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Summary of
PhD THESIS

Frequency Control Solutions in the Future Power Systems

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Chapter 1

CHALLENGES OF INTEGRATING RES IN POWER SYSTEMS

1.1 Introduction

The integration of Renewable Energy Sources (RES) into existing power systems is a critical step towards achieving a sustainable and environmentally friendly energy future. RES, including solar, wind, hydro, and geothermal energy, offer clean and abundant energy, but their integration presents a set of complex challenges. This chapter explores the key challenges associated with the seamless integration of RES into power systems.

- **Variability and Intermittency:**
  One of the primary challenges is the inherent variability and intermittency of RES generation. Solar and wind power, for instance, are dependent on weather conditions and time of day, leading to fluctuations in energy output. This variability poses difficulties in maintaining a stable and reliable power supply.

- **Grid Integration:**
  Integrating RES into the existing grid infrastructure requires significant upgrades and modifications. The grid must accommodate bidirectional power flows, manage voltage and frequency fluctuations, and ensure the proper synchronization of RES with conventional power sources.
- **Energy Storage:**
  Effective energy storage solutions are essential to mitigate the intermittency of RES. Batteries, pumped hydro, and other storage technologies are required to store excess energy during peak generation periods and release it during low generation periods.
- **Grid Stability and Reliability:**
  The integration of RES can impact grid stability and reliability. Rapid fluctuations in generation can lead to voltage and frequency deviations, potentially causing power outages. Advanced grid control and stability measures are necessary to address these issues.
- **Economic Considerations:**

While RES offers long-term cost savings, the initial investment in renewable infrastructure can be high. The economics of integrating RES into the power system, including subsidies, incentives, and financing options, must be carefully assessed.

- **Regulatory and Policy Frameworks:**
  The development and implementation of effective policies and regulations are critical for the successful integration of RES. Clear guidelines for grid access, market incentives, and renewable energy targets are essential to promote RES adoption.
- **Environmental Impact:**
  The environmental benefits of RES integration are clear, but the environmental impact of renewable energy projects, such as habitat disruption and resource extraction, must be carefully managed.
- **Grid Resilience:**
  The power system must be resilient to external factors, such as extreme weather events or cyberattacks, which can affect both conventional and renewable energy sources. Ensuring grid resilience is a vital consideration.

1.2 Frequency Control Strategies in Europe

Frequency control strategies in Europe are implemented to maintain the stability and reliability of the continent's interconnected electrical grids, which span numerous countries and regions. These strategies are vital in ensuring that the grid frequency remains close to its nominal value (e.g., 50 Hz in most of Europe) despite fluctuations in power generation and consumption. Here are some key aspects of frequency control strategies in Europe:

- **Frequency Deviation Limits:** European grid codes specify acceptable limits for grid frequency deviations from the nominal frequency. Grid operators work within these limits to ensure that the frequency remains stable.
- **Primary Frequency Control:** Also known as automatic primary control or droop control, this strategy involves adjusting generator output based on changes in grid frequency. Generators automatically increase or decrease their output to help restore the frequency to its nominal value. The amount of adjustment is determined by the speed droop characteristic.
- **Secondary Frequency Control:** Secondary frequency control, also known as automatic secondary control or frequency restoration reserve, provides additional support to maintain grid frequency. It involves resources that can respond within seconds to minutes to more significant frequency deviations.
- **Tertiary Frequency Control:** Tertiary frequency control comes into play when frequency deviations persist beyond the response times of primary and secondary controls. It addresses longer-term frequency deviations that can result from factors like unexpected changes in power demand, supply, or generation mix.

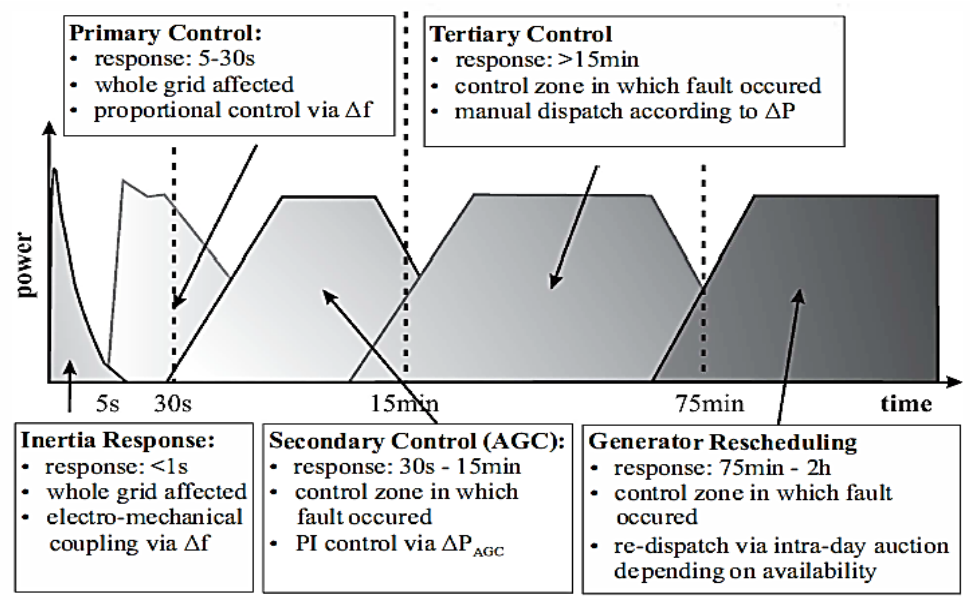


Fig 1. 1 Frequency and time control stages for each stage and power reserves deployment [17].

Conclusion:

The integration of Renewable Energy Sources into power systems is a complex and multifaceted process, marked by challenges related to variability, grid integration, energy storage, grid stability, economics, regulations, environmental considerations, and grid resilience. Addressing these challenges is crucial to realizing the full potential of RES and transitioning towards a sustainable and reliable energy future. This chapter provides an overview of these challenges, setting the stage for further exploration in subsequent chapters.

