



Modelling and Simulating a Microgrid System at Åland University's Energy Lab Using MATLAB Simulink and Simscape

Kottage Don Chamila Nanda Jayawardana

Master's Thesis

MEng in Energy Automation Sustainable Engineering

2025

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Arcada University of Applied Sciences: M.Eng in Energy Automation Sustainable Engineering, 2025.

Commissioned by:

Åland University of Applied Sciences

Abstract:

This thesis investigates Microgrid modelling and the simulation of a Microgrid system based on the Energy Lab at Åland University of Applied Sciences. The dynamic system consists of a central photovoltaic (PV) roof with Fronius inverters, two 100 kW diesel generators, a battery energy storage system (BESS) and several controllable (dynamic) loads. A comprehensive simulation model was built for the Microgrid with MATLAB Simulink and Simscape to investigate the Microgrid's performance in different operation modes such as grid-connected, planned islanding, black start and resynchronisation. Detailed models of generation sources, storage, and loads are implemented in the study, including realistic control strategies, such as frequency control, load shedding, and power-sharing logic. System response to dynamic load changes, grid faults and transitions among operating modes are evaluated in the simulation. The results show that the system maintains voltage and frequency stability, prioritises load, and coordinates source synchronization. This work offers significant implications related to improving Microgrid operation, control and applications for teaching and further supports research on sustainable and resilient power systems.

Keywords:

Microgrid, MATLAB Simulink, Simscape, Battery Energy Storage System (BESS), Diesel Generator, Photovoltaic System, Frequency Control, Load Shedding, Islanded Operation, Resynchronization, Black Start, Åland University of Applied Sciences

Acknowledgements

This thesis marks the culmination of my studies in the Master's Degree Programme in Energy Automation Sustainable Engineering at Arcada University of Applied Sciences. The journey has been both transformative and enriching, allowing me to deepen my expertise in modern energy systems, automation, and control technologies.

First and foremost, I would like to express my sincere gratitude to Professor Matias Waller for his exceptional mentorship and leadership, as well as for organising a high-quality, practically oriented program. His commitment to creating a stimulating learning environment, through valuable lectures, hands-on lab sessions, and industry exposure via company visits, played a key role in shaping my academic and professional development.

I am deeply thankful to my thesis supervisor, Dr. Florian Haug, for his expert guidance, constructive feedback, and continuous support throughout the research process. I am especially grateful for the opportunity to contribute to his ongoing research work, which was both a privilege and a learning experience.

I would also like to thank Mr. Rizwan Ullah for his valuable advice during the thesis process and extend my appreciation to all my lecturers: Kim Skön, Kim Roos, Dr. Leonardo Espinosa-Leal, as well as the many guest lecturers and industry presenters who added depth and relevance to the curriculum.

I am grateful to all my batchmates, whose collaboration and support made this academic journey more enjoyable and inspiring.

I also extend my warm thanks to my relatives and friends for their encouragement and support throughout this time.

Lastly, I would like to extend my heartfelt thanks to my parents, wife, and son, whose love, patience, and sacrifices enabled me to pursue this goal. Their unwavering support, despite my long absences and busy days, has been the foundation of my success.

May 25, 2025

Nanda Jayawardana

Abbreviations and Symbols

AC	Alternating Current
AVR	Automatic Voltage Regulator
BESS	Battery Energy Storage System
DC	Direct Current
DER	Distributed Energy Resource
FCR-N	Frequency Containment Reserve – Normal
FCR-D	Frequency Containment Reserve – Disturbance
FFR	Fast Frequency Response
GFDPR	Gradual Frequency Dependent Power Reduction
GVDPR	Gradual Voltage Dependent Power Reduction
I	Output Current (A)
I_{ph}	Photogenerated Current (A)
I_s	Diode Saturation Current (A)
MPPT	Maximum Power Point Tracking
PCC	Point of Common Coupling
PID	Proportional–Integral–Derivative (Controller)
PMU	Phasor Measurement Unit
PV	Photovoltaic
R_s	Series Resistance (Ω)
R_{sh}	Shunt Resistance (Ω)
SOC	State of Charge
T_m	Mechanical Torque (Nm)
T_e	Electrical Torque (Nm)
V	Output Voltage (V)
V_t	Thermal Voltage (V)
ω	Angular Velocity (rad/s)

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1 Introduction

Today, renewable energy is more important day by day in the attempts to limit carbon emissions and promote sustainable development. This thesis addresses the development of a Microgrid model for the Energy Lab at Åland University of Applied Sciences. The goal of the model is to simulate the behaviour of the power source, load, and energy storage system using MATLAB Simulink Simscape. The rest of this thesis will be background material followed by a description of the research objectives and the thesis structure.

1.1 Background and Motivation

People worldwide are engaging in energy transitions because they want safer ecosystems while needing more electricity. Many people use photovoltaic and wind power to meet their energy needs while decreasing carbon emissions. This transformation fits perfectly with the UN Sustainable Development Goals: SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).

Modern power networks known as microgrids enable the efficient use of various renewable energy resources today. These small power units work alone or alongside the leading electrical network to create safer energy systems that work better and protect our environment. Microgrids offer important support for dependable energy supply on campuses of universities, factories, and remote areas.

The Åland University of Applied Sciences built the Energy Lab as a contemporary educational and research facility focusing on hybrid and renewable energy systems. The lab includes:

1. A 60 kWp rooftop solar PV system made up of 150 high-performance panels.
2. A diverse set of Fronius inverters: one 8.2 kW, two 20 kW, and a 10 kW Gen24Plus hybrid inverter.
3. A Battery-Box Premium HVS storage system with a capacity of 10.2 kWh/9 kW.
4. Two Caterpillar 100 kW diesel-electric generators with manual, semi-automatic, and automatic operational modes.
5. A 15 kW Keysight solar emulator for PV performance simulations.
6. Dynamic loads, including a 55 kW induction pump, multiple 22–23 kW resistive heaters, and EV charging infrastructure.

7. Additional systems, such as an electrolyser, heat pumps, and grid-protection relays, support studies of frequency regulation and islanded operation.

This research aims to build a high-fidelity Microgrid simulator based on an Energy Lab setup using MATLAB Simulink and Simscape. With this model, system-level analysis under grid-connected and islanded states is performed considering load sharing, integration of renewables, frequency control and support of reserve power. This research provides the study with an impact on improving operational strategies and energy efficiency and is educational on the lab infrastructure.

1.2 Problem Statement

Microgrids, in turn, play a significant role in facilitating the integration of renewable energy into the global energy landscape, which is shifting toward sustainability and distribution. Together, these systems create a network to connect various energy sources like solar photovoltaic, diesel generators, battery storage and electrolysers that can operate both on their own and in a grid-connected configuration.

The Åland University of Applied Sciences Energy Lab is a real-world hybrid energy experimentation platform. The infrastructure is composed of two 100 kW Caterpillar diesel-electric generators, a 60 kWp rooftop PV array with several Fronius inverters (8.2 kW, 20 kW ×2, and 10 kW Gen24Plus), 10.2 kWh battery, 15 kW solar emulator, resistive and inductive loads and electrolyser 500 NL/h for hydrogen production. Advanced functionalities such as Fast Frequency Response (FFR), Frequency Containment Reserve (FCR-N and FCR-D), island mode operation, and dynamic grid support are supported.

Although the lab's physical setup is theoretically advanced, a complete, integrated simulation model that recapitulates the system's behaviour does not exist. Therefore, without a digital twin, it becomes challenging to evaluate the system-level dynamics, energy dispatch optimisation, fault condition simulation, and testing of new control strategies under realistic scenarios. Moreover, it does not allow for system planning and operational improvement because of the lack of predictive modelling capabilities.

This thesis fills the gap and develops a detailed MATLAB Simulink and Simscape model of the Energy Lab's microgrid. The model will allow for replicating islanded and grid-connected operation modes, considering the main components of renewable generation, diesel backup, battery energy storage, and controllable loads. The intention is to study dynamic performance, develop advanced control strategies and facilitate future deployment of smart grid capabilities using the laboratory setup.

1.3 Research Objectives

Model Key Components:

- Develop detailed Simscape-based models for the Energy Lab's core assets, including two diesel-electric generators, photovoltaic systems with Fronius inverters, battery energy storage system (BESS), breakers and power measurement units.
- Integrate switching devices such as circuit breakers and a swing generator to enable mode transition and system protection features.

Simulate Load Variations:

- Implement varying load profiles, including step-by-step addition and removal of resistive heaters, pumps, and lighting systems.
- Analyse the system's voltage, frequency, and power-sharing response under these dynamic load scenarios.

Monitor System Behaviour:

- Track the real-time power flow from each source (diesel, PV, BESS) to evaluate power-sharing and load matching.
- Observe frequency deviations and system stability under different operating conditions, including grid disturbances.

Evaluate Performance in Island Mode:

- Simulate islanded mode operation emphasising frequency control, droop characteristics, and load prioritisation.
- Test and evaluate Fast Frequency Response (FFR) and Frequency Containment Reserve (FCR-N and FCR-D) behaviour using generator droop control and inverter-based responses.

1.4 Significance and Relevance

The research findings assist Åland University of Applied Sciences in its mission to drive sustainable energy autonomy since they stem from their applied research and education activities. The development of an elaborate Simulink/Simscape-based model for the university's hybrid microgrid enables comprehensive system evaluation when functioning under grid-connected or islanded operation conditions.

The commercial-grade equipment at the Energy Lab within Åland University includes a diesel-electric generator, multiple photovoltaic inverters, battery storage, and electrolyser facilities for authentic laboratory testing. The modelling of these assets produces a model that represents operational behaviour to find control difficulties and enhance energy flow optimisation and frequency stability.

The lab performs FFR, FCR-N and FCR-D testing using coordinated inverter and generator units as one of its essential objectives. The analysis capability of this thesis is crucial because it helps evaluate important power grid resilience services which support operation stability during low inertia phases with high renewable generation share.

