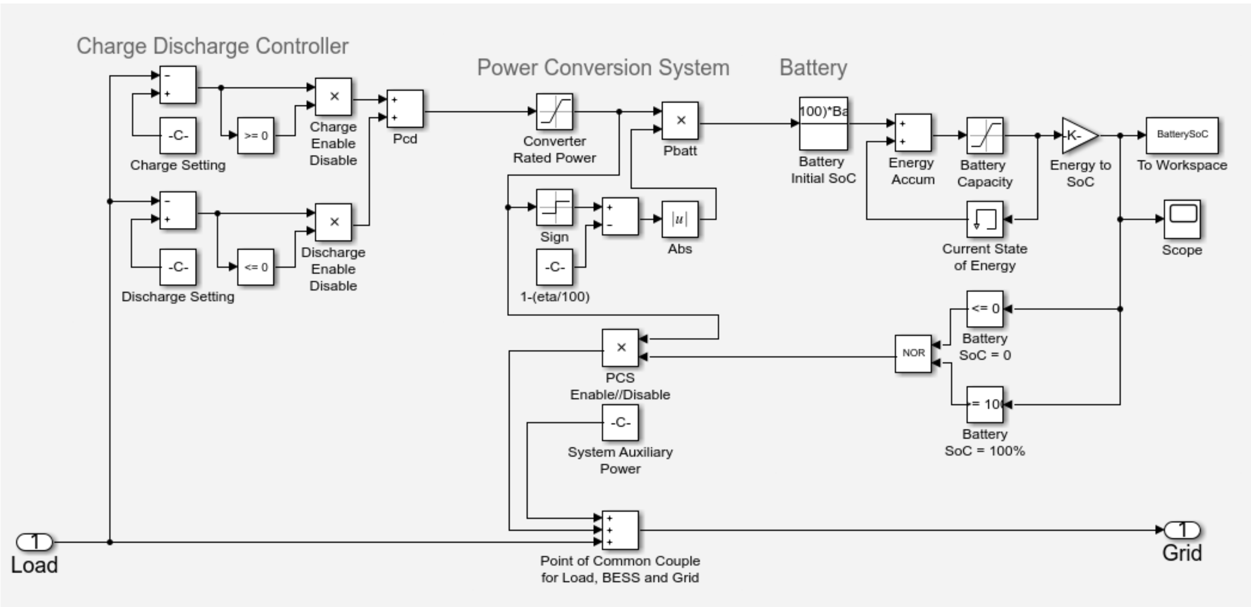


Figure 4. 21: Battery energy storage system BESS MATLAB-Simulink model.

4.4.2. Charge discharge controller

The charge-discharge controller is an essential part of the Battery Energy Storage System (BESS), and it carries out the control of regulating the battery's loading and draining operations. It guarantees that the desired charge or discharge power is taken into consideration by the BESS additional power.

The controller compares the load consumption to the charge setting in kilowatts (kW) during charging. If the load usage is less than the charge setting, the power conversion system uses the grid supply to charge the battery. The charge enables (Cen) is obtained by subtracting the charge setting power from the load consumption power. If the result is positive, indicating an excess of power, the Cen is activated, and the charge controller delivers the required power to the battery charger.

$$\mathrm{Cen} = 0: \text{if } (\text{charge setting} - \text{load consumption}) < 0 \qquad 4.1$$

$$\text{Cen} = 1: \text{ if (charge setting} - \text{load consumption)} \geq 0 \quad 4.2$$

Similarly, while discharging, the controller compares load consumption to the discharge setting. If the load usage exceeds the discharge level, the power conversion system draws energy from the battery to supply the load and decrease dependency on the grid. The discharge enables (Den) is obtained by subtracting the discharge setting power from the load consumption power. If the result is negative, indicating excess load demand, the Den is activated, and the discharge controller supplies the necessary power for the discharge of the battery.

$$\text{Den} = 0: \text{ if (discharge setting} - \text{load consumption)} > 0 \quad (4.3)$$

$$\text{Den} = 1: \text{ if (discharge setting} - \text{load consumption)} \leq 0 \quad (4.4)$$

The charge-discharge controller output (Pcd) is the sum of the charge and discharge operations. Since the Cen and Den values are additive, charging and discharging cannot occur at the same time. The Pcd is determined by multiplying the charge setting minus the load consumption by Cen and then adding it to the discharge setting minus the load consumption by Den. This combined output is then sent to the power conversion system.

$$\text{Pcd} = [(\text{charge setting} - \text{load consumption}) * \text{Cen}] + [(\text{discharge setting} - \text{load consumption}) * \text{Den}] \quad (4.5)$$

The charge-discharge controller plays an essential role in controlling the BESS's charge and discharge procedures. It provides optimal grid supply usage by allowing charging when there is extra power and discharging when there is excessive load demand. The output from the controller controls the power of the conversion system to maintain the desired charge and discharge operations of the battery.

4.4.3. Power conversion system

The power conversion system is an important component of the Battery Energy Storage System (BESS) that allows the battery, load, and grid to charge and discharge. It takes the output power from the charge-discharge controller as input, with a positive sign indicating charging and a negative sign indicating discharging. The input power flows through a saturation block, which represents the maximum charge and discharge power that the BESS is capable of handling.

The system's power conversion efficiency is important in calculating the charge and discharge power of the battery. The actual power flow into the battery can be determined by including a conversion efficiency value in the power conversion system (usually ranging from 80-95%). If the conversion efficiency is 90%, 100 kW grid charging will result in just 90 kW flowing into the battery.

$$\text{Pbatt} = \left(\text{sign} + \left(1 - \frac{\theta}{100}\right)\right) * \text{Pcd} \quad (4.6)$$

The output of the power conversion system is regulated by battery feedback and linked to the load and the grid through an Addition block. The system auxiliary power, which covers different energy requirements for operating the BESS, is also considered. This extra power is generally 5-20% of the rated power of the power conversion system. The final output consists of the total load, system auxiliary power, and grid charge or discharge power.

In the BESS, the power conversion system acts as an essential intermediate, controlling the flow of power between the battery, load, and grid. It takes into account power conversion efficiency, saturation limitations, and system auxiliary power to guarantee that the BESS operates efficiently and reliably. The resultant output power is directed to fulfill the total power demands of the load while taking into account the system's auxiliary power requirements.

4.4.4. Battery

The model's battery section takes input from the power conversion system in the form of a signed integer indicating power in kilowatts (kW) on an hourly basis from the power conversion system. A positive sign represents a charge, whereas a negative sign represents a discharge. The Battery Initial SoC block allows the user to specify the battery's initial state of charge (SoC) as a percentage. Before the Battery Energy Storage System (BESS) is activated, the battery is often pre-charged to a specific SoC, commonly up to 30%.
The Battery section has an additional block and a Memory block, which together constitute the battery energy accumulator and maintain track of the battery's current energy level. The saturation block guarantees that the battery's energy status stays within capacity limitations, preventing the SoC from going below 0% or exceeding 100%. The Gain block transforms the battery energy from kWh to a percentage of the state of charge.