Chapter 2

Applications of battery energy storage systems for power balancing and frequency control

2.1 Introduction

Frequency is a critical parameter in an AC electric power system, symbolizing the equilibrium between power supply and demand. Any disparity between these two aspects can lead to deviations from the standard frequency. When there's an excess of power generation, the frequency rises, whereas an excess of demand causes the frequency to drop. To mitigate these discrepancies, the kinetic energy stored in the rotating masses of large synchronous generators is employed as an initial mechanism to balance power imbalances. Both primary and secondary frequency response control systems are tasked with rectifying these imbalances, although their effectiveness has limitations. Excessive deviations in frequency can result in violations of legal and operational constraints, generator disconnections, and potentially catastrophic system failures. Figure 2.1 provides an illustration of the operational and legal constraints governing the power systems in Great Britain (GB).

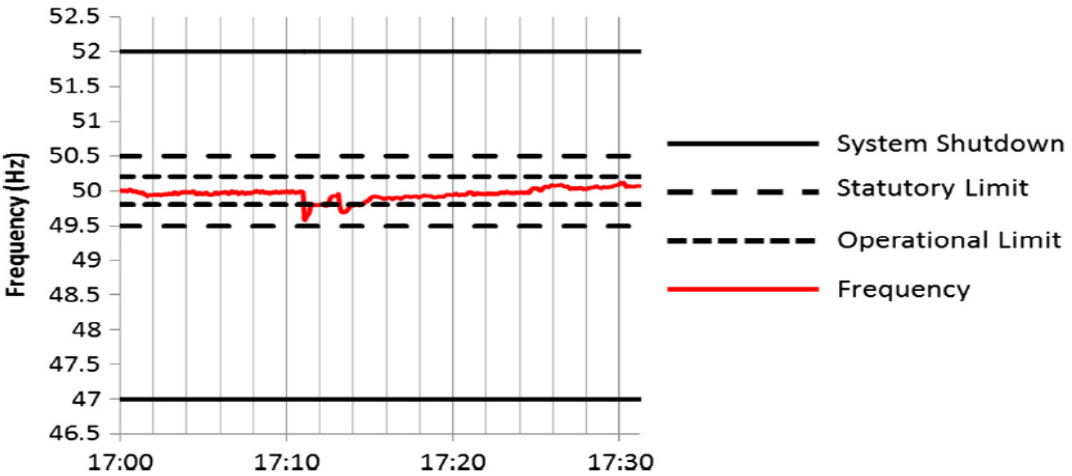


Fig 2. 1 The statutory and operational frequency limits are important in relation to the actual frequency response of the GB system [70].

2.2 Model BESS Described in detail

A buck/boost converter, a dc link capacitor, a three-phase bidirectional dc-ac converter, an ac filter, and a transformer that connects the system to the microgrid are among the essential parts of the BESS models used in this study. This section provides an in-depth description of these components, including their respective models and relevant parameters. Additionally, the control strategies employed for each BESS converter are discussed. A detailed illustration of the BESS components can be found in Figure 2.20 [94].

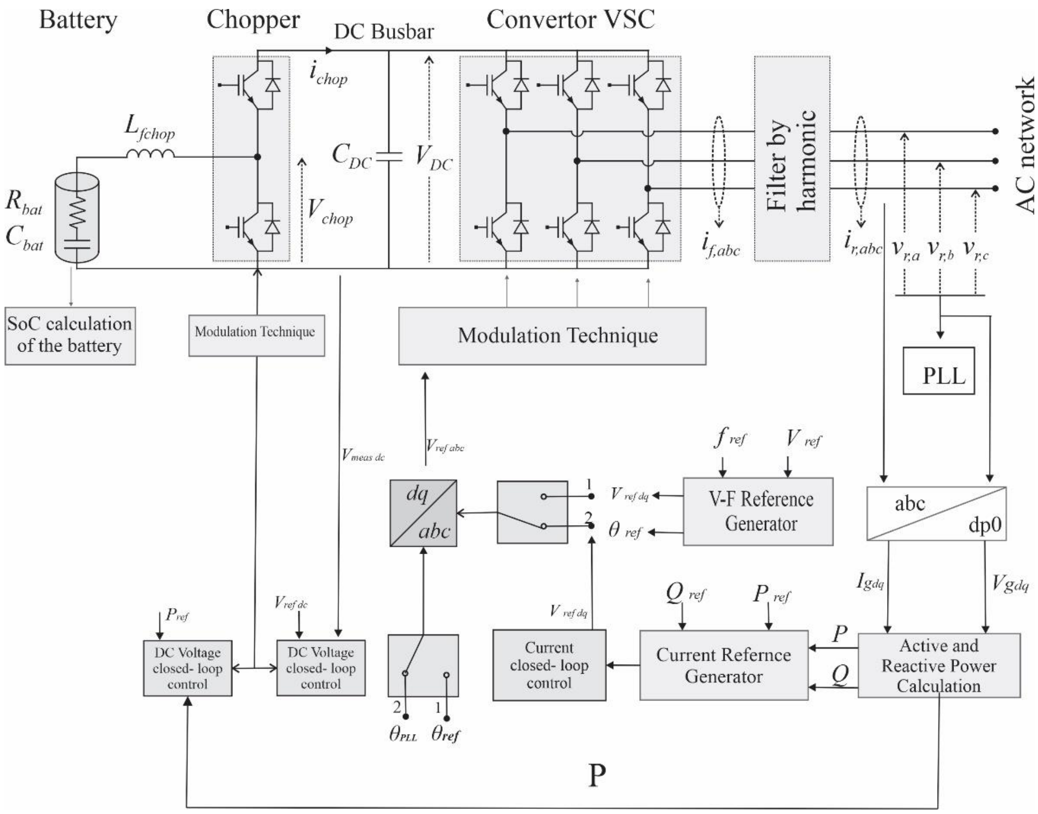


Fig 2. 2 BESS Described in detail [94].

The battery model utilized in this study is based on a previously established model. In this model, the battery is connected in series with an internal resistance RB and is represented as an ideal regulated DC source. It employs a nonlinear equation that considers the battery's state-of-charge (SOC) to calculate the battery's EB no-load voltage[95].

$$E_B = E_0 - K\frac{1}{SOC} + A^{-BQ(1-soc)} \tag{2.22}$$

The battery model employed in this study incorporates several variables, including Q, representing the battery's capacity in ampere-hours (Ah), E_0, denoting the battery's constant voltage in volts, and K, which signifies the polarization voltage in volts. To account for the battery's charging and discharging characteristics, factors A and B are also introduced. These parameters can be adjusted to emulate the discharge behavior of specific battery types.