This research improves demand-side dynamics by examining multiple load profiles, including testing resistive heaters, induction pumps, and lighting usage. This research explains practical ways to manage load-shedding alongside energy dumping and smart charging, corresponding to existing features delivered through Ohmpilot, Wattpilot, and Ziehl relay systems in lab environments.

This study possesses essential value for the academic world and society by contributing to energy automation and serving the fields of sustainable engineering and digital models for smart grids. The study joins initiatives to decrease energy operations while securing power in decentralised, robust networks.

The work establishes an essential framework enabling educational instruction and joint industrial research activities, thus establishing Åland University of Applied Sciences as a leading institution for hybrid power system examination and digital energy advancement.

1.5 Scope of Study

The research examines microgrid modelling by representing the Energy Lab facilities at Åland University of Applied Sciences. The simulated microgrid contains two 100 kW Caterpillar diesel generators as well as a 60 kWp photovoltaic system with Fronius inverters, an electrolyser, a Battery Energy Storage System (BESS), lighting and a resistive heater, 55 kW induction pump loads.

The research investigates the operational behaviour of this dual-function hybrid system when running in a grid-powered state and standalone power mode. The simulation platform based on MATLAB Simulink and Simscape will observe three essential system parameters: power flow mechanics, load distribution characteristics and frequency stability dynamics. The model provides evaluation capabilities for the system regarding energy distribution management alongside operational reliability maintenance at different load scenarios.

The study does not cover the implementation of real-time operations, hardware testing, or predictive control algorithm development. The project stops at the modelling stage since its primary purpose is to establish an operational simulation framework and a comprehension platform for microgrid behaviour while setting the groundwork for upcoming control methods or experimental evaluations.

1.6 Structure of the Thesis

The thesis has six distinct chapters where information builds progressively to take readers from background research to system modelling, then simulation and concludes with final assessments.

Chapter 1: Introduction

The first chapter provides essential groundwork for the entire research project. The initial part of this section introduces background information surrounding the study and its motivational factors, followed by objectives and scope definitions, as well as a quick overview of the document structure.

Chapter 2: Literature Review

The analysis focuses on a detailed literature review from this chapter. The presented work describes the basic concepts of Microgrids while exploring renewable technology interfaces and modelling strategies that implement MATLAB and Simscape. This section discusses the main research findings in conjunction with discovered knowledge gaps

Chapter 3: System Description and Modelling

The Åland Energy Lab contains several main components, including diesel generators and photovoltaic systems with battery storage, different kinds of loads and control systems. A description explains how these elements are modelled in MATLAB Simulink and Simscape, along with a model configuration and breakdown of assumptions.

Chapter 4: Simulation Setup and Implementation

The simulation environment is described at this point. This section describes the model setup method while providing details on scenario testing, including grid-connected operations, islanded modes, black start, resynchronization and defined performance metrics. A description accompanies simulation parameters together with an explanation of data handling practices.

Chapter 5: Results and Discussion

The chapter delivers simulated results as well as their corresponding analysis. The analysis investigates system reactions to load variations, together with assessing power stability, frequency stability, and the contribution of each energy source during different conditions. An interpretation of results according to system reliability and efficiency standards takes place.

Chapter 6: Conclusion and Future Work

The final section presents a summary of essential contributions from the research study. This conclusion examines the study's important discoveries and resulting meanings before proposing new academic paths and system model enhancement possibilities.

References are then given in a standard format for citing works, along with appendices containing supplementary materials such as MATLAB model screenshots, system parameters, and additional test results.

2 Literature Review

Companies now value combining renewable energy solutions with Microgrid systems because these innovations save power and reduce carbon. This chapter outlines important elements, including technical systems required to design the Energy Lab Microgrid model.

At the start, the study explains basic Microgrid principles and then delves into ways to combine renewable energy resources. This section examines different methods for modelling diesel generators, focussing on solar power with details about batteries and hydrogen generator power solutions. The research explores different ways to control Microgrid operations, especially for maintaining power quality while managing loads and reducing energy usage. This section explains how MATLAB Simulink and Simscape support dynamic power system simulations and control system development.

Chapter 2 presents the main research findings regarding the studies published on Microgrid systems, which are referred to in the development of my microgrid system.

2.1 Overview of Microgrid Systems

Microgrid work independently or with the primary grid to create local power systems for specific energy supply areas. These units combine distributed energy resources such as natural energy assets, storage systems, and power plant modules (U.S. Department of Energy, n.d.).

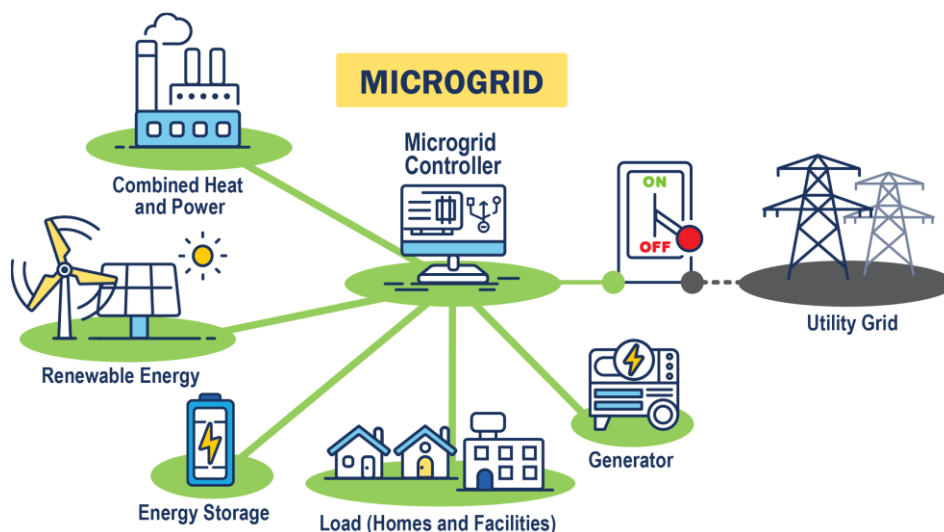


Figure 1. Features of an example microgrid. (U.S. Department of Energy, 2024)

Key Components of Microgrids:

1. **Distributed Energy Resources (DERs):** This comprises distributed generation, which could be renewable energy systems such as photovoltaic systems or wind turbines, as well as conventional power sources such as diesel generators (U.S. Department of Energy, n.d.).
2. **Energy Storage Systems (ESS):** Batteries and hydrogen storage employ technologies to store energy for later use to improve Microgrid reliability and stability (Lawrence Berkeley National Laboratory, n.d.).
3. **Loads:** The load includes the electrical requirement of the Microgrid assets, such as residential, commercial, or industrial consumers (U.S. Department of Energy, n.d.).
4. **Control Systems:** Sophisticated systems that supervise and coordinate the operation of the Microgrid by meeting the supply and demand balancing and guaranteeing the quality of the electricity supplied (U.S. Department of Energy, 2024).

Structure of Microgrids:

1. **AC Microgrids:** Use alternating current (AC) for power distribution, compatible with most existing electrical infrastructure (U.S. Department of Energy, 2024).

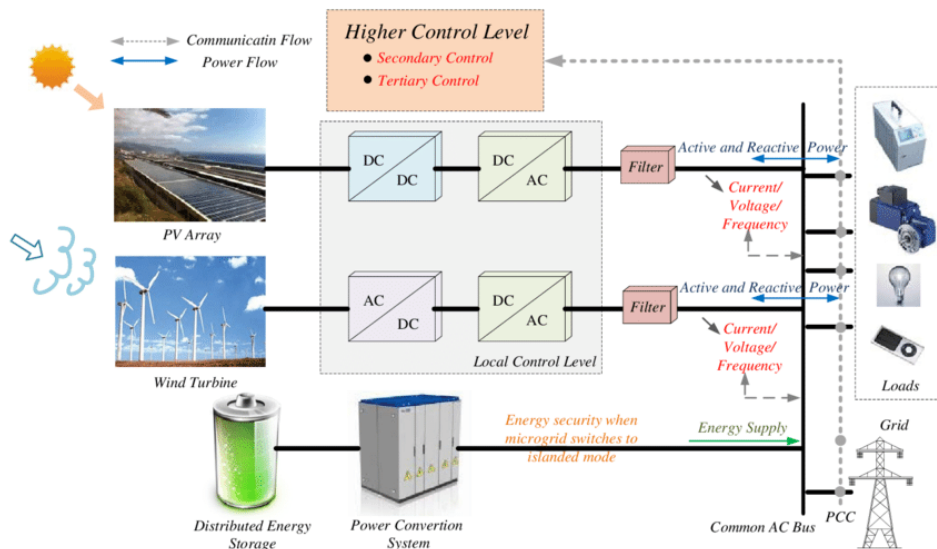


Figure 2. Architecture of the AC Microgrid (Han Y. M., 2016)

2. **DC Microgrids:** DC for power distribution is advantageous for DC DER integration and reduces conversion losses for DER and load connections (U.S. Department of Energy, 2024).

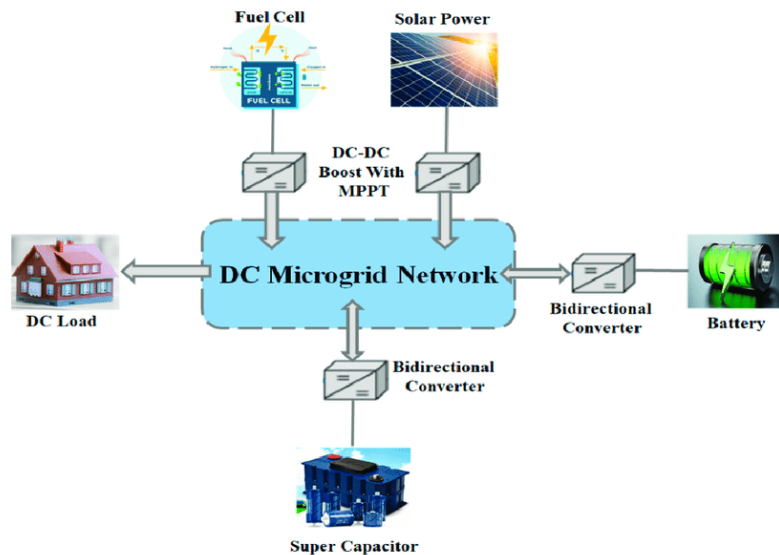


Figure 3. Architecture of the DC Microgrid (Vasantharaj, 2021)

3. **Hybrid AC/DC Microgrids:** This structure allows both AC and DC systems to be combined to use the advantages of each, depending on the load and DER types connected.