The battery's output, which represents the state of charge, is routed to different components for monitoring, performance analysis, charting, and feedback to the power conversion system. The condition for the PCSen (Power Conversion System enable) signal is defined by Equation (5). If the SoC is less than 0% or larger than 100%, indicating an incorrect condition, the PCSen signal is adjusted to logical zero, thereby turning off the power conversion system output via the PCS enable and disable product block.

$$\mathrm{PCS_{en}} = \mathrm{SoC} \leq 0 \cup \mathrm{SoC} \geq 100 \qquad (4.7)$$

This logic assures that the charge converter stops charging the battery once it has reached 100% charge, preventing overcharging. Similarly, it prevents the battery from being discharged when it reaches 0% charge, preventing further depletion. The battery section allows the safe and optimal functioning of the BESS by monitoring and managing the status of the charge.

4.4.5. BESS model parameters setting

To assist user configuration of the BESS model for simulation and performance analysis, a parameter setting menu has been designed. Figure 4.22 presents the menu, which contains self-explanatory explanations for each option.

The Energy Storage Battery System Rated Power characteristics determine the maximum charge and discharge power (in kW) that the BESS power conversion system can manage. The nominal battery capacity describes the battery's energy capacity in kWh.

The Initial Battery State of Charge parameter indicates the battery's initial charge level before the simulation starts. Just before starting the BESS, it is typical to pre-charge the battery at an appropriate level of charge.

Users can adjust the converter efficiency as a percentage using the power conversion system efficiency. The BESS technical specifications provide this information.

The system auxiliary power, given as a percentage of the rated power of the BESS, accounts for the power necessary to run the BESS, such as cooling, monitoring, communication, protection, switchgear, and lighting.

The "charge battery when load consumption is below (kW)" parameter in the charge/discharge controller settings section specifies that the battery should be charged from the supply grid when load consumption falls below the specified value in kW. The "discharge battery when load consumption exceeds (kW)" parameter, on the other hand, indicates that the battery should be drained to provide power to the load when consumption exceeds the set value (kW).

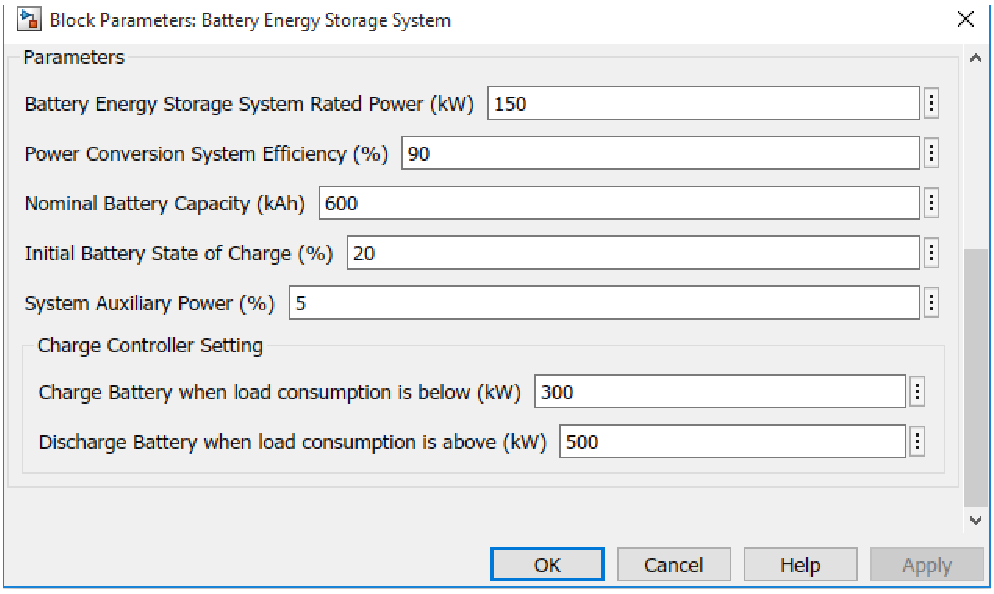


Figure 4. 22: BESS block parameters setting menu.

4.4.6. Outcomes and Discussion

The Battery Energy Storage System (BESS) result demonstrates the system's effectiveness and performance in controlling energy needs and improving power supply. The BESS results give vital insights into the system's efficiency, battery use, load-balancing capabilities, and total energy savings after examining the data and assessing critical factors. These results provide a detailed understanding of how the BESS model efficiently solves the issues of changing energy demand and improves grid stability, resulting in enhanced energy management.

4.4.6.1. Peak shaving

Maintaining frequency stability is critical for the stable performance of an electrical grid. Variations in power consumption can induce frequency variations, possibly leading to system instability. Battery Energy Storage Systems (BESS) provide an effective solution for frequency stability through peak shaving. The system may manage and stabilize grid frequency by deploying BESS to store extra energy during low-demand times and provide it during high-demand ones. This brief overview will look at how peak shaving with BESS helps to reduce frequency variations, improve grid stability, and provide a continuous and reliable supply of power.

In this case study, the performance of the Battery Energy Storage System (BESS) is examined. The BESS is rated at 150 kW and has a battery capacity of 720 kWh. The charge converter efficiency is 90%, and the initial state of charge is set at 10%. The auxiliary power of the system is 5%.

The load consumption is lower than the charging power set at 300 kW during off-peak hours (0 to 7 hours and 21 to 23 hours). As a result, the charge controller has been configured to charge the battery during certain times. To avoid exceeding the specified limit, the charging power is restricted to 300 kW. This allows the battery to charge up to 84.2% of its capacity, resulting in significant energy storage.

When the load consumption exceeds the predefined figure of 500 kW after 10 hours, the BESS begins draining power from the battery. Until 17 hours, the discharge power is kept at the intended trimmed power level of 500 kW. During this time, the battery's depth of drain hits 5.8%.

The BESS begins charging the battery again after 21 hours. The battery reaches a state of charge of 17.5% after 23 hours, which is greater than the original 10% charge level at the start of the experiment. This signals that enough energy has been saved for the next day, ensuring the cycle's sustainability.