To regulate the voltage of the DC link capacitor and manage the charging and discharging of the battery, the buck/boost converter plays a crucial role. Figure 2.21 illustrates the use of a cascaded proportional-integral (PI) controller to govern the duty cycle of the switches. This control strategy is based on the difference between the DC link voltage and its set-point. Notably, the efficiency of the buck/boost controller in maintaining the DC link voltage is significantly enhanced by introducing a second PI controller that primarily responds to changes in the system's active power.

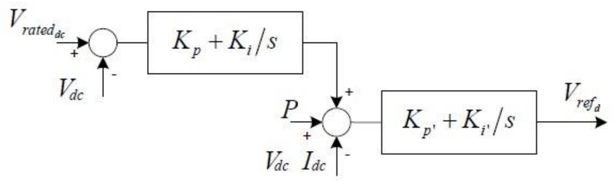


Fig 2. 3 Buck/boost dc link voltage controller [97].

When the DC link voltage falls below the predefined set-point, the converter operates in boost mode to discharge the battery. Conversely, when the DC link voltage surpasses the set-point, it operates in buck mode to charge the battery. The selection of the inductance value, denoted as Lchopf, is critical to minimize current ripple, as demonstrated in the model [96] :

$$\Delta I = \frac{E_B}{L_{chopf}} \Delta t = \frac{E_B}{L_{chopf}} \frac{1}{2 f_s} \tag{2.22}$$

Where f_s is the switching frequency

Figure 2.21 illustrates the connection of the battery and buck/boost converter to the grid through the DC-AC converter and AC filter. The converter's Pulse Width Modulation (PWM) technique relies on sinusoidal reference signals provided by the converter control system, determining the voltage magnitude and phase set-points.

When the switches are in State 1, the voltage magnitude and phase set-points are established based on the reference voltage and frequency. In this configuration, the BESS performs grid-forming control, also known as the master voltage and frequency controller. Conversely, when the switches are in State 2, the battery operates in continuous PQ mode, injecting or absorbing constant active and reactive power. This mode is referred to as grid-feeding mode, and it utilizes reference active and reactive powers to generate the voltage magnitude and phase set-points.

These control methods serve as the foundation for grid-supporting and grid-following control modes, as they are rooted in the fundamental concepts of grid-forming and grid-feeding modes. Adjustments to the reference voltage, frequency, active power, and reactive power are made to implement these control modes. It is essential to emphasize that these controls are based on Park's dq-axes transformations. The voltage dq-axes reference set-points are directly employed to generate the abc-reference signals when forming the grid [97].

The reference angle is computed through the integration of the reference angular frequency. To maintain the Point of Common Coupling (PCC) voltage at its rated value, a PI controller is also employed.

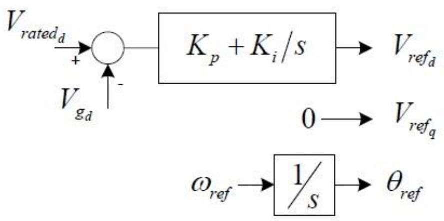


Fig 2. 4 Grid-forming voltage and phase reference generator [97].

The injected active and reactive power are initially computed in grid-feeding control mode as follows:

$$p = \frac{3}{2}(V_{gd} I_{gd} - V_{gq} I_{gq}) \quad (2.23)$$

$$q = \frac{3}{2}(V_{gd} I_{gd} - V_{gq} I_{gq}) \quad (2.24)$$

The determination of the corresponding active (P) and reactive (Q) components is achieved through the following steps: The instantaneous active and reactive powers (p and q) are obtained and subsequently filtered using low-pass filters. The filtered active power is then used as the input for the current reference calculation, which in turn yields the reference for reactive power. To obtain the most recent reference setpoints for the dq-axes, the generator block is utilized.

$$I_{refd} = \frac{3}{2} \frac{P_{ref} V_{gd} + Q_{ref} V_{gq}}{V_{gd}^2 + V_{gq}^2} \quad (2.25)$$

$$I_{refq} = \frac{3}{2} \frac{P_{ref} V_{gq} + Q_{ref} V_{gd}}{V_{gd}^2 + V_{gq}^2} \quad (2.26)$$

To derive the final voltage dq-axes references, these current references are subsequently passed through the current closed-loop control. It is essential to incorporate feed-forward terms to effectively decouple the two axes and consider the voltage difference before and after the AC filter. When disregarding Rd, a simplified single-line diagram, as depicted in Fig. 2.28, can be employed to deduce this relationship, leading to the following equations:

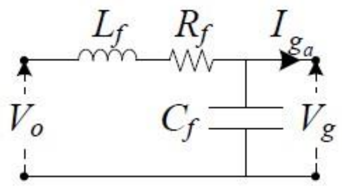


Fig 2. 5 Single line diagram of ac filter [97].

$$V_{od} = V_{gd}(1 - \omega^2 L_f C_f) + I_{gd} R_f - I_{gq} \omega L_f - V_{gq} \omega R_f C_f \quad (2.27)$$

$$V_{oq} = V_{gq}(1 - \omega^2 L_f C_f) + I_{gd} R_f - I_{gd} \omega L_f - V_{gd} \omega R_f C_f \quad (2.28)$$

These equations lead to the final current closed-loop control block seen in Figure 2.24. The voltage references V_{refd} and V_{refq}, which are the output of the current controller, are translated back into the abc-reference frame to provide the sinusoidal control signals for the converter's PWM scheme. [97] provides more details on other converter settings including grid-supporting and grid following.