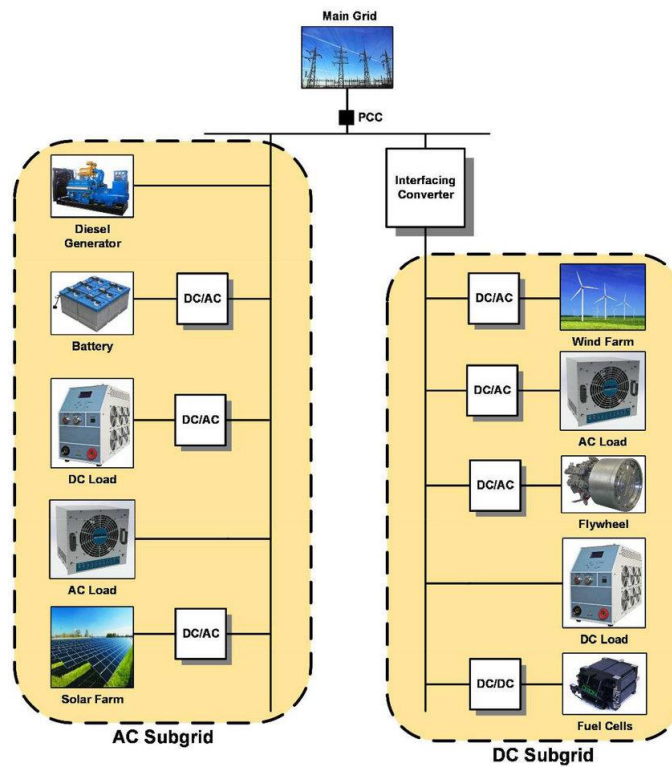


Figure 4. Hybrid AC/DC Microgrid (Mirsaeidi, 2017)

Advantages of Microgrids:

- **Enhanced Energy Resilience:** In independent operation, Microgrids supply critical facilities with power during main grid blackouts (U.S. Department of Energy, n.d.).
- **Integration of Renewable Energy:** The reason is that these energy systems allow operators to use renewable power sources and decrease environmental pollutants, assisting with ecological stewardship initiatives (Lawrence Berkeley National Laboratory, n.d.)
- **Improved Energy Efficiency:** Localised operation and distribution setup help to minimise energy losses in a distribution network and maximise the potential of power utilisation (U.S. Department of Energy, 2024).
- **Economic Benefits:** Financial savings can be realised through peak shaving operations, demand response programs and decreased import fuel costs (Lawrence Berkeley National Laboratory, n.d.).

Challenges in Microgrid Implementation:

1. **Technical Complexity:** The Microgrids need advanced controls to create and oversee to operate without safety (U.S. Department of Energy, 2024).
2. **Regulatory and Policy Barriers:** Some regulations are yet to be written to handle Microgrid operations, resulting in difficulty dealing with regulations (U.S. Department of Energy, 2024).
3. **Economic Viability:** This makes it difficult for companies to invest in setting up a Microgrid, and the high costs involved in such a system and the uncertain earnings because of it (Lawrence Berkeley National Laboratory, n.d.).

To have a more resilient and sustainable energy future, one needs to understand these aspects of Microgrids and their underlying technologies and incorporate them when designing, implementing, and operating Microgrids.

2.2 Overview of Åland Islands and its Energy System

The Åland Islands function as both an autonomous region and a demilitarised territory of Finland within their position between Sweden and Finland in the Baltic Sea. Even though

Åland ranks under Finnish political authority, it can make laws about energy and other areas directly through parliament and local bodies (Wikipedia, n.d.).

The electricity system in Åland stands apart because of its isolated setup and need for external electrical connections. The principal power supply comes from Sweden to Åland via (Kraftnät Åland Ab, 2025) (Kraftnät Åland Ab, n.d.-a) Sverige kabeln, which delivers HVAC over a submarine cable network (Figure 5). HVDC Ål-Link connects to Finland's Fingrid system through a direct current power line that offers backup power to the Åland's electricity system (Kraftnät Åland Ab, n.d.-b).

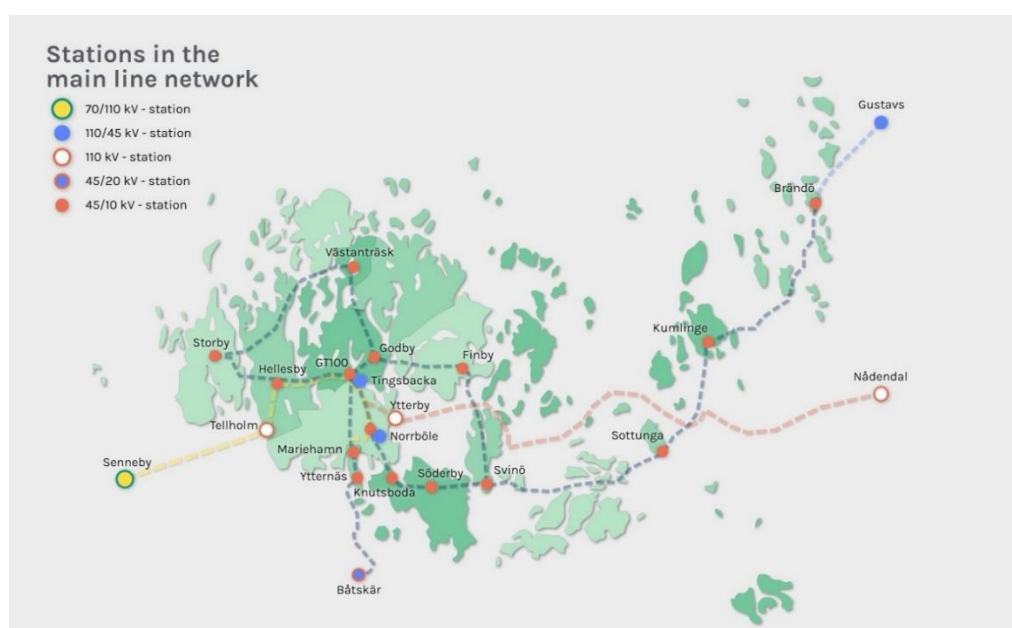


Figure 5. The geographical location and grid structure of the Åland Islands (Kraftnät Åland Ab, n.d.-a.)

After the electricity market deregulation on 1 January 2000, Åland residents could pick their electricity provider. The authorities introduced these changes to help numerous users save money through market competition. People can select from multiple business plans, including pre-set costs or rates that match Nord Pool spot prices, while small energy producers can trade their extra electricity through the grid (Wikipedia, n.d.) (Kraftnät Åland Ab, n.d.-c).

Nord Pool runs hourly electric pricing in Åland that changes based on operational data from wind turbines, information about nuclear power plant maintenance, and everything from nearby fuel prices (Kraftnät Åland Ab, n.d.-c) Åland's electricity system has undergone significant evolution in recent years. As of April 2025, approximately 51% of the island's

electricity demand was met by wind power, reflecting the growing contribution of renewable energy to the local grid (Kraftnät Åland Ab, 2025) . In contrast to earlier reliance on diesel generators, these units have now been fully decommissioned. Today, backup power is provided by two gas turbines rated at 10 MW and 25 MW, which support the system during outages or critical demand situations (Kraftnät Åland Ab, n.d.-b). Kraftnät Åland Ab, the local transmission system operator (TSO), is responsible for maintaining the power balance between generation and consumption in real time. It also operates the island's electricity market, ensuring transparent competition and high power quality standards.

Åland's electricity market operates within a deregulated Nordic system, where electricity is primarily imported via the Sweden cable and traded through the Nord Pool Spot exchange. Locally, Kraftnät Åland Ab is responsible for maintaining system balance and monitoring the electricity trading marketplace. Currently, there are four entities with balancing responsibility in Åland's local electricity market: Mariehamns Energi, Ålands Elandelslag, Allwinds, and Kinect Energy. However, only Mariehamns Energi and Ålands Elandelslag supply electricity directly to households and industries. These companies can also act as producers, with some engaged in local generation from wind power. Electricity traders may also purchase balancing services from another market participant (Kraftnät Åland Ab, n.d.-c).

The Åland Islands take sustainable energy development as their core strategic objective. The area wants to become more self-sufficient in energy while lowering its carbon footprint and using intelligent power networks as part of its global sustainability efforts (Kraftnät Åland Ab, n.d.-c).

To explore a fully sustainable energy future, (Child, Nordling, & Breyer, 2017) have developed several modelled scenarios of the energy system of the Åland Islands in 2030. Based on the EnergyPLAN tool (Lund & Østergaard, n.d.), their research indicated that Åland could have a 100% renewable energy system by increasing wind and solar capabilities, employing storage technologies, and utilising Power to Gas and Vehicle to Grid (V2G) strategies. Among the 203 Sustainable Modelling (SM) Electricity (El) scenarios (most innovative, highest electrification, and emphasis on V2G), the 2030 SM El, i.e. the one with the highest electrification and emphasis on V2G, was the least costly scenario, economically and with low emissions. This shows Åland's role as a live example of sustainable island-based energy systems globally.