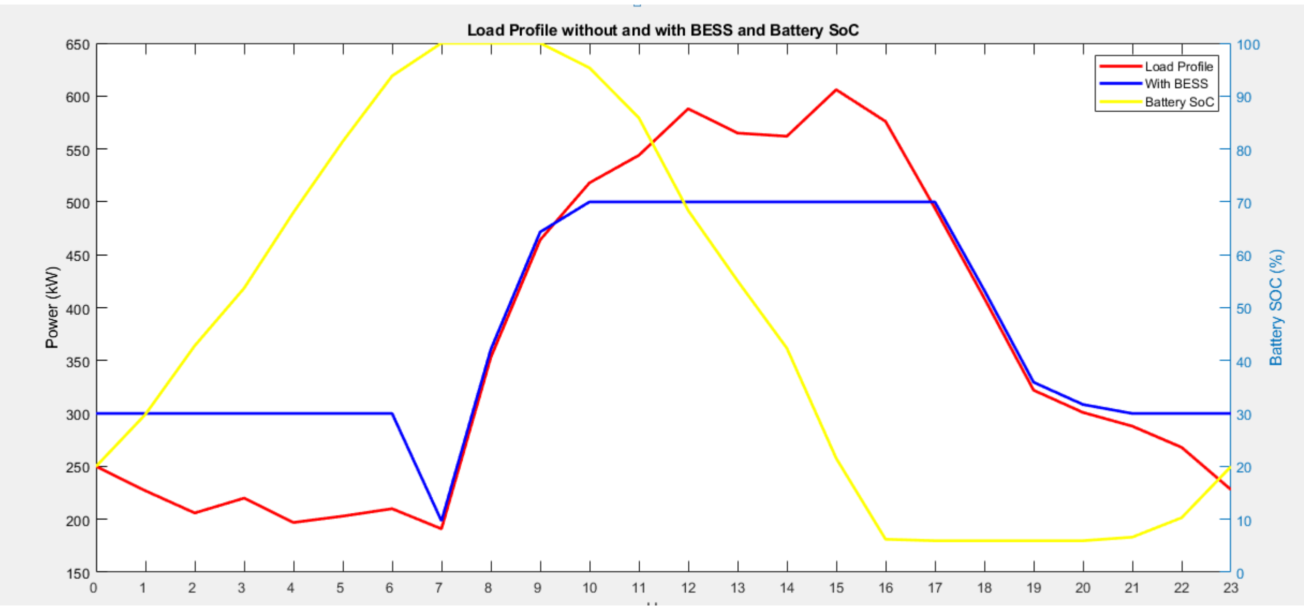


Figure 4. 23: Peak shaving load profile without and with BESS and battery SoC.

Peak shaving can help to stabilize the frequency of an electrical system. Fluctuations in power demand frequently result in frequency variations, which may lead to grid instability. Peak shaving techniques combined with Battery Energy Storage Systems (BESS) allow the system to actively control and limit power flow during periods of high demand.

During peak hours, when the demand for power is highest, BESS can discharge stored energy to fulfill load requirements, minimizing system strain. This helps to reduce frequency fluctuations caused by a power generation/consumption imbalance.

Furthermore, BESS can absorb extra electricity during periods of low demand or surplus output, smoothing out the supply and demand curve. By storing extra energy, the BESS may then release it at high demand periods, successfully filling in the gaps and maintaining a constant frequency.

The capacity of BESS to give instant reaction and swiftly modify its power output makes it a suitable choice for frequency control. Peak shaving using BESS helps to maintain the frequency by minimizing unexpected spikes or reductions in power consumption. This ensures that the electrical grid operates reliably and efficiently.

4.4.6.2. Load shifting

Load shifting with Battery Energy Storage Systems (BESS) can also help to stabilize an electrical grid's frequency. Load shifting is the process of relocating energy consumption from peak demand times to off-peak or low-demand periods.

Excess energy generated during off-peak hours can be stored and subsequently released during peak demand periods using BESS. This load shifting approach helps to balance power supply and demand throughout the day, minimizing grid pressure during peak hours.

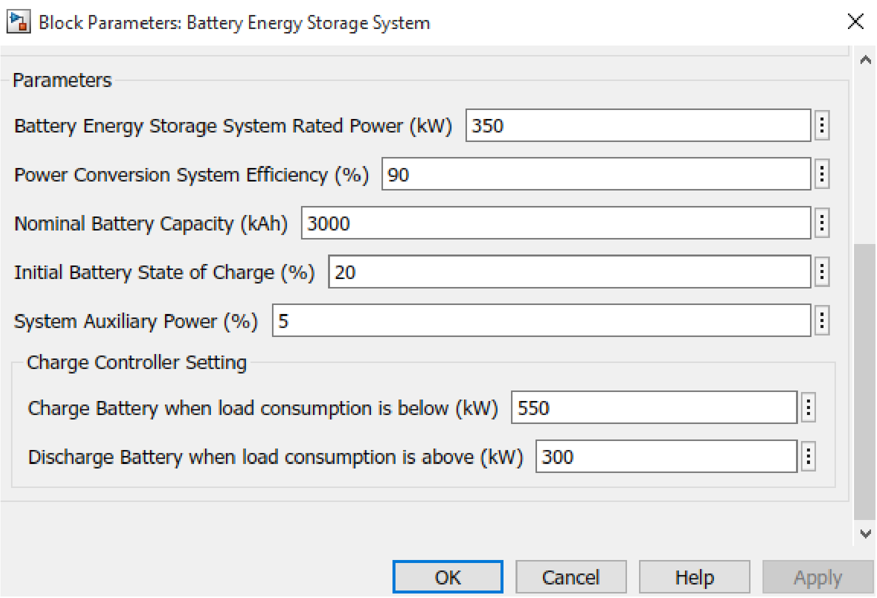


Figure 4. 24: Block parameters of load shifting using BESS.

Load shifting using BESS can assist stabilize the frequency in a variety of ways, including:

- Smoothing demand: Load shifting lowers power demand spikes by moving energy consumption from high-demand to low-demand times. This helps to minimize rapid frequency shifts, which might cause instability.
- Reducing peak power demand: Load shifting helps to relieve grid strain by deliberately releasing stored energy during peak demand periods. This reduces peak power demand and allows for more balanced energy distribution, supporting frequency stability.
- Increasing grid flexibility: BESS has a quick reaction capability, allowing for fast changes in power production. This adaptability allows load shifting to respond to fluctuations in demand while maintaining a steady frequency through effective power flow management.

Load shifting using BESS leads to a more stable frequency by successfully controlling energy consumption patterns and maximizing the use of stored energy, enhancing the overall dependability and efficiency of the electrical grid.

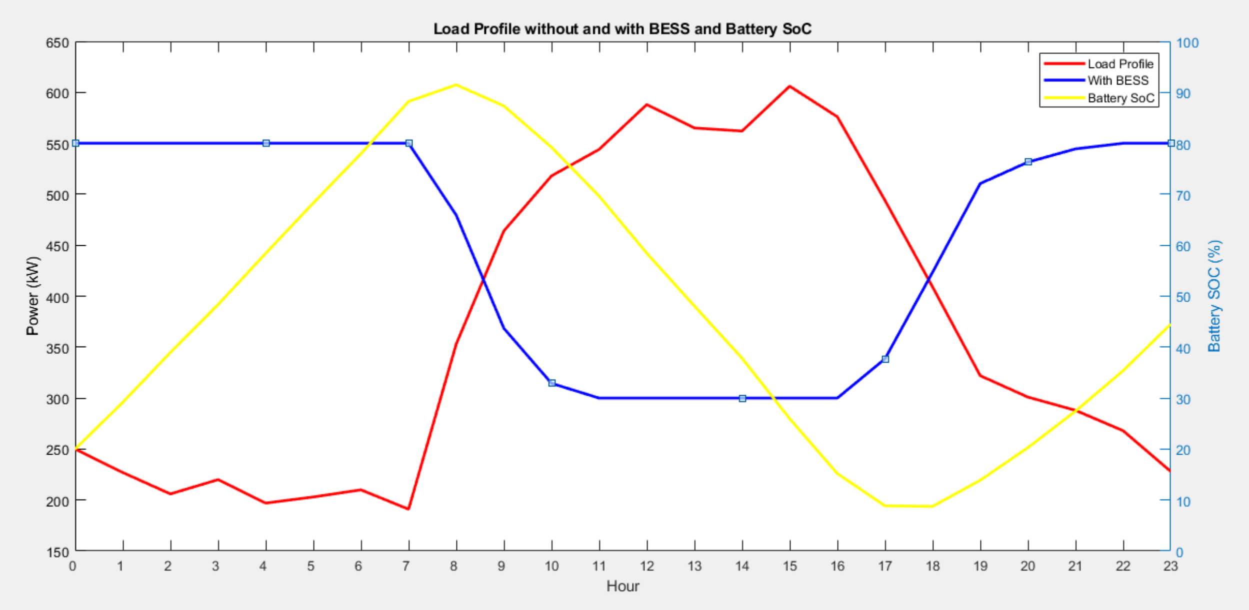


Figure 4. 25: Load shifting profile without and with BESS and battery SoC.