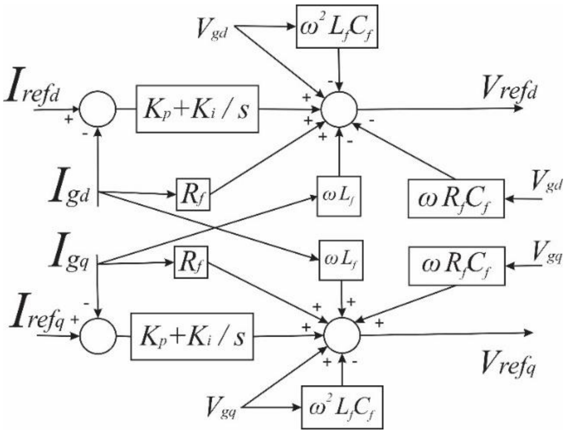


Fig 2. 6 Current closed-loop control [97].

To derive the final voltage dq-axes references, these current references are subsequently passed through the current closed-loop control. It is essential to incorporate feed-forward terms to effectively decouple the two axes and consider the voltage difference before and after the AC filter. When disregarding Rd, a simplified single-line diagram, as depicted in Figure. 2.23, can be employed to deduce this relationship, leading to the following equations [98]:

$$\Delta I_{\max} = \frac{V_{dc}/3}{L_f 4 f_s} \tag{2.29}$$

The reactive power injection of the ac filter capacitor Cf should remain below 5% of the converter's rated power [98]. Additionally, it's worth noting that approximately 0.2% of the rated power is consumed by a series damping resistance, effectively mitigating harmonic vibrations [98] .

$$R_d = \frac{V_I^2}{0.002P_I} - \sqrt{\left(\frac{V_I^2}{0.002P_I}\right) - \frac{1}{(\omega C_f)^2}} \tag{2.30}$$

In order to reflect the filter's parasitic resistance losses, a resistance R_f is also added in series with the inductance.

Chapter 3

Frequency Control Using Battery Energy Storage System

3.1 Modelling and simulation in Simulink of a BESS

Battery energy storage systems (BESS) have become increasingly popular because they provide reliable and environmentally friendly energy solutions. A comprehensive understanding of how BESS operates and interacts with the power grid is essential to ensure their optimal performance and efficiency. Modelling and simulation techniques are powerful tools for analyzing and optimizing BESS performance.

Engineers and researchers use mathematical models to simulate how BESS behaves under various operating conditions and to test different control strategies and algorithms. Simulink, a simulation and modelling tool provided by MathWorks, is commonly used for this purpose. Simulink allows users to create block diagrams that represent the various components of a BESS, including batteries, inverters, and control systems. These block diagrams make it easy to simulate how the system responds to different inputs and operating scenarios, ultimately leading to performance optimization.

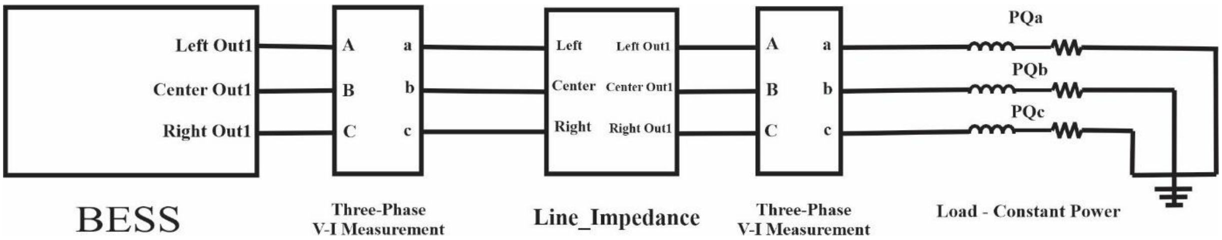


Fig 3. 1 Battery circuit modeling schematic with net work and load [155].

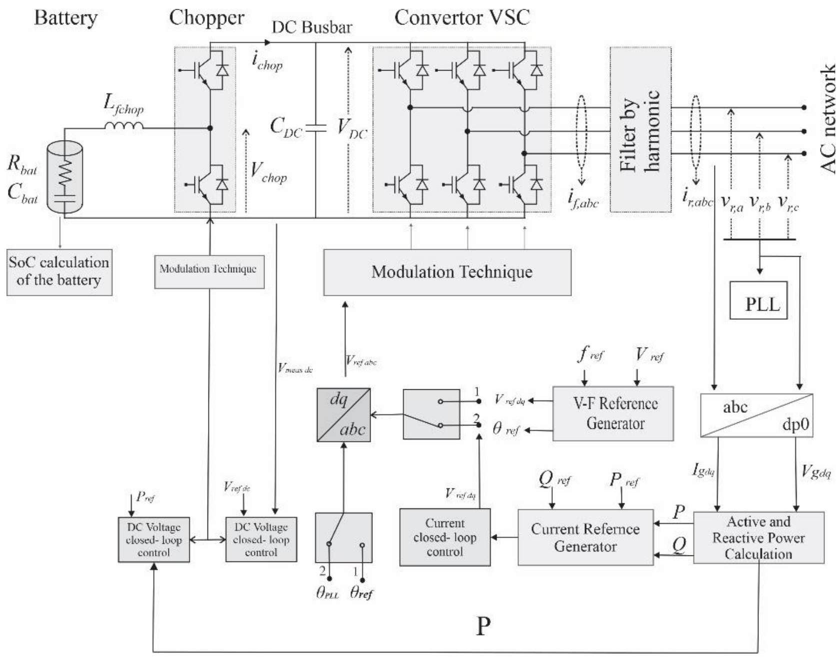


Fig 3. 2 Battery circuit modeling schematic [154].