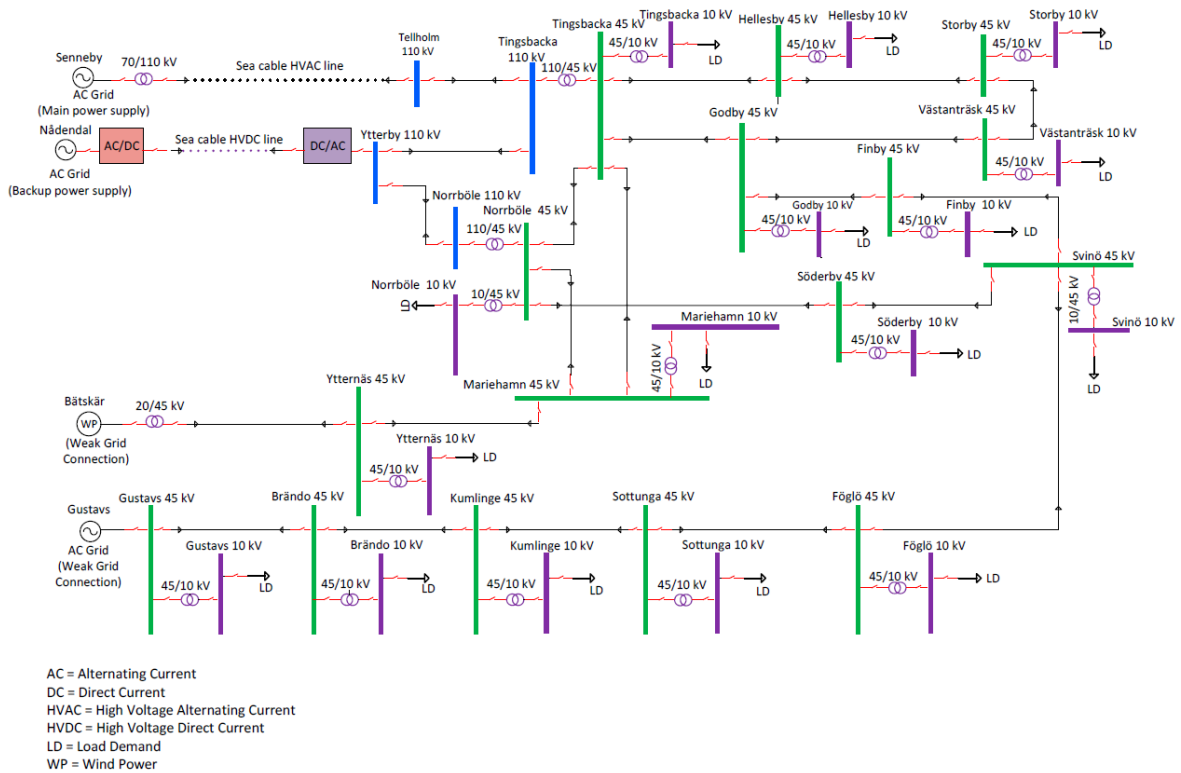


Figure 6 Single line diagram of the Åland Islands power system (Kumar et al., 2020)

2.3 Åland University of Applied Sciences and Its Role in Energy Research

For the region, the Åland University of Applied Sciences essentially acts as a centre for research and education related to energy matters. It is an institution concerned about proactive learning and industry linkages and has specialised programs for applying theoretical knowledge with practical experience (Åland University of Applied Sciences, n.d.).

This mission is key supported by the state-of-the-art energy laboratory at the university as research and education on hybrid power systems. The laboratory is set up to deal with integration and development challenges in renewable energy and smart grid. A photovoltaic (PV) system at this facility is central and capable of operating Microgrid environments in island mode, in addition to those with high shares of intermittent renewable energy and inverter-based power (Haug, et al., 2025).

A 60 kWp rooftop installation is divided into several strings for flexible installation. The inverters offer dynamic power management capabilities with advanced inverters, a 10 kW storage inverter paired with a 10 kWh battery, and a 10 kW PV emulator. They have, for

instance, modular expansion and real-time monitoring, remote control and support for adjustable grid support curves like Gradual Voltage Dependent Power Reduction (GVDPR), Gradual Frequency Dependent Power Reduction (GFDPR), and Volt-Var, and support for dynamic load-balancing and spot price management (Haug, et al., 2025).

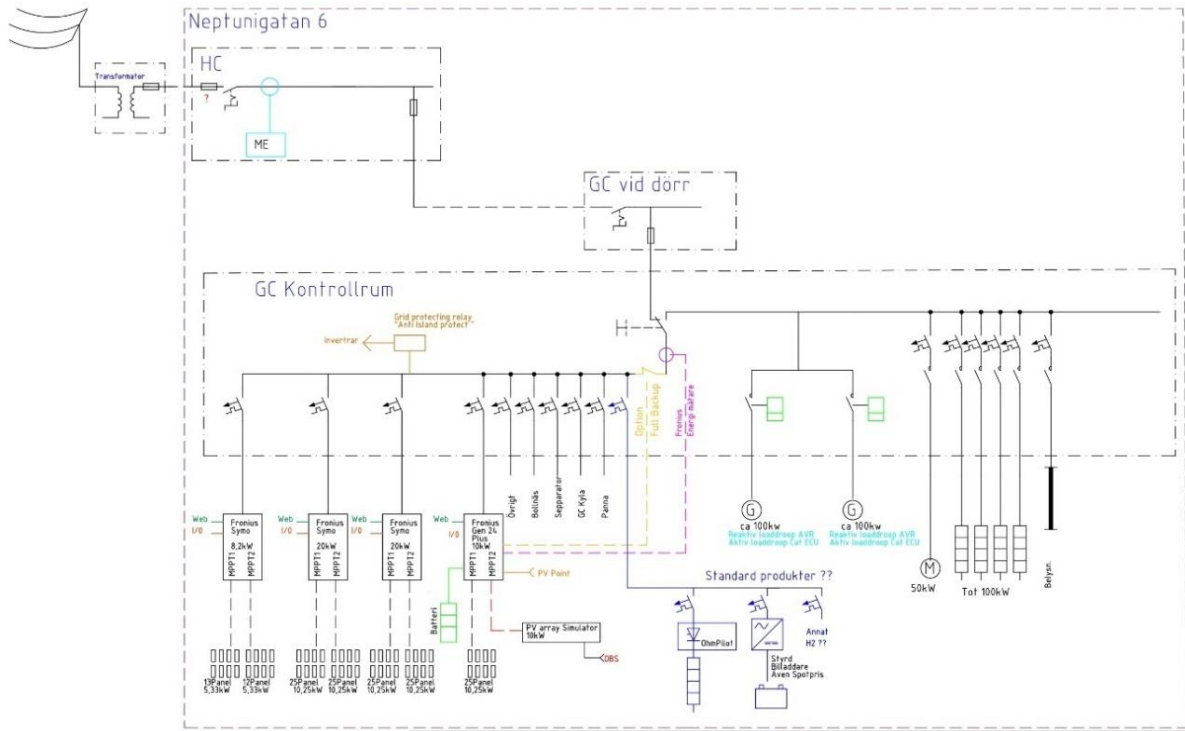


Figure 7. Electrical Diagram of Åland University of Applied Sciences

The Åland Energy Laboratory features two 100 kW diesel-electric generators, which can be utilised to study grid stability and provide support services. These generators are particularly (Haug, et al., 2025) suitable for experiments related to automatic Frequency Restoration Reserve (aFRR). However, other ancillary services such as Frequency Containment Reserve Normal (FCR-N), Frequency Containment Reserve for Disturbance (FCR-D-up and FCR-D-down), Fast Frequency Response (FFR), and manual Frequency Restoration Reserve (mFRR) must be simulated using additional components within the laboratory environment.

These include programmable grid emulators, inverter-based resources, and control systems designed to replicate the dynamic conditions required by such services (Haug, et al., 2025). The laboratory setup enables advanced experimentation in frequency-dependent power

reduction and rapid load change testing for energy conversion technologies, such as electrolysers and heat pumps.

It offers an integrated infrastructure for reasoning about the power needed for energy storage optimisation, inverter performance in Microgrids, and the ability of renewable energies to disrupt grid stability. Island mode simulations, rapid load change testing, and energy quality assessments are basic laboratory capabilities essential to advancing education and collaborative research with industry stakeholders.

2.4 Renewable Energy Integration in Microgrids

Integrating renewable energy sources into Microgrids has become important for modern energy systems. Microgrids are small-scale, low-power networks mainly used for decentralised or localised power generation using the energy system. The integration of renewable energy in Microgrids can pose utility and technical challenges to grid stability and efficiency.

The photovoltaic (PV), wind, and energy storage technologies are key renewable sources in the Microgrids. However, PV systems currently make a significant contribution to Microgrid energy inputs. Combining these systems with advanced inverters and battery storage is popular now. These configurations enable dynamic load balancing, real-time monitoring and control functionalities to increase energy management (Haug, et al., 2025).

Battery Energy storage systems BESS are also key to helping overcome the intermittency of renewable sources. Battery systems can serve as means of energy buffering, voltage and frequency stabilisation and backup power during grid disturbances. In addition, energy management strategies such as demand response, spot price optimisation, and dynamic load shedding enhance the performance of Microgrids (Haug, et al., 2025).

Increasing the share of wind and solar renewable power in microgrids is critical for achieving sustainable energy goals, and the Åland Islands serve as a successful example of renewable integration. Advances in energy generation and diesel-electric backup system design are probed in the advanced energy laboratory of the Åland University of Applied Sciences region (Åland University of Applied Sciences, n.d.). It provides grid stability while maximally using renewable energy resources.