4.4.6.3. Load leveling

Load leveling with Battery Energy Storage Systems (BESS) may be extremely helpful to stabilize an electrical grid's frequency. Load leveling is the process of reducing the discrepancies between electricity supply and demand by storing extra energy during low-demand times and releasing it during high-demand periods.

Load leveling using BESS aids frequency stability in the following ways:

- Supply and demand balance: BESS can store extra energy when power output exceeds immediate need. This stored energy can be released at high-demand periods when generation capacity may be insufficient. Load leveling using BESS helps maintain a steadier frequency by bridging the gap between supply and demand.
- Smoothing out fluctuations: Electricity demand fluctuations can cause frequency discrepancies and grid instability. BESS helps to smooth out these fluctuations by

discharging stored energy during periods of high demand and augmenting it during periods of low demand, minimizing the possibility of frequency deviations.

- BESS improves grid flexibility by allowing it to adapt quickly to changes in demand or generating capacity. It can instantly release or absorb power as needed, assisting in system balance and frequency stabilization. BESS's quick reaction time enables it to successfully offer grid assistance and reduce frequency variations.

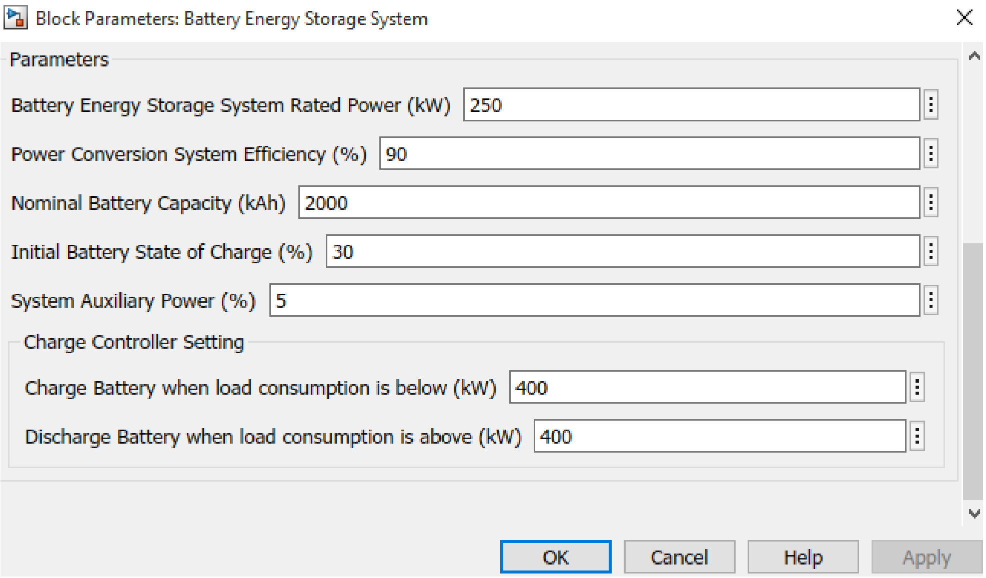


Figure 4. 26: Block parameters of load leveling using BESS.

Load leveling using BESS helps stable grid frequency by actively controlling the balance between power supply and demand. This enables a more dependable and economical operation, reducing the possibility of frequency fluctuations and consequent electrical system disturbances.

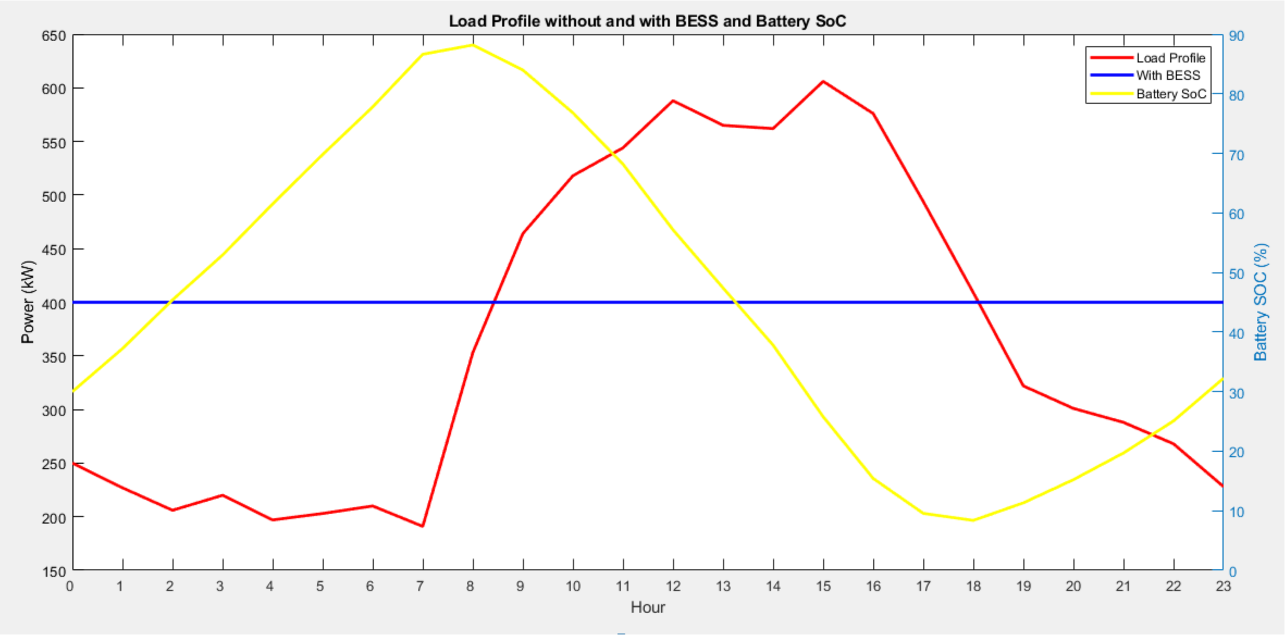


Figure 4. 27: Load leveling profile without and with BESS and battery Soc.

Load shifting, load leveling, and peak shaving with BESS improve grid flexibility, balance supply and demand, and reduce power consumption fluctuations. These techniques minimize energy use, reduce peak power demand, and promote more dependable and efficient grid operation, eventually contributing to grid frequency stability.

4.4.7. Discussion

The results of implementing Battery Energy Storage Systems (BESS) to conduct load shifting, load leveling, and peak shaving techniques are very promising for grid stability and efficiency.