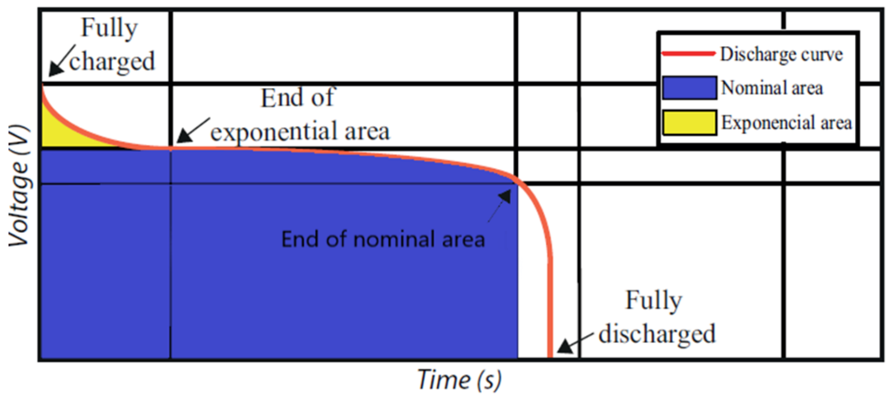
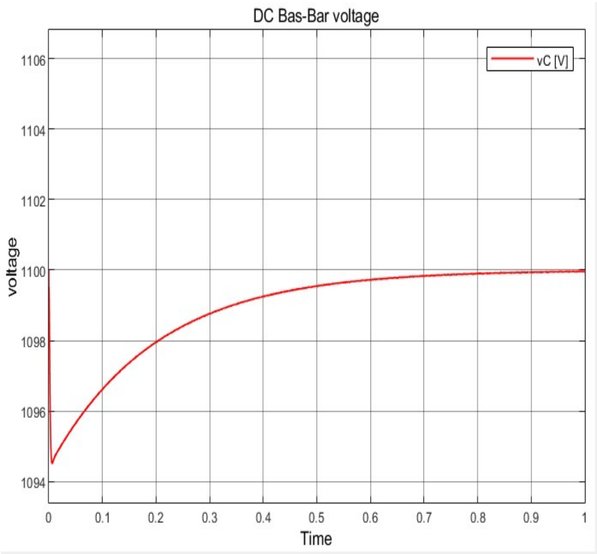


Fig 3. 3 Typical discharge curve for a battery [155].



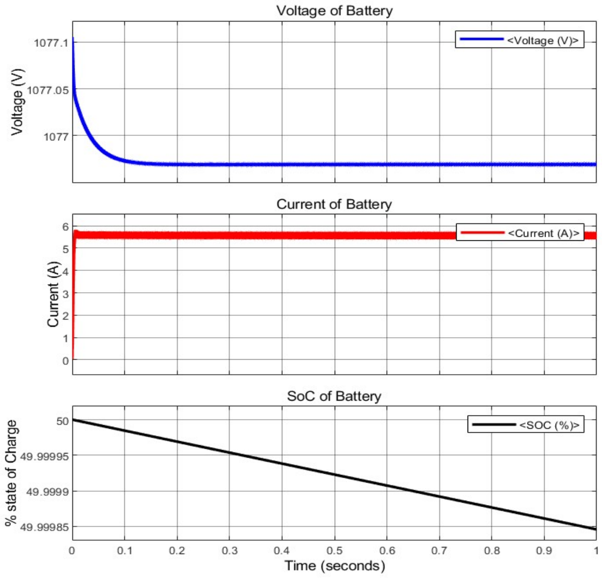


Fig 3. 4 Battery scope result [155].

Fig 3. 5 DC busbar voltage [155].

3.2 Integration in AGC of a BESS system

The WSCC 9-bus test case is a simplified representation of the Western System Coordinating Council (WSCC) power system, condensed into an equivalent system with nine buses and three generators. The base voltage levels in this case are 13.8 kV, 16.5 kV, 18 kV, and 230 kV. The complex power ratings of the transmission lines are in the range of hundreds of MVA each. This test case is considered relatively straightforward to control because it has a limited number of voltage control devices. Simulations of this system were conducted using the Eurostag software program. The WSCC 9-bus test case is a useful power system analysis and simulation benchmark. Its simplicity allows researchers and engineers to study fundamental power system behaviors and test various control and optimization techniques. Despite its simplicity, it provides valuable insights into voltage and power flow control and transient stability analysis. In Eurostag simulations of this test case, researchers can investigate how the system responds to changes in generation, load demand, and line conditions. Additionally, it can be used to assess the effectiveness of different control strategies for voltage regulation and reactive power management. While the WSCC 9-bus test case may not represent the complexity of real-world power systems, it serves as a starting point for understanding key principles and testing new methodologies. As the power industry continues to evolve, such test cases remain relevant for ensuring the reliability and efficiency of modern power grids.