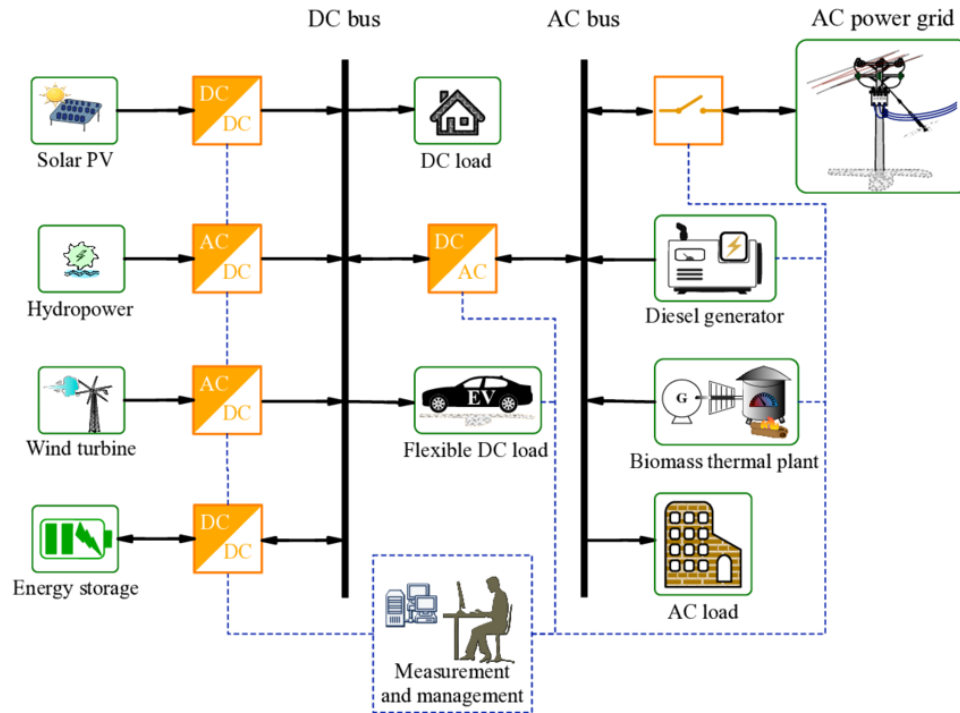


Figure 8. Schematic of a Microgrid with Renewable Energy Integration (Agha Kassab et al., 2024)

The Microgrid control strategy involves following the grid and forming inverters to address the power quality issue. These technologies maintain power balance for everyday grid operations during changes in load conditions (Haug, et al., 2025).

As the penetration rate of renewable energy increases, Microgrid systems must adapt to forecast improved models, adaptive control schemes, and more robust grid interconnection standards to enable supportive green energy goals.

2.5 Diesel Generator Modelling Techniques

Microgrids widely use diesel generators as a backup or source of reliable power when the grid fails. To predict the dynamic behaviour of diesel generators and their operation in a Microgrid, accurate modelling of diesel generators is necessary. Electric, mechanical and control aspects of diesel generators are represented using various modelling techniques.

2.5.1 Mathematical Modelling

Differential equations are used to describe the dynamic behaviour of the diesel generator using mathematical models. Key aspects include:

Mechanical Dynamics: Newton's second law is used to model the torque, speed, and Inertia (prime mover: diesel engine) (Tudorache, 2010).

Electrical Dynamics: As noted in (Tudorache, 2010), the dynamics of the synchronous generator are modelled based on the voltage equations expressed in terms of the dq-axis reference frame.

Fuel System and Governor Control: Fuel injection delays and governor response are accounted for through models to keep at the desired speed and frequency (Vu Hoa Nguyen, 2024).

$$J \frac{d\omega}{dt} = T_m - T_e - D\omega$$

Where,

J is the Inertia constant

ω is the Angular velocity

T_m is the Mechanical torque from the prime mover

T_e is the Electrical torque

D is the Damping coefficient

2.5.2 Transfer Function Modelling

The system is simplified into a transfer function (relationship of input fuel flow or control signal and output generator speed or voltage) (Shah, 2022).

Transfer Function Structure:

$$G(s) = \frac{K}{\tau s + 1}$$

Where,

K is the System gain

τ is the Time Constant

s is the Laplace variable

Such a method is more appropriate for control design and stability analysis.

2.5.3 State-Space Modelling

In the sense of first-order differential equations in matrix form, these models describe the system for the state space models (Lawrence Berkeley National Laboratory, n.d.).

State-Space Representation:

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

Where,

x are the State variables (e.g., generator speed, voltage)

u are the Input variables (e.g., control signal)

y is the Output variable

A, B, C, D are the System matrices

The utility of this approach for modelling multi-variable control systems can be exploited.

2.5.4 Simscape-Based Modelling

The Simscape Electrical toolbox of Simulink forms a strong environment for diesel generator modelling through its connection of mechanical drives and electrical control elements (Shah, 2022). The Simscape block named Synchronous Machine (Salient Pole) effectively captures how the generator produces power (Shah, 2022). Engine dynamics and control systems can be built directly in Simulink to test diesel generator performance (Shah, 2022).

2.5.5 Empirical and Data-Driven Models

Using data from real diesel generator systems, these models are developed. This can be done using techniques such as system identification and neural networks (Mendoza-Armenta, n.d.) and never requires knowing detailed physical equations.

2.6 Solar Energy System Modelling

This section explains PV array modelling for solar energy and its application within Microgrid networks. Here, we explain basic PV system procedures, mathematical formulas, and simulation tools for designing PV systems. We will use MATLAB Simulink and Simscape tools to build correct and time-saving simulations.

2.6.1 Fundamentals of Photovoltaic (PV) Systems

Semiconductor materials convert sunlight directly into electricity, employing photovoltaic systems for this conversion (Asghar, 2015). Internal losses can be represented by series and shunt resistances, arranged in series and parallel to a current source, which signifies the current in a single PV cell. Factors influencing the current-voltage (I-V) characteristics of a PV cell include solar irradiance and temperature.

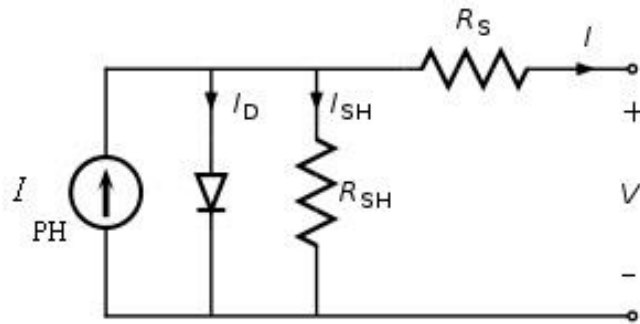


Figure 9. PV Cell Equivalent Circuit Model (Khyani, 2013)

The performance of a PV array Equation can be described using the following equation (Dhar, Sridhar, & Avasthy, 2012):

$$I = I_{ph} - I_s \left(e^{\frac{V+IR_s}{nV_t}} - 1 \right) - \frac{V + IR_s}{R_{sh}}$$

Where,

I is the Output Current

I_{ph} is the Photogenerated current

I_s is the Diode saturation current

V is the Output voltage

R_s is the Series resistor

R_{sh} is the Shunt Resistor

n is the Diode Identification factor

V_t is the Thermal Voltage

It is an important equation that represents the nonlinear characteristic of PV cells, such that it could simulate their performance under varying environmental conditions.

2.6.2 Simulation of PV Systems Using MATLAB Simulink and Simscape

PV systems can be effectively modelled and simulated using MATLAB Simulink and its Simscape add-on. The Solar Cell block in Simscape operates as a single PV cell that uses irradiance and temperature parameters to facilitate a detailed evaluation of PV system behaviour across various environmental conditions. Users can achieve accurate PV module electric characteristics modelling through Solar Cell block configuration with short-circuit current, open-circuit voltage and diode saturation current data. By exposing the thermal port of the Solar Cell block in Simscape, users can study how temperature affects PV performance.

2.6.3 Maximum Power Point Tracking (MPPT) Techniques

PV systems work best when Maximum Power Point Tracking (MPPT) algorithms are used for operations. Under the Perturb and Observe method, the MPPT technique helps PV systems find their ideal power production location. A voltage parameter change tests the system's power and fixes adjustments until it reaches the highest power level. The control logic part of an MPPT algorithm will interact with the PV model in MATLAB Simulink to modify DC-DC converter duty cycle parameters for the best power output from the array.

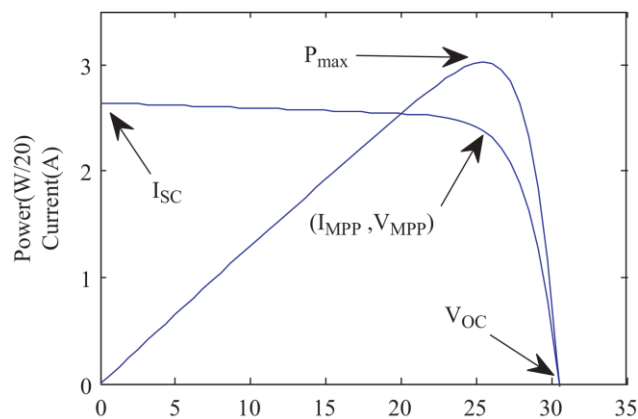


Figure 10. I-V and P-V curve of a PV cell (Podder et al., 2019)

2.6.4 Integration with Power Electronics

PV systems need power electronic converters to connect with user equipment and the electricity grid. The schematic model uses average-value DC-DC converters alongside ideal DC-AC inverters for power conversion. The components let researchers test how well PV systems convert power and react to control changes in Microgrid systems.

2.7 Battery Energy Storage Systems (BESS)

2.7.1 Role of BESS in Microgrids

Battery Energy Storage Systems (BESSs) play a crucial role in enhancing microgrid reliability, flexibility, and resilience through a hybrid configuration of renewable and conventional power sources. In outages (islanded mode), the system can operate independently of the primary grid, load balancing, backup power, and critical services such as black start and resynchronisation (Altin, 2022).

2.7.2 Control Strategies

Depending on operating conditions, BESS can be operated in either grid-following or forming mode. Control strategies are typically common and include:

- Frequency and voltage stability by droop control.
- To ensure battery longevity, we conduct State of Charge (SOC) management and develop a battery selector and the battery state estimation strategy.
- Capabilities such as Fast Frequency Response (FFR) and Frequency Containment Reserve (FCR) as a form of dynamic grid support.