Load shifting using BESS proven its efficacy in regulating energy usage by transferring it from peak to off-peak demand times. Load shifting minimized unexpected spikes in power consumption by intelligently storing and discharging energy, contributing to a steadier frequency. This strategy proved useful in optimizing energy use and reducing grid strain during peak demand periods.

Load leveling using BESS proved to be a viable approach for balancing power supply and demand. Load leveling bridged the generation-consumption gap by storing extra energy during low-demand times and releasing it during high-demand ones. The regulated release of stored energy helped to preserve frequency stability by reducing fluctuations and ensuring a more consistent power supply.

Peak shaving using BESS has shown its potential to cut peak power consumption efficiently. The BESS innovations reduced grid strain by releasing stored energy during high-demand periods, minimizing frequency variations, and boosting stability. This strategy proved useful in regulating peak power demand, resulting in more efficient grid functioning.

From an economic perspective, rated power and battery capacity are essential elements in deploying Battery Energy Storage Systems (BESS). The maximum charge and discharge capacities are determined by the rated power, with greater ratings often raising the cost. Proper component size guarantees that the BESS can satisfy energy demands effectively. Battery capacity, measured in kWh, has an impact on expenses as well, as greater capacities give more storage at a higher cost. When selecting battery capacity, it is critical to balance energy requirements with economic concerns. Components like as the charge discharge controller and power conversion system may be readily replaced or improved since the BESS was designed with flexibility in mind, supporting changes in energy profiles without needing a full system overhaul. This flexibility lowers costs by enabling gradual modifications while also ensuring compatibility with future energy demands. Taking into account the economic factors of rated power and battery capacity allows for cost-effective BESS systems that fulfill energy demands while avoiding needless costs. The flexibility to repair or upgrade components improves economic viability even more, increasing return on investment during the system's lifecycle.

In general, the results show that load shifting, load leveling, and peak shaving approaches can improve grid stability and frequency management. BESS-equipped systems provide major benefits to grid operators and users alike by optimizing energy consumption patterns, balancing supply and demand, and decreasing peak power demand.

4.5. The frequency response analyzing program using MATLAB script

```
close all;
clear all;
clc;
data = xlsread('frequency record.ods', 'Sheet1', 'A1:G297');
t = 1:297;

for i = 3:7
    figure;
    plot(t, data(:, i));
    title(['power over time ', num2str(i-1), ' vs. Time']);
    xlabel('Time in seconds');
    ylabel(['power ', num2str(i-1)]);
    hold on; grid on;
end

hold on; grid on;
hold off;
x=xlsread('frequency record.ods','Sheet1','B1:B297');
t=1:1:297;
plot(t,x);
hold on;
t0_point = 30;
x0_point = 50.02;
plot(t0_point, x0_point, 'ro');
t1_point = 95;
x1_point = 49.80;
plot(t1_point, x1_point, 'ro');
t2_point = 49;
x2_point = 49.51;
plot(t2_point, x2_point, 'ro');
```

```
grid on;
hold off;
dTAC=t2_point-t0_point;%Time difference in seconds
dTAB=t1_point-t0_point;%Time difference in seconds
% Display frequency range and limits
freq_range = [-0.2, 0.2]; % in Hz

text(25, 50.5, sprintf('Frequency Range: %.1f Hz to %.1f Hz', x0_point +
freq_range(1), x0_point + freq_range(2)));

% Display frequency limits of ±200 Hz
line([0, 300], [50 - 0.2, 50 - 0.2], 'Color', 'r', 'LineStyle', '--');
line([0, 300], [50 + 0.2, 50 + 0.2], 'Color', 'r', 'LineStyle', '--');

title('Frequency change with respect to time');
xlabel('Time in seconds');
ylabel('Frequency in Hz');

Installed_capacity=15000;%in MW
primary_reserve=Installed_capacity*0.05% in MW
regulating_energy=Installed_capacity*0.1% in MW per 0.1Hz
%.........................................................................
........................
% Nominal frequency
f_nominal = 50; % Hz

% Calculate frequency deviation
delta_f = x - f_nominal;
percentage_deviation = (delta_f / f_nominal) * 100;
%..............................................................
% Calculate minimum and maximum frequency deviation
min_deviation = min(delta_f);
max_deviation = max(delta_f);
min_index = find(delta_f == min_deviation);
max_index = find(delta_f == max_deviation);
% Plotting the graph
figure;
plot(t, delta_f, 'b');
hold on;
plot(t, percentage_deviation, 'r');
hold off;
title('Frequency Deviation');
xlabel('Time (s)');
ylabel('Deviation (Hz / %)');
legend('Delta f', 'Percentage Deviation');
grid on;
% Calculate minimum and maximum frequency deviation
min_deviation = min(delta_f);
max_deviation = max(delta_f);
% Displaying the minimum and maximum frequency deviation
fprintf('Minimum Frequency Deviation: %.2f Hz\n', min_deviation);
fprintf('Maximum Frequency Deviation: %.2f Hz\n', max_deviation);
%.........................................................................
.........................
%.........................................................................
..
% Manually enter the data
L_load = 8473; % Total load demand in MW
G_capacity = 8558; % Available generation capacity in MW
G_in_use = 8473; % Total capacity in use in MW
G_total = 8800; % Total available capacity in MW
```

```
% Calculate Load Generation Balance
load_generation_balance = L_load - G_capacity;

% Calculate Reserve Capacity
reserve_capacity = G_total - G_in_use;

% Display the results
fprintf('Load Generation Balance: %.2f MW\n', load_generation_balance);
fprintf('Reserve Capacity: %.2f MW\n', reserve_capacity);

%.........................................................................
..

% Define system parameters
H = 3; % Inertia constant of the generator (in seconds)
D = 0.1; % Damping coefficient of the generator
Pm = 1; % Mechanical power input to the generator (in pu)
Pl = 0.8; % Active power load demand (in pu)

% Define simulation parameters
tspan = 0:0.01:10; % Time span for simulation (start:step:end)
X0 = [0; 0]; % Initial conditions for state variables

% Simulate the system dynamics
[t, X] = ode45(@(t, X) power_system_dynamics(t, X, H, D, Pm, Pl), tspan,
X0);

% Extract state variables
delta = X(:, 1); % Rotor angle deviation (in radians)
omega = X(:, 2); % Rotor speed deviation (in pu)

% Plot the results
figure;
subplot(2, 1, 1);
plot(t, delta);
xlabel('Time (s)');
ylabel('Rotor Angle Deviation (rad)');
title('Rotor Angle Deviation vs. Time');

subplot(2, 1, 2);
plot(t, omega);
xlabel('Time (s)');
ylabel('Rotor Speed Deviation (pu)');
title('Rotor Speed Deviation vs. Time');

% Function representing the power system dynamics
function dXdt = power_system_dynamics(t, X, H, D, Pm, Pl)
    delta = X(1); % Rotor angle deviation
    omega = X(2); % Rotor speed deviation

    % Parameters
    M = 2*H; % Total inertia constant of the system
    Pmax = 1.2; % Maximum power output of the generator

    % Calculate derivatives
    d_delta = omega;
    d_omega = (1/(2*H)) * (Pm - Pmax*omega - D*omega + Pl*sin(delta));

    % Return derivatives
```

```
    dXdt = [d_delta; d_omega];
end
```

Figure 4. 28: The analysis script of the frequency response using MATLAB.