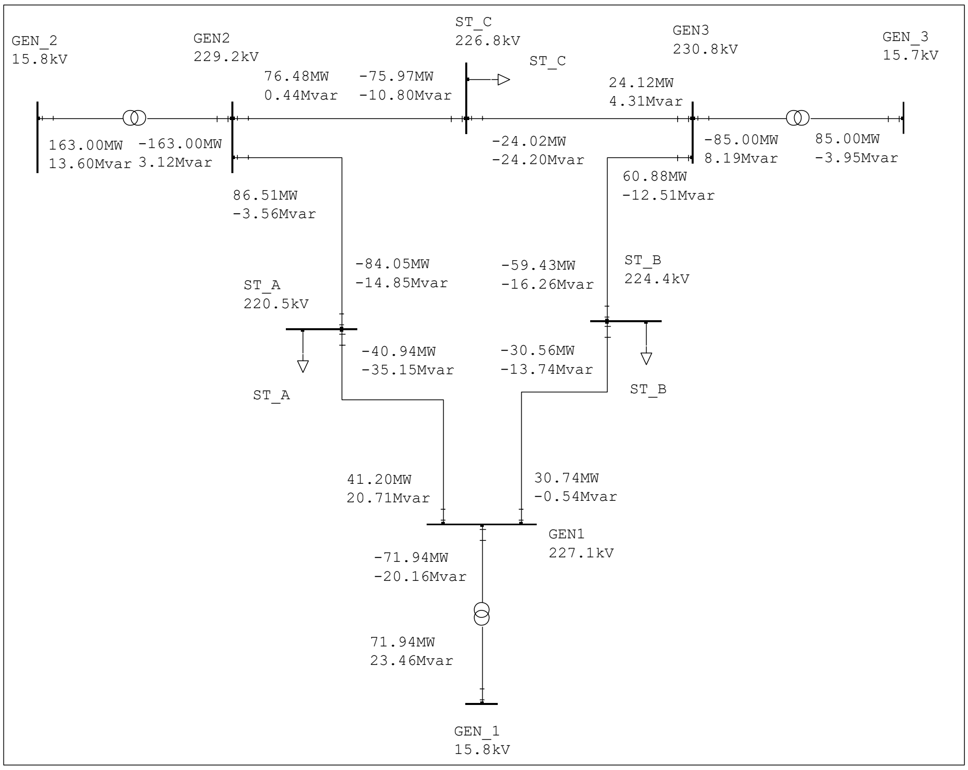
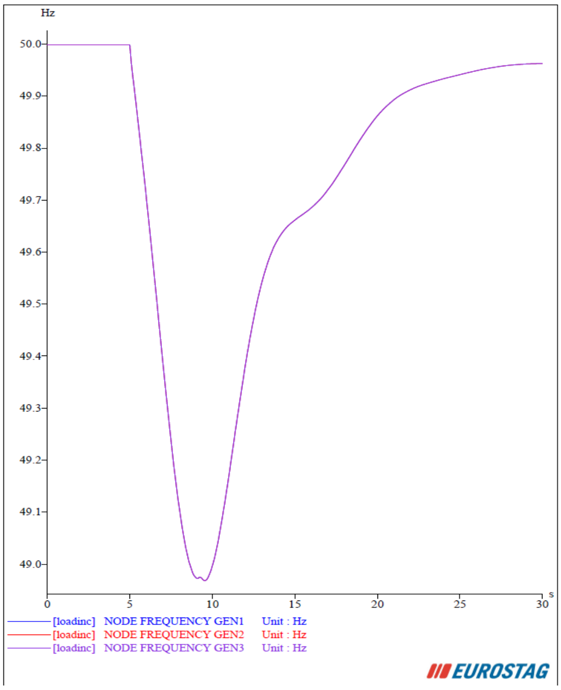
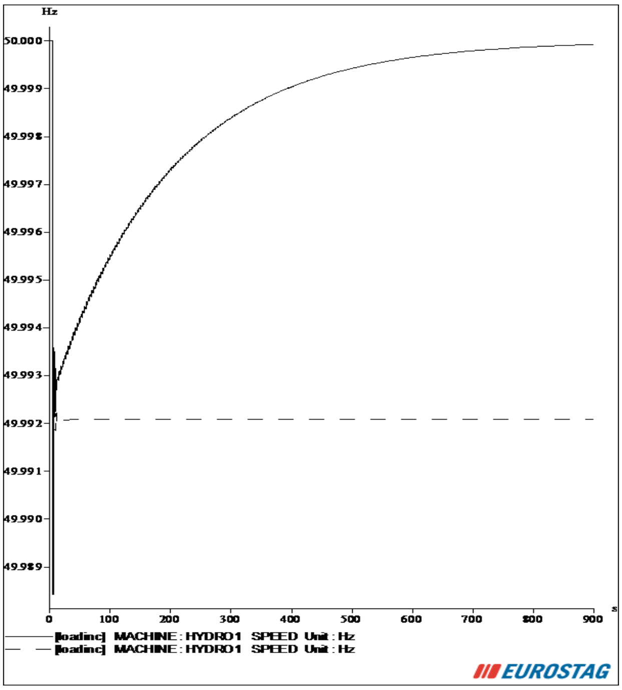


Fig 3. 6 WSCC 9 Bus test system [156].

Fig 3. 7 A load variation occurs in bus ST-A , at time 5 second [156].



A



B

Fig 3. 8 A The frequency of the machines without the effect of battery [156].

Fig 3. 9 B The frequency of the machines with the effect of battery [156].

Chapter 4

Economic Aspects of Battery Integration for Frequency Control

Battery integration for frequency control, often referred to as grid energy storage, has significant economic implications in the context of the electrical grid. Frequency control is crucial for maintaining grid stability, and batteries play a vital role in this by providing rapid-response energy services. Here are some key economic aspects of battery integration for frequency control:

- Grid Reliability and Avoided Costs: Batteries can respond quickly to sudden changes in supply and demand, helping to stabilize the grid and prevent blackouts. This reliability can save utilities and consumers substantial costs associated with power outages, equipment damage, and production losses.
- Ancillary Service Revenue: Grid operators compensate battery operators for providing ancillary services like frequency regulation, which creates an additional revenue stream for battery owners. This can help offset the initial investment and ongoing operational costs.
- Peak Load Management: Batteries can store excess energy during periods of low demand and discharge it during peak demand, reducing the need for expensive peaker plants and reducing electricity costs.
- Renewable Energy Integration: Batteries can store surplus energy from intermittent renewable sources, such as wind and solar, and release it when demand is high. This enhances the integration of renewables into the grid, reducing the need for fossil fuel-based backup generation.
- Avoided Transmission and Distribution Upgrades: In some cases, battery storage can defer or eliminate the need for costly grid infrastructure upgrades by providing localized voltage and frequency support.
- Energy Arbitrage: Battery operators can buy low-cost electricity during periods of surplus supply and sell it back to the grid when prices are high. This arbitrage can be a lucrative source of revenue.
- Capacity Market Participation: Batteries can participate in capacity markets by offering their stored energy as a resource available for dispatch during periods of high demand. This can provide a steady income stream for battery owners.
- Environmental Benefits: While not directly economic, the reduction in greenhouse gas emissions associated with battery integration for frequency control can have economic value in the form of avoided climate change-related costs.
- Cost Reductions: The cost of battery technology has been decreasing, making battery integration more economically attractive over time. Economies of scale, technological advancements, and increased competition contribute to cost reductions.

- Regulatory Incentives: Governments often provide financial incentives, tax credits, or grants to promote the integration of energy storage technologies, which can further enhance the economic viability of battery systems for frequency control.