Such functionalities make BESS very important for power systems with a high penetration rate of intermittent renewable energy resource.

2.7.3 Integration with Renewable Energy

BESS can store surplus power from photovoltaic (PV) and wind production to improve energy utilization and reduce diesel generator dependence. For several Microgrid systems, BESS operates as buffer for power output smoothing and load mismatching management during system transitions from one operating mode to another.

2.7.4 Modelling Approaches

In MATLAB Simulink and Simscape Electrical environments, BESS is usually represented with a combination of:

- Electrical equivalent battery models
- Bidirectional converters or inverters
- Custom control blocks for power management and mode switching

(Bouchaala and Boukadoum, 2023) demonstrated a similar modelling approach in their simulation of an off-grid Microgrid system using MATLAB/Simulink. Their study emphasised the integration of renewable energy sources and BESS, highlighting how simulation can be used to evaluate operational stability, power flow, and control strategies in Microgrids.

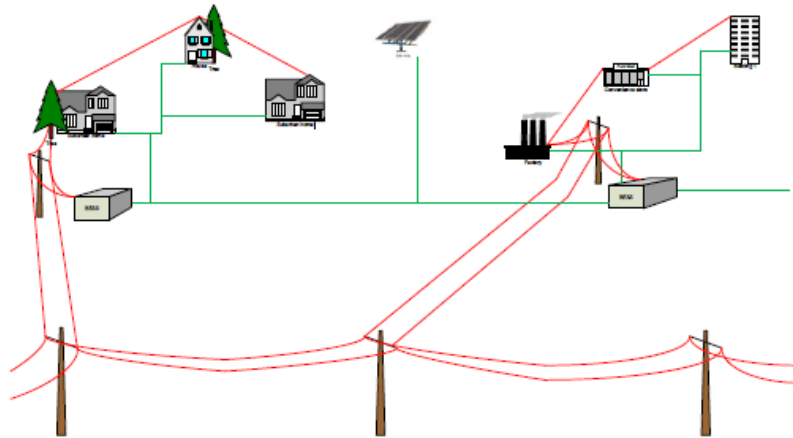


Figure 11. Layout example of Microgrid BESS (Chandran & Master, 2018)

2.8 Control Strategies for Microgrids

The control strategies for Microgrids are important to ensure stable and efficient operation as the energy source is diverse. Specifically, these strategies seek to tackle problems like power quality, the problems of load management, and the adverse effects of renewable energy generation (Altin, 2022).

The control strategies in the Microgrid can be divided into three levels: primary, secondary, and tertiary. The primary aim is to stabilise the voltage and frequency deviations using droop control techniques, which constitute the primary control. Secondary control helps to compensate for errors in the steady state and synchronises with the primary grid. Power flow between the Microgrids and economic dispatch of energy in terms of those factors are managed by tertiary control (Altin, 2022).

Grid-following and grid-forming inverters are crucial for the integration of renewable energy. In microgrid systems with a high level of renewable energy penetration (Altin, 2022), these inverters enhance voltage regulation and frequency stability.

Most recent approaches to Microgrid control are based on model predictive control (MPC), reinforcement learning (RL) and adaptive control. System flexibility is increased using these methods, real-time decisions are better made, and the system can adapt better to dynamic conditions (Altin, 2022).

A traditional element of our activities at the Åland University of Applied Sciences in its energy laboratory is to look for new ways of implementing innovative control strategies, integrating renewable generation with diesel-electric systems for enhanced reliability and performance (Haug, et al., 2025).

2.9 MATLAB Simulink and Simscape in Power System Modelling

MATLAB Simulink and Simscape are essential tools for modelling, simulating, and analysing power systems. Using Simulink, designers can develop models in a graphical programming environment for dynamic systems; in fact, Simscape enhances Simulink's capabilities by providing physical modelling components that replicate electrical, mechanical, and thermal systems (MathWorks, n.d.-a).

Simulink is used in power system modelling to simulate dynamic system behaviours under different operating conditions, develop control strategies, and test the system response. An engineer may begin with the block-based interface in which functional blocks are interconnected to represent the system components such as generators, transformers, etc.

However, power electronics, electrical machines, and renewable energy sources are pre-built in libraries available in Simscape. This allows engineers to create detailed physical models with minimal computationally intensive mathematical equations deregulation. For example, the Three-Phase Series RLC Load block (Specialized Power Systems), located under Simscape, makes modelling complex impedance networks easier (MathWorks, n.d.-a).

Since Simscape can be used to model both the electrical systems and the control algorithms, the co-simulation process is easy when Simulink and Simscape are combined. Since this integration streamlines the development of grid control systems, renewable energy integration models and dynamic load analysis, we believe it is an appropriate focus. Researchers use this

approach to study modern power systems' stability, voltage control, and protection schemes (MathWorks, n.d.-a).

In the energy laboratory of the Åland University of Applied Sciences, the Åland University of Applied Sciences uses MATLAB Simulink and Simscape to simulate in detail the functioning power system for Microgrid, energy load balancing and the integration of renewable energy (Haug, et al., 2025).

2.10 Summary of Key Findings and Research Gaps

It is shown that Åland's energy system is highly dependent on imported electricity and is increasingly integrating renewable energy but finishes with several key findings regarding insights and further work to be done for renewable energy blending and Microgrid control strategy (Kraftnät Åland Ab, n.d.-a). This work is also actively supported by developing an advanced energy laboratory with photovoltaic systems, energy storage capabilities and dynamic load management, which was developed and set up by the Åland University of Applied Sciences (Haug, et al., 2025).

MATLAB Simulink and Simscape have been valuable tools for hybrid power system modelling and detailed simulation of dynamic behaviour and control strategies (MathWorks, n.d.-a). Nevertheless, there are challenges to applying these models for real-time applications in complex Microgrid environments with highly renewable energy sources (Altin, 2022).

Some research gaps have been revealed and need further work:

Control Strategies for Enhanced Stability: Many Microgrid control strategies are proposed (Mendoza-Armenta, n.d.), but the ones that are good at fast frequency response and dynamic load balancing in the real world remain to be invented.

Renewable Energy Integration: While Åland has introduced several renewable energy initiatives, it is necessary to develop improved forecasting models, adaptive inverter control and energy storage optimisation techniques to improve the system's reliability (Haug, et al., 2025).

Simulink-Simscape Integration: To drive R&D of metrology equipment with minimal impacts upon experiment while avoiding excessive costs due to inefficiencies in simulation models and timescales, it would be helpful to develop new scalable models that can balance accuracy and computational efficiency (MathWorks, n.d.-a).

Addressing these gaps can enhance the resilience and sustainability of microgrids, particularly for the islanded systems in Åland. Areas for further research include the development of real-time control solutions, the incorporation of advanced storage technologies, and the improvement of modelling techniques to boost system performance.

3 System Description and Modelling

A detailed description of the Microgrid system and its constituent parts of the Åland Energy Lab is present in this chapter. First, a brief description of the lab setup is provided. Then, the technical details of the bulk of the major subsystems, such as diesel generators, photovoltaic panels and inverters, battery energy storage system (BESS), and various electrical loads, are given. The Microgrid system is also modelled using MATLAB Simulink and Simscape, and how each component is modelled and how the system transitions from grid-connected to islanded mode is discussed. The control and the control strategies for stable and efficient operation in response to load variations and frequency disturbances are explored. It is essential to this foundation that the simulation and analysis presented in the following chapters are based on this understanding.

3.1 Overview of Åland Energy Lab Setup

The Åland University of Applied Sciences is now the owner of a state-of-the-art research and educational facility to be used in the studies of hybrid power systems, renewable energy integration, and Microgrid operation, which is called the Åland Energy Lab. This most recent facility is a hands-on training for scholars and students as they learn and apply energy management, grid stability, and multiple power sources. One of the useful features of the lab is that it has equipment for generating, storing, and controlling energy, which can be used to test and study how microgrids function both when connected to the main grid and when operating independently (in islanded mode). Diesel generators, photovoltaic (PV) systems with several inverters, a battery energy storage system (BESS), electrolyser, and loads such as pumps, heaters, and illumination systems are considered key elements of the lab setup.

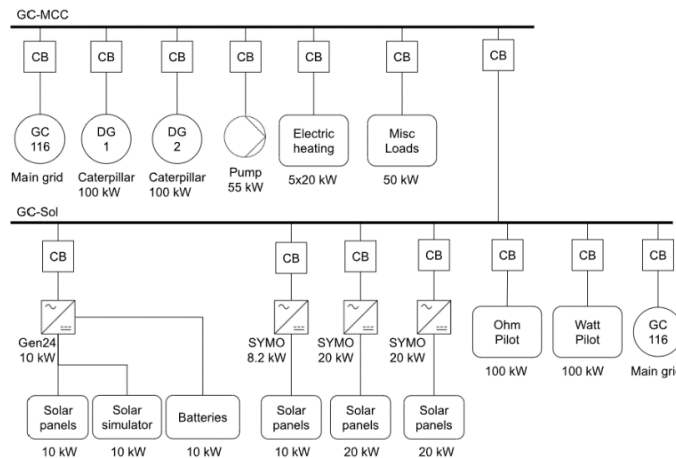


Figure 12. Layout of Åland Energy Lab (Haug et al., 2025)



Figure 13. Solar inverters and battery energy storage system (BESS) setup at the Åland Energy Laboratory.

Key Components of the Åland Energy Lab

1. Diesel Generators

The lab features two Caterpillar 6.6L common rail diesel-electric generators, each rated at 100 kW (+10% margin) and equipped with Leroy Somer alternators. These generators support manual, semi-automatic, and fully automatic operation. In fully automatic mode, Generator 2 is started and synchronised automatically when the system load exceeds 80 kW, with Generator 1 prioritised by default. Both units are set with a 3% droop control, ensuring stable frequency response and enabling studies of load sharing, frequency regulation, and reserve power support.