The results:

```
Command Window

primary_reserve =

  352.9000


regulating_energy =

  564.6400

Minimum Frequency Deviation: -0.49 Hz
Maximum Frequency Deviation: 0.06 Hz
Load Generation Balance: -85.00 MW
Reserve Capacity: 352.00 MW
```

Figure 4. 29: The calculated parameters.

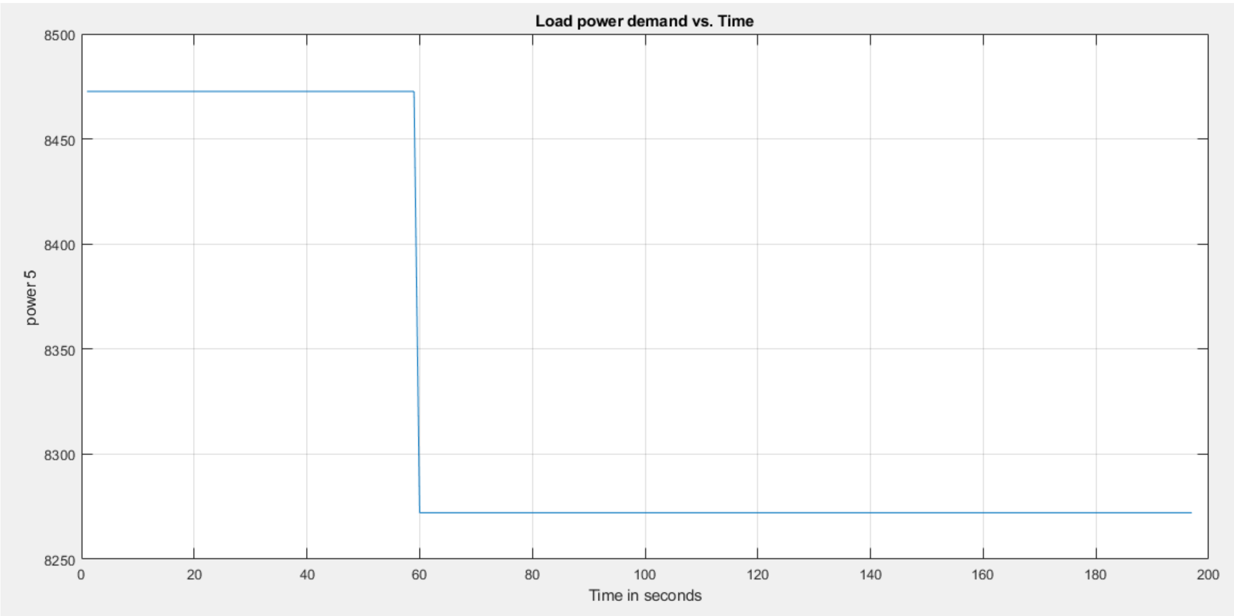


Figure 4. 30: The power demand over time.

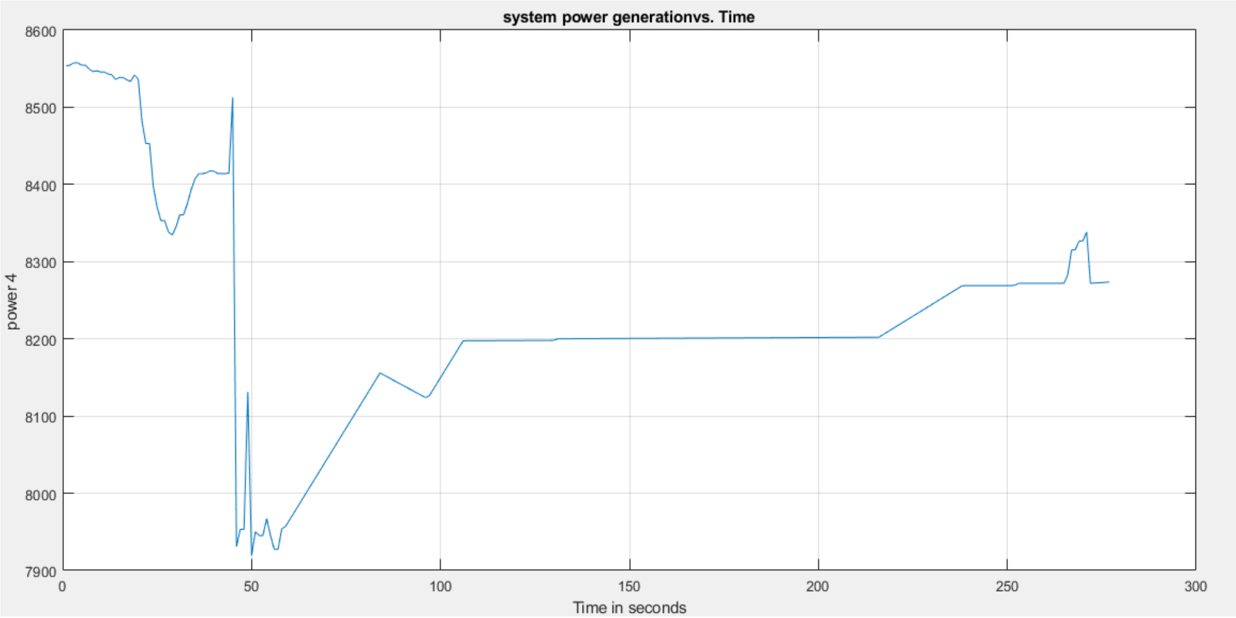


Figure 4. 31: The power generation by the system over time.

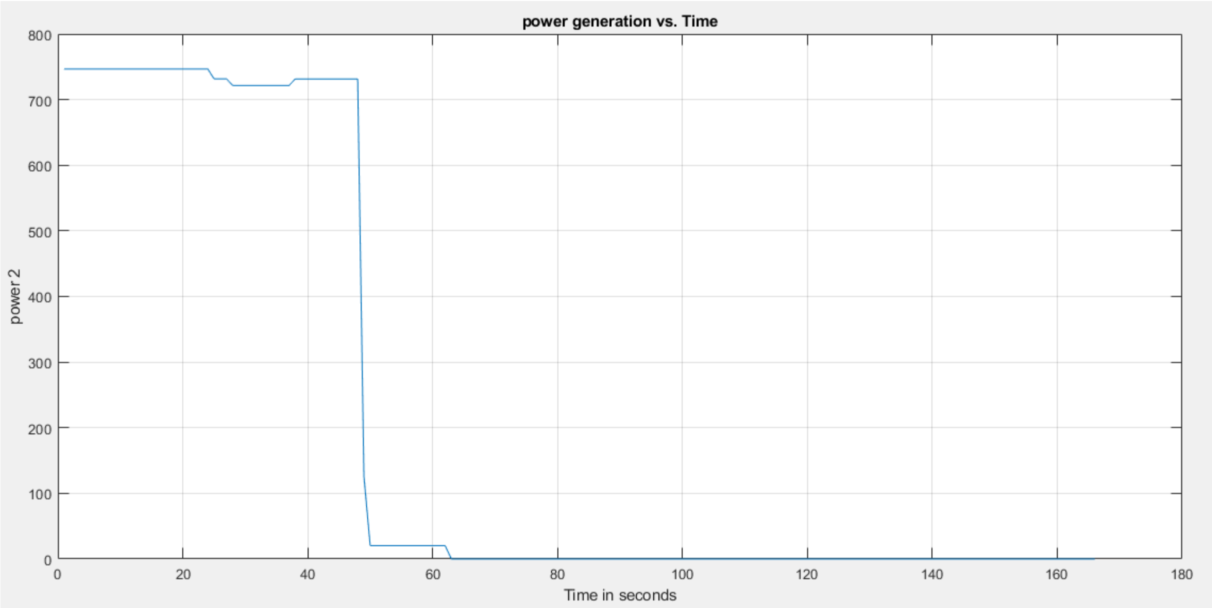


Figure 4. 32: Bellarat power generation over time.