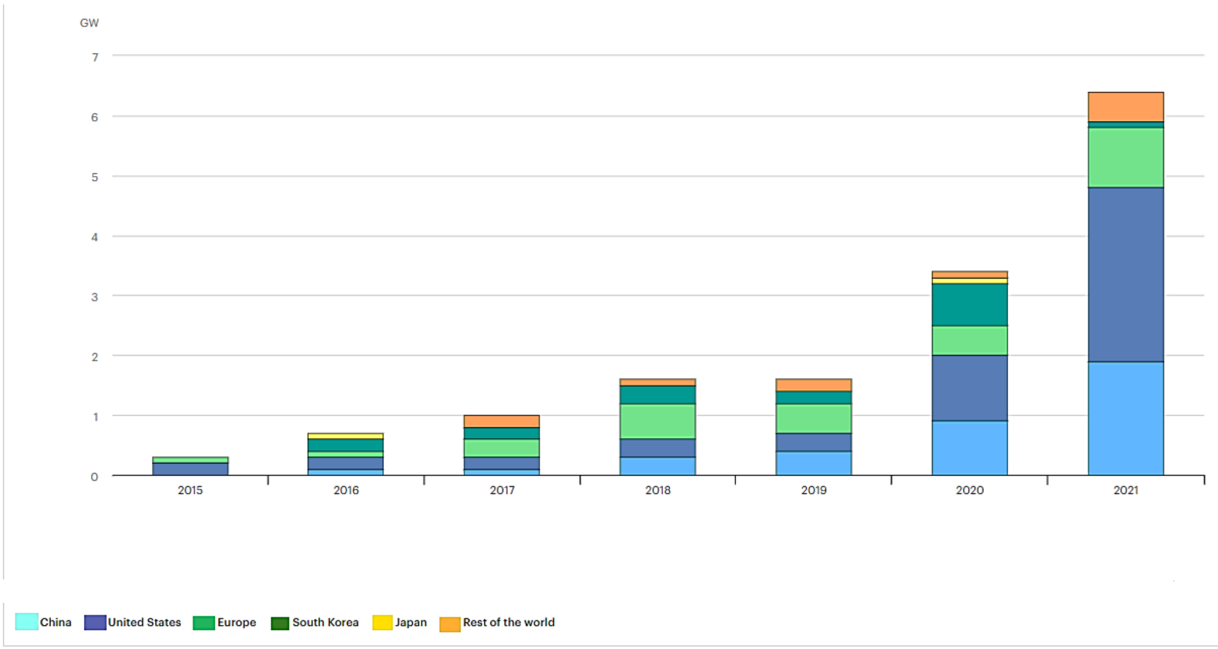


Fig 4. 1 Annual grid-scale battery storage additions, 2016-202 [140].

4.1 Applications for Batteries in the (Future) Energy System

The applications that energy storage may provide inside the system are what give it its value to the energy system. The uses batteries may provide for the energy system have been uncovered by several investigations. This much research have various uses and definitions. We have compiled a list of potential uses for batteries in the European energy system in this section based on a number of reports [IEA 2014a, IEA 2014b, RMI 2015, Sandia 2010, ISEA 2012], the classification of ancillary services in accordance with the System Operations Guideline [EC 2016b], the unique characteristics of battery storage, and our own internal analysis.

The properties of various energy storage devices may be mapped. The ranges for power capacity and discharge time for various energy storage methods are shown in the figure below. The graph demonstrates that there are technologies that can handle power ranges from 1 kW to around 100 MW and that batteries are well suited for applications that vary from minutes to several hours.

Additionally, they are often very dependable and responsive, with reaction times of only seconds or less.

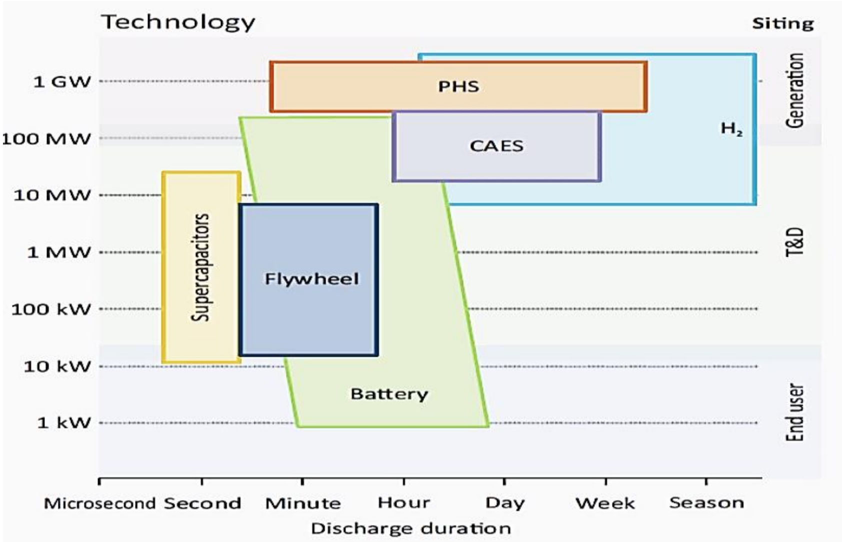


Fig 4. 2 Energy storage technologies according to their characteristics (power capacity versus discharge duration) [IEA 2014b] [142].

Keeping this in consideration and drawing from various sources (as mentioned above), we have compiled a list of potential applications for batteries within the European Energy system. These applications have been categorized into four main groups: End-User Applications (Residential and Industrial), Ancillary Services, Transmission & Distribution (T&D) System Applications, and Renewable Generation Applications (RES applications). Figure 6 provides an overview of the diverse services that will be explored.

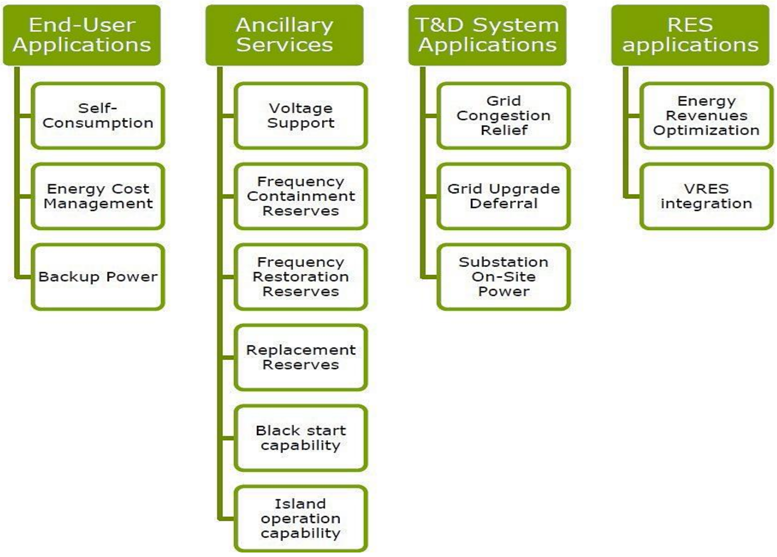


Fig 4. 3 Potential applications for batteries in the (future) EU energy system [143].