2. Photovoltaic (PV) System and Inverters

The PV system includes a 60 kWp rooftop installation comprising 150 GEF-410-HM108 LP Black panels arranged in multiple strings for greater operational flexibility. The inverter setup consists of:

- One Fronius Symo 8.2 kW inverter
 - Two Fronius Symo 20 kW inverters
 - One Fronius Gen24Plus 10 kW hybrid inverter, integrated with energy storage
- A PV emulator (Keysight, 15 kW/1500 V) is also available for controlled simulation of solar input.

3. Battery Energy Storage System (BESS)

A Battery-Box Premium HVS with a capacity of 10.2 kWh/9 kW is integrated with the Fronius Gen24Plus inverter. It supports dynamic power management, frequency support, and energy buffering, which is key to grid stability during islanded operations.

4. Microgrid Control and Protection

- A Ziehl UFR1002IP grid-protection relay enables anti-islanding protection and compliance with grid codes.
- The system supports reactive and active load droop control, such as Generator Reactive Load Droop and Generator Active Load Droop.
- A Fronius smart meter enables real-time management of energy flows, supporting functionalities like spot price tracking, SCADA integration, and remote configuration.

5. Load Types and System Components

- Dynamic loads include:
 - One 55 kW induction pump (startup current 450–500 A)
 - Five resistive heaters, each around 22–23 kW
 - A base load of approximately 3 kW
- Ohmpilot 9 kW stepless controller manages heat dumping and load diversion.
- Fronius Wattpilot G22 facilitates controlled EV charging.
- Compact electrolyzers and heat pumps are integrated for advanced energy conversion and thermal management experiments.

The real-world challenges of overlaying Microgrid challenges, including integrating intermittent renewable energy sources, managing peak loads and optimising power distribution, are facilitated by the Åland Energy Lab. Researchers can conduct experiments in setting frequency containment reserves (FCR-N, FCR-D), Automatic Frequency Restoration Reservefast (aFRR), Manual Frequency Restoration Reserve (mFRR), frequency response (FFR), and demand response strategies. Furthermore, as the lab is modular, it can grow into future expansions, including hydrogen-based energy storage through electrolyzers and advanced grid-forming inverters. This laboratory provides a unique opportunity to learn about the interaction between conventional and renewable energy sources, develop new control strategies, and prepare more energy professionals in an environment as close to real as it gets.

3.2 System Components and Specifications

The Åland Energy Lab consists of a carefully integrated set of power generation, storage, and load components forming a Microgrid system that emulates actual hybrid energy systems. The roles of all elements, including diesel generators, solar photovoltaic systems, battery storage, electrolyzers, and dynamic loads, are specified for reliable and flexible operation in connection to the grid and as an island. In the following subsections, these components are specified and described in detail so that such modelling and simulation in MATLAB Simulink and Simscape are possible.

3.2.1 Diesel Generators

The Energy Lab's Microgrid system is based on diesel generators, which provide dependable power generation and primary frequency control support. Two Caterpillar 6.6L standard rail diesel electric generators rated at 100 kW (+ 10% margin) with Leroy Somer alternators are supplied to the lab, being two generators. They can operate in manual, semi-automatic, or fully automatic manners to provide flexible responses to varying load conditions. By default, Generator 1 is automatically run in automatic mode, and Generator 2 is automatically started and synchronized automatically when the load exceeds 80 kW, 3% droop control can be configured for both generators as they are suitable for experiments involving load sharing, frequency containment and reserve power applications. A study of how diesel generators behave under various demand scenarios in island conditions and hybrid integration with renewable sources can be done in a laboratory environment.



Figure 14. CAT C6.6 Diesel Generators at the Åland Energy Laboratory

A high-level block diagram of a diesel-electric generator can illustrate the key internal components as adapted from (Shah, 2022), Figure 15, which shows the turbine governor, excitation system and synchronous machine interactions.

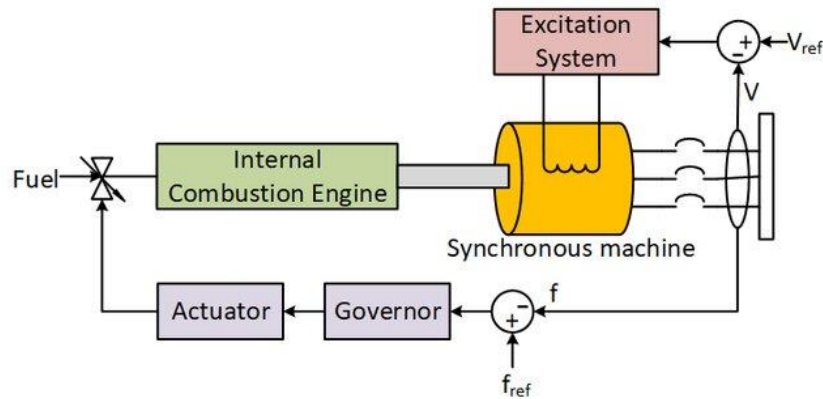


Figure 15. A block diagram of a diesel–electrical generator with a turbine–governor and excitation system components (Shah, 2022)

In MATLAB Simulink, the diesel generator is implemented using Simscape Electrical in this thesis. A Salient Pole Synchronous Machine driven by an Ideal Torque Source (representing the prime mover (diesel engine)) is presented in the model. The ripple in the generator terminal voltage is regulated by an automatic voltage regulator (AVR), and the govern subsystem controls the mechanical input torque and produces droop characteristics.

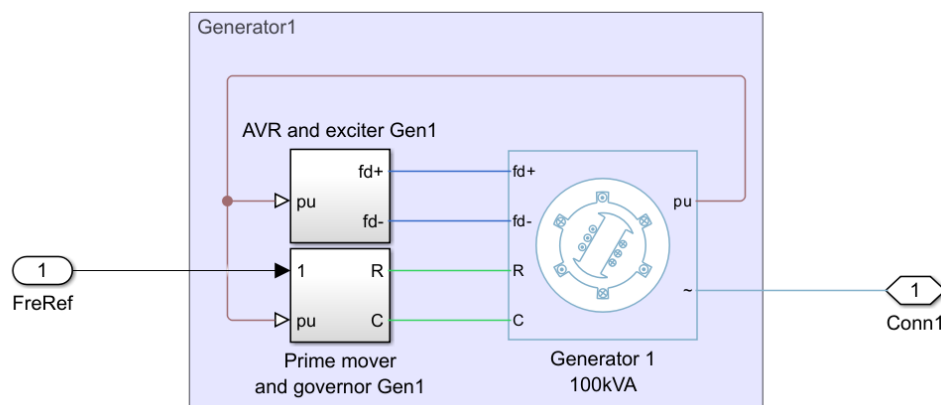


Figure 16. Implementing diesel generator model in MATLAB Simulink

This implementation facilitates the dynamic study of generator performance, e.g. the frequency deviation, transients in some load cases, or response to islanding events, which are necessary components for hybrid Microgrid operations.

3.2.2 Solar Panels and Inverters

At the Åland Energy Lab, in the central role of testing renewable energy integration and power conversion within a Microgrid stands the photovoltaic (PV) system. On the rooftop is mounted a total crew of 150 GEF-410-HM108 LP Black PV panels with a combined capacity of 60 kWp. Multiple strings of these high-efficiency panels are arranged for modularity and flexibility in configuration and control.

The LP Black panel from GEF 410 HM108 LP is shown in Figure 17 to illustrate its monocrystalline structure and sleek black frame that provide a good appearance and performance in partial shading conditions. First, they are the primary DC power source of the solar energy system.

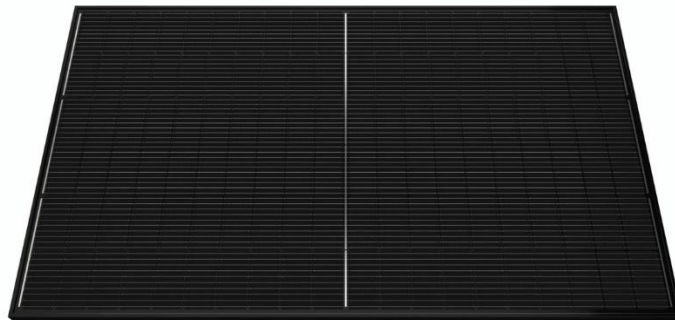


Figure 17. GEF-410-HM108 LP Black PV panel (CW Enerji, n.d.)

Several Fronius inverters connect the PV system to the Microgrid for DC to AC conversion, power regulating, etc.

These include:

- One Fronius Symo 8.2 kW inverter,
- Two Fronius Symo 20 kW inverters,
- One Fronius Gen24Plus 10 kW hybrid inverter.

Figure 18 and Figure 19 are the Fronius Symo and Gen24Plus inverters, respectively. The Fronius Symo range is designed for versatile grid-oriented operation and is perfect for residential and commercial systems. Concerning Section 3.2.3, the Gen24Plus hybrid inverter with the Battery Box Premium HVS integrated can provide backup power, energy storage, and intelligent load prioritization during grid outages or islanded mode operation.



Figure 18. Fronius Symo inverters (Punto Energia Italia, n.d.)

In addition to a PV emulator (Keysight, 15 kW/1500 V), which is integrated into the lab to simulate PV behaviour and irradiance levels, they can test different scenarios without any natural sunlight conditions.



Figure 19. Fronius Gen24Plus 10 kW hybrid inverter (Nord Solar, n.d.)

Figure 20 is the solar system's wiring diagram (overall connectivity and energy flow), including panel strings, inverter, meters and interconnection points. It thus permits both precise energy management and performance monitoring, dynamic load control, spot price regulation, and ease of switching between grid-connected and islanded operation.