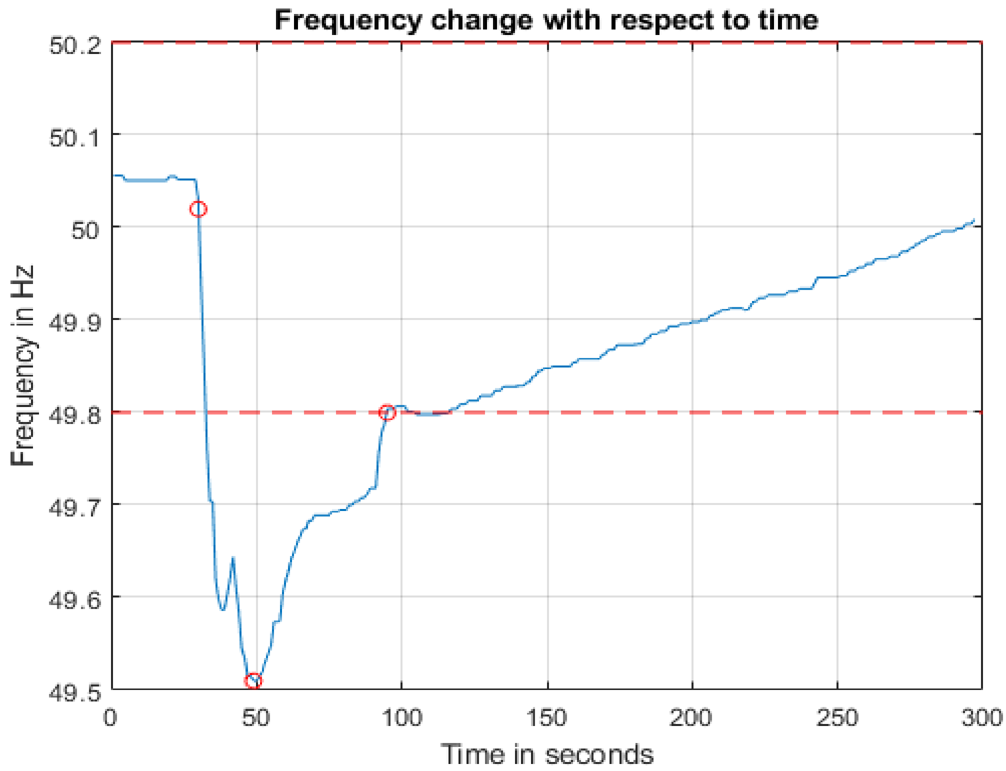


Figure 4. 33: The system frequency flactuation over time.

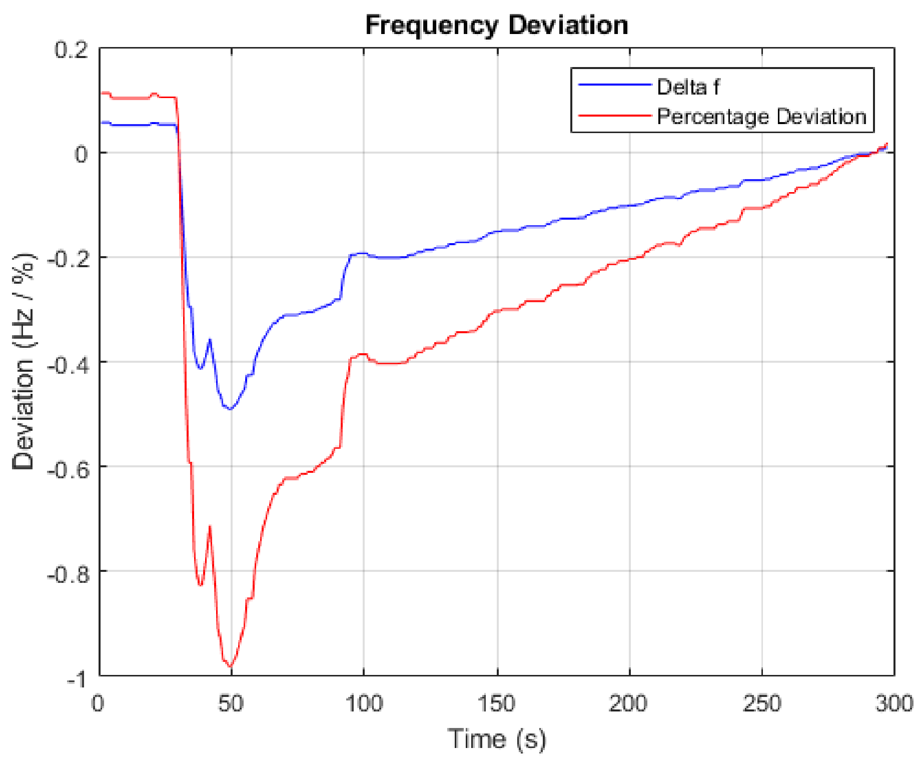


Figure 4. 34: The curves of frequency deviation and percentage of deviation over time