Chapter 5

Conclusions and Personal Contributions

5.1 General conclusions

The future of frequency control solutions in power systems is multifaceted and dynamic. It necessitates the seamless integration of renewable energy, energy storage, advanced technologies, and collaborative efforts among stakeholders. As the energy landscape continues to evolve, addressing frequency deviations will remain a critical aspect of ensuring the reliability, resilience, and sustainability of power grids worldwide.

Battery integration for frequency control has the potential to provide numerous economic benefits to grid operators, including increased reliability and resiliency, reduced emissions and fossil fuel consumption, and improved grid stability. While there are costs associated with integrating batteries into the grid, these costs are declining rapidly as battery technology continues to improve. As such, battery integration for frequency control is becoming an increasingly attractive option for grid operators looking to modernize their infrastructure and improve the efficiency and reliability of their operations.

However, the challenges of managing the intermittency of renewable energy sources, optimizing the siting and sizing of frequency control resources, ensuring cybersecurity, adapting regulatory frameworks, securing resource availability, and modernizing the grid are not to be underestimated. These challenges require concerted efforts from grid operators, policymakers, researchers, and industry stakeholders to navigate successfully.

In the face of these challenges, it is essential to emphasize the pivotal role that frequency control plays in the reliability and resilience of power systems. Grid reliability is not solely determined by the availability of energy sources but also by the ability to maintain a stable and consistent frequency. Frequency deviations, if left unaddressed, can lead to grid instability, blackouts, and economic disruptions.

As such, investments in advanced frequency control solutions, including energy storage systems, are investments in the future sustainability of power grids. These investments can yield long-term economic benefits, reduce the environmental impact of power generation, and enhance the overall quality and reliability of electricity supply. Grid operators and stakeholders must seize the opportunities presented by evolving energy landscapes, technological advancements, and changing consumer expectations to build a resilient and sustainable energy future.

1- Renewable Energy Integration: The proliferation of renewable energy sources, such as wind and solar, has introduced variability and uncertainty into power generation. These fluctuations pose challenges to maintaining grid frequency and necessitate advanced frequency control solutions.

2- Energy Storage Integration: Energy storage systems (ESS), including battery energy storage, have emerged as a pivotal tool for frequency control. Their ability to rapidly inject or absorb power into the grid makes them valuable assets for mitigating frequency deviations.
3- Advanced Grid Technologies: The deployment of advanced grid technologies, including phasor measurement units (PMUs) and synchro phasors, enables real-time monitoring and control of grid parameters, aiding in more precise and efficient frequency regulation.
4- Market Mechanisms: Evolving market mechanisms and regulatory frameworks play a crucial role in incentivizing frequency control services. Market designs that value fast response and grid stability are essential for encouraging investment in frequency control resources.
5- Distributed Energy Resources (DERs):The proliferation of DERs, such as distributed solar panels and small-scale wind turbines, presents both challenges and opportunities for frequency control. Coordinated control of these resources can contribute to grid stability.

5.2 Personal contributions

The personal contributions consist in:

i. An in-depth literature review was performed in order to clearly identify the need for advanced solutions to provide frequency control under the increased penetration of renewable energy sources. As support for this review a number of papers may be referred to;
ii. The frequency control levels and the stability principles have been described in the thesis. These have been used in order to identify the problems that are generated by RES in the future power systems and to proposed new or improved approaches for integration of the battery energy storage systems into the frequency control schemes;
iii. The usefulness of several models of energy storage system control systems and types of energy storage systems to determine the best energy storage system with a rapid response to changes that occur in the network frequency in general was identified and classified;
iv. Two software have been used in order to model and simulate the BESS and the frequency control schemes. This software is MATLAB/Simulink and Eurostag. While Simulink is a more research software, Eurostag allows implementing the more professional models. Both oh them has allowed implementation of frequency control schemes using battery energy storage systems;
v. The detailed model of a Battery Energy Storage System was modelled in Simulink, which consists of a battery element, a DC/DC converter, a DC busbar, a DC/AC converter, and a filter. This model was integrated into a simple configuration, which is

the battery as a source supplying a load. In this case, the battery is operated in grid forming mode. The simulation results showed that the model is stable and provides a good understanding of the physical and control parts of a battery;

vi. A battery model and a frequency control scheme for the secondary control level (AGC) were implemented in Eurostag software. Dynamic simulations were done to demonstrate the effectiveness of a battery in providing frequency control in a professional software. The simulations were performed on the WSCC 9-bus test system. The synchronous generators are modelled in detail, i.e., the generator model available in Eurostag was completed with detailed automatic voltage regulators and speed governors. For the BESS model, a detailed control scheme was also implemented;

vii. A complex scheme for frequency control was also implemented in Simulink. It consists of a two-area interconnected system, specifically developed for frequency control demonstrations. In this thesis, the new aspects are a realistic series of input data, consisting of 1440 values, to represent the power variation created RES and by the load; a detailed BESS that includes state of charge evaluation, power limitation to the capability limits, energy limitation to the SoC limits, and the control loops for FCR and AGC. The battery was integrated into the AGC scheme of the interconnected power system;

viii. An economic analysis regarding the development of battery energy storage systems and their use in various power system applications was performed. This analysis is important because it provides a vision on the potential of the storage systems to the frequency stability and control under the increased share of generation from renewables energy sources.

5.3 Future Prospects

Directions of developing the work are:

1. Extend the frequency control solutions to the use of virtual power plants and microgrids;
2. Perform optimal sizing of battery energy storage systems appropriate for the various solutions of using them in the power system;
3. Perform simulations on larger power systems, eventually on national wide models;
4. Perform simulations related to the frequency response required by grid code for the battery energy storage systems.

5.4