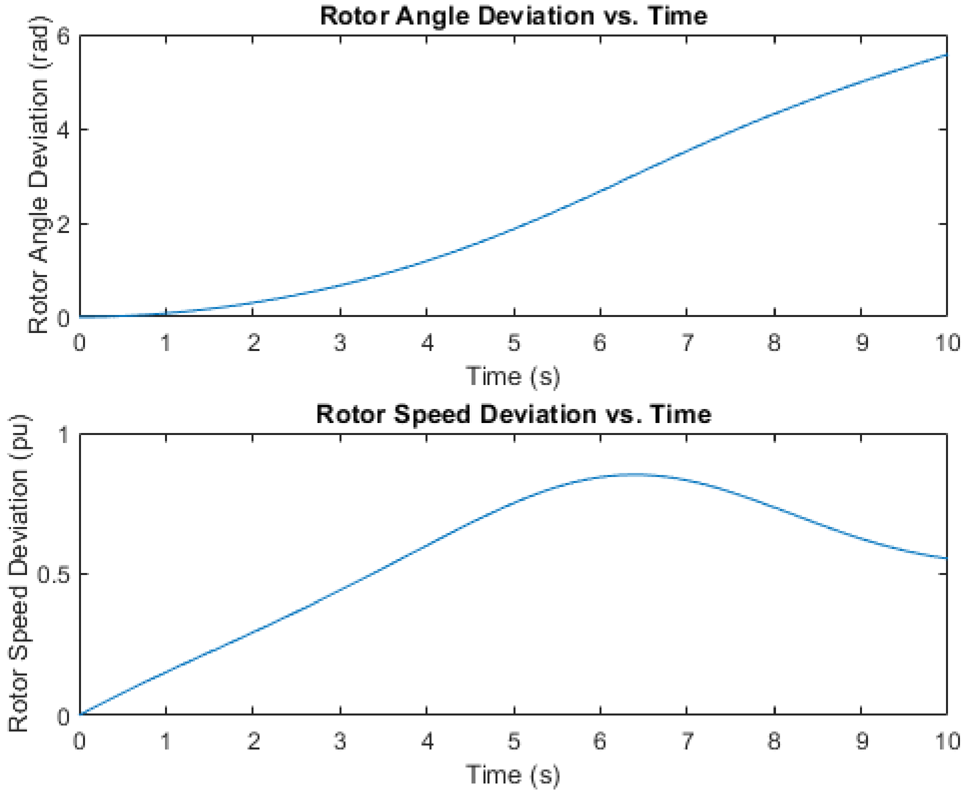


Figure 4. 35: The rotor angle deviation and speed deviation over time.

4.5.1. **Discussion**

The script creates several charts and calculates frequency and power analysis findings. Here's a quick rundown of the results:

- Frequency fluctuation: Multiple curves are displayed to indicate frequency fluctuation over time. Each curve is associated with a distinct column of data from the original Excel file.

- The script computes the frequency deviation and percentage deviation from the nominal frequency. The findings are shown to show the patterns in deviation over time.

- Minimum and Maximum Deviations: The script calculates and shows the minimum and maximum frequency deviations, as well as their related values and time indices.

- The script computes and shows the load generation balance, which is the difference between total load demand and available generating capacity.

- Reserve Capacity: The script calculates and shows the reserve capacity, which reflects the remaining available generating capacity after accounting for capacity in use.
- Power System Dynamics: The script simulates the dynamics of a power system, especially the rotor angle deviation and rotor speed deviation over a defined time span. The findings are shown in distinct subplots.

These findings shed light on the frequency behavior, load-generation balance, reserve capacity, and power system dynamics, allowing for the study and evaluation of the system's performance.

4.6. Conclusion

In conclusion, the simulation chat revealed the significance of utilizing flywheel energy storage systems (FESS) and battery energy storage systems (BESS) in maintaining the stability of a power system's frequency. Through the simulation, we observed the contribution of FESS and BESS in regulating and balancing power fluctuations.

The simulation showcased the effectiveness of the flywheel energy storage system in stabilizing the frequency of the power system. By harnessing the rotational energy of a flywheel, FESS can absorb excess power during periods of high generation and release stored energy during periods of low generation. This mechanism helps to maintain a stable system frequency, preventing deviations that could lead to instability or blackouts.

Similarly, the simulation of battery energy storage systems demonstrated their capability in supporting system frequency stability. BESS operates by storing electrical energy in batteries and dispatching it when needed. During periods of high demand or low generation, BESS can inject power into the system, effectively raising the frequency. Conversely, during periods of excess generation or low demand, BESS can absorb excess power, mitigating frequency deviations.

The MATLAB script used for frequency response analysis allowed for a comprehensive examination of the system's behavior. By plotting the frequency and power response, the script provided valuable insights into how the system responds to fluctuations and the effectiveness of FESS and BESS in maintaining stability. These visual representations helped in identifying potential issues and optimizing the system's performance.

General Conclusion

This project has provided a comprehensive analysis of frequency response in Sonelgaz's electrical power system, covering various aspects from system overview to simulation and analysis. The project has shed light on the importance of frequency control and the role of different strategies and technologies in maintaining system stability.

First, we introduced the Algerian power system, highlighting the significance of electric power transmission and distribution. The classification of power plants into non-conventional and conventional sources of energy was discussed, emphasizing the diversity of energy resources. The structure of the power system and the main structures for electric power systems were presented, setting the foundation for understanding frequency control.

Then, we delved into frequency control methods. Primary, secondary, and tertiary frequency control were explained, along with load and generation balance and frequency deviation. The implementation methods of primary frequency response, including governor droop control, under-frequency load shedding, automatic generation control, fast frequency response, dynamic demand control, and reserve power, were explored. The advantages and disadvantages of each strategy were examined, and the requirements of primary frequency response from UCTE and NERC were compared. The availability of resources and risk tolerance in the Algerian frequency power system, as well as Sonelgaz's contingency plans and risk mitigation strategies, were analyzed.

Next, we focused on primary frequency response implementation and emerging solutions. The fundamental elements of implementation were discussed, and the challenges associated with it, such as control system design, communication delays, grid integration, cost, system inertia, and policy/regulatory barriers, were examined. The limitations of current methods for primary frequency response were identified, and emerging technologies like virtual synchronous generators, battery energy storage systems, power system stabilizers, demand response, flexible AC transmission systems, and flywheel energy storage systems were presented as potential solutions. The feasibility of these solutions was evaluated, and the chapter concluded with an analysis of energy storage systems, particularly flywheel energy storage systems and battery energy storage systems.

Finally, we focused on simulating the flywheel energy storage system and frequency analysis. The simulation methodology and parameters used in the simulation models were described. The MATLAB script for frequency analysis was explained in detail, enabling a comprehensive examination of the power system's behavior. The simulation and analysis showcased the contribution of flywheel energy storage systems and battery energy storage systems in regulating power fluctuations and maintaining system stability. The results provided valuable insights into system performance and optimization.

This project has highlighted the critical role of frequency control in Algerian power system. It has explored various frequency control strategies and emerging solutions, showcasing the potential of energy storage systems in maintaining system stability. The simulation and frequency analysis have provided a deeper understanding of the system's behavior and offered valuable insights for system optimization and enhancement.

Future Work

Building upon this project, there are several areas for future work that can further advance the understanding and implementation of frequency response in Algerian’s power system:

- Advanced control algorithms: Investigate and develop advanced control algorithms for frequency response, taking into account the dynamic behavior of the system and the integration of renewable energy sources. Explore the use of machine learning techniques and advanced optimization algorithms to enhance the performance of frequency control strategies.
- Integration of emerging technologies: Explore the integration of emerging technologies, such as advanced power electronic devices, microgrids, and advanced grid control systems, to enhance frequency response capabilities. Investigate the potential synergies between different technologies and their combined benefits in maintaining system stability.
- Economic analysis and cost optimization: Conduct a comprehensive economic analysis to evaluate the cost-effectiveness of different frequency control strategies and energy storage systems. Consider factors such as capital costs, operation and maintenance expenses, and the potential benefits derived from improved system stability. Optimize the deployment and utilization of resources to maximize the economic benefits.

- Grid modernization and planning: Assess the impact of renewable energy integration and emerging technologies on Sonelgaz's power grid. Develop grid modernization plans that incorporate frequency control strategies and energy storage systems into the overall grid planning and expansion process. Consider the long-term implications of system upgrades and develop a roadmap for future grid development.

By focusing on these areas of future work, Sonelgaz can further enhance its frequency control capabilities and ensure a reliable and stable electrical power system. The integration of advanced technologies, advanced control algorithms, and comprehensive planning strategies will contribute to a more resilient and efficient power system.

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