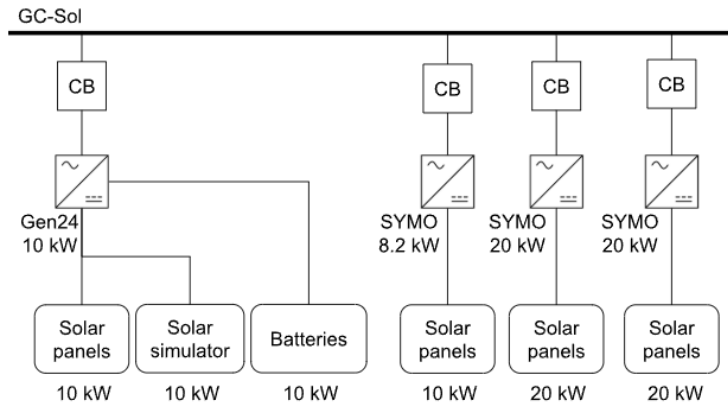


Figure 20. Solar system's wiring diagram (Haug et al., 2025)

A MATLAB Simulink Simscape model was developed to represent the PV system in simulation. The real-world PV system electrical characteristics and behaviour are replicated by this model using solar panels, MPPT controller, inverter, and measurement unit blocks. The Simscape implementation of the solar PV system, in Figure 20, can be used to test control strategies in real-time, analyse dynamic responses caused by irradiance and temperature changes, and study inverter grid interactions in different circumstances.

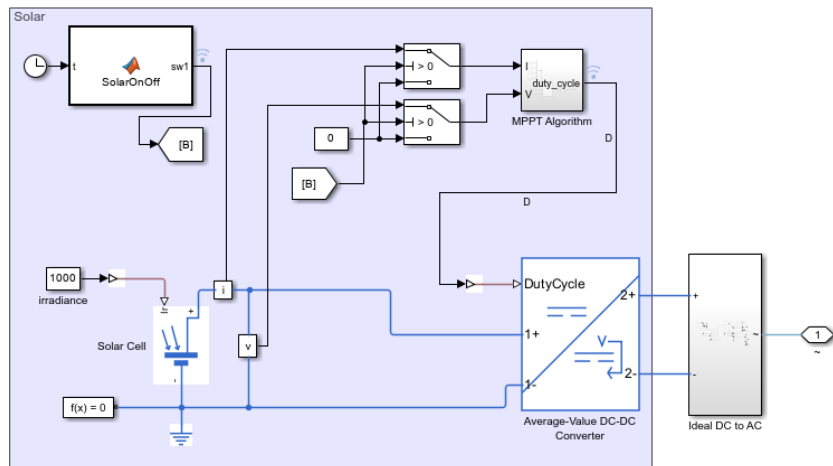


Figure 21. Simscape implementation of the solar PV system

3.2.3 Battery Energy Storage System (BESS)

Åland Energy Lab relies on the BESS to guarantee a steady and flexible energy use within the Microgrid. The system comprises a 10.2 kWh capacity Battery-Box Premium HVS and a Fronius Gen24Plus 10 kW hybrid inverter rated at 9 kW. With this setup, the system can store power, manage its input and output and transmit electricity in grid and island modes.



Figure 22. Battery-Box Premium HVS 10.2 kWh ([Aurinkosähkötuukku, n.d.](#))

To model the BESS in Simulink/Simscape, the Simscape Electrical battery block represents how the system discharges or charges in real life. It supports frequency regulation, helps with voltage stability and allows for a black start. When a grid fails, the BESS can quickly supply critical loads with stable power until the diesel generators or the power grid returns. It was decided to use a custom control strategy to govern the BESS and control its operating mode.

The BESS is activated by state-based rules when a voltage fault or the power grid shuts down. So, for case 1, the system waits 0.2 seconds when the voltage is not in the acceptable range of 207 V to 253 V and then conducts the BESS starting at 0.3 s and connecting to the PCC at 0.4 s. In islanding and resynchronisation scenarios, the BESS connects and disconnects from the grid without interrupting the electricity supply.

Simulation enables the recording of BESS power, its voltage level and the state of charge, which makes the controls more precise and accurate in the simulation. The model also allows us to include droop control and virtual inertia features, since the research focuses on improving fast frequency response and other important grid functions.

3.2.4 Load Types (Lights, Pumps, Heaters)

A wide variety of electrical loads is present in the Åland Energy Lab to test and analyse the Microgrid behaviour 'in the wild'. These loads include constant base loads, dynamic industrial loads, and smart controllable loads. They allow us to study the stability and efficiency of the Microgrid under load variation, peak demand conditions, and load management strategies.

1. Induction Pump Load

A large industrial load and its simulation using a 55 kW three-phase induction pump are included as system features. This pump nominally operates at 90 A, with a high inrush current of 450–500 A during startup. This is ideal for testing the data that tells us the response of a generator under a sudden high load condition, the frequency support, the load sharing, and its fast frequency response (FFR). The actual image of the 55 kW induction pump used in the lab is shown in Figure 23.



Figure 23. The 55 kW Induction Pump at the Åland Energy Laboratory


kW	Hz	V	A	r/m	Cos ϕ
55	50	380-400	90-91	1483	0.91
3400					
IEC 34-1		Iclass F	IP 54	S 1	
 BEVI		3-Mot.			
Blomstermåla, Sweden		Type SKG 250 M-4			

Figure 24. 55kW Induction Pump Name Plate at the Åland Energy Laboratory

2. Resistive Heater Loads

A total of approximately 120 kW of controllable resistive load is added by five resistive heaters, each ranging between 22–23 kW. The power ramp-up testing, frequency containment reserves (FCR-D), and coordinated load dispatch with diesel generators or renewable sources are experimental, and these heaters are crucial. For example, figure 25 displays images of the resistive heater units in the lab.



Figure 25. Resistive heater units at the Åland Energy Laboratory

3. Base Load

Across the system, there is a constant base load of about 3 kW, which serves as background consumption for basic lighting, monitoring systems, and auxiliary devices. This load guarantees that no-load conditions never exist when evaluating the performance of the generators and inverters.

4. Heat Dumping and Smart Load Management

Ohmpilot steps 9 kW step-less load controller optimises the use of surplus energy, especially from Solar PV systems. The excess PV power is directed towards resistive heating elements in water heaters. In his Ohmpilot, energy usage optimisation is supported and seamless integration with Fronius inverters is facilitated. For load diversion, Fig. 22 shows the Ohmpilot controller.



Figure 26. Ohmpilot controller (Fronius International GmbH, n.d.)

5. EV Charging

As a part of the lab setup, the Fronius Wattpilot Go 22 J is a controllable EV charger. It allows for establishing dynamic charging strategies according to grid conditions, spot pricing and PV surplus. It brings demand-side management capability and offers an opportunity to test flexible loads and intelligent charging algorithms. The installed Wattpilot EV charger is illustrated in Figure 27.



Figure 27. Wattpilot EV charger (Fronius International GmbH, n.d.)

The wide range of loads offered by the lab allows the lab flexibility to simulate a wide range of operational scenarios such as peak shaving, dynamic load shedding and smart energy redistribution. The lab integrates these loads into simulation and experimental routines to achieve a deep understanding of system response and a better ability to design more resilient Microgrid control strategies.

3.3 Microgrid Configuration for Islanded and Grid-Connected Modes

The Åland Energy Lab offers dual functionality for both islanded and grid-connected operations, creating various testing conditions for hybrid energy systems control strategies. Important configurations enable scientists to examine the operational relationship between diesel generators, solar PV systems, battery energy storage systems (BESS), and dynamic loads during different operational states.

Grid-Connected Mode

The Microgrid operated by the lab synchronises with the primary utility grid using the Sverige-kabeln submarine cable to Sweden and an optional connection to the Finland network. The power system functions bidirectionally in this mode. The grid supplies power during limited lab generation, while allowing surplus energy from the PV system or battery storage to be exported back to the grid. This grid-connected operation offers the optimal setting for experimental purposes, including:

- Peak shaving
- Spot price-based load dispatch
- EV charging control is possible with Fronius Wattpilot G22 devices
- Solar power feed-in from Fronius inverters
- Dynamic load response

The real-time management of power quality, voltage, and frequency stability is achieved through the Ziehl UFR1002IP grid protection relay and the Fronius Smart Meter. Disruptions or faults are resolved by enforcing protection systems such as anti-islanding which safeguards grid and laboratory components.

Islanded Mode

The Microgrid exists in isolated conditions, operating exclusively using local energy resources to fulfil load requirements. This operational state replicates situations during power disruptions and isolated utility environments, thus providing needed assessments of energy independence and operational durability.

The Microgrid controller shifts to internal coordination where:

- The base frequency of the diesel generators gets regulated through droop control mechanisms.
- The BESS supports fast frequency stabilisation and load balance functions.
- Accurate simulation of renewable power generation through the combination of a PV emulator and panels allows testing of renewable power under different irradiance conditions.
- Realistic system consumption patterns occur using heaters and the 55 kW induction pump as load types.

- The Fronius Gen24Plus hybrid inverter manages AC-DC power coupling while operating under dynamic conditions.

Using MATLAB, Simulink/Simscape users can enable FFR, FCR-N and FCR-D functions to achieve advanced operation performance through controller configuration. Such a modular operational system with dual capabilities creates an advanced research platform that allows testing of power system controls and optimisation of renewable energy integration and forecast of energy system evolution.

3.4 Modelling of Power Sources in MATLAB Simulink Simscape

The exact performance analysis of the Åland Energy Lab required constructing a comprehensive primary power source model, which MATLAB® Simulink® and Simscape™ developed. The tools offer the ability to simulate physical systems by joining electrical, mechanical and control components as blocks within block diagram constructs. The developed model includes diesel generators in conjunction with solar photovoltaic (PV) components, their inverters, and the battery energy storage system (BESS). Simscape blocks built the sources to model their actual operating interactions among components while operating with and without a grid connection.

3.4.1 Full System Architecture

The entire model layout combines all energy sources with their control systems. Each generator's inverters and energy storage unit connect through a shared distribution bus, as depicted in Figure 28. This system setup enables the evaluation of power redistribution and the response to frequency changes and transitions among different grid modes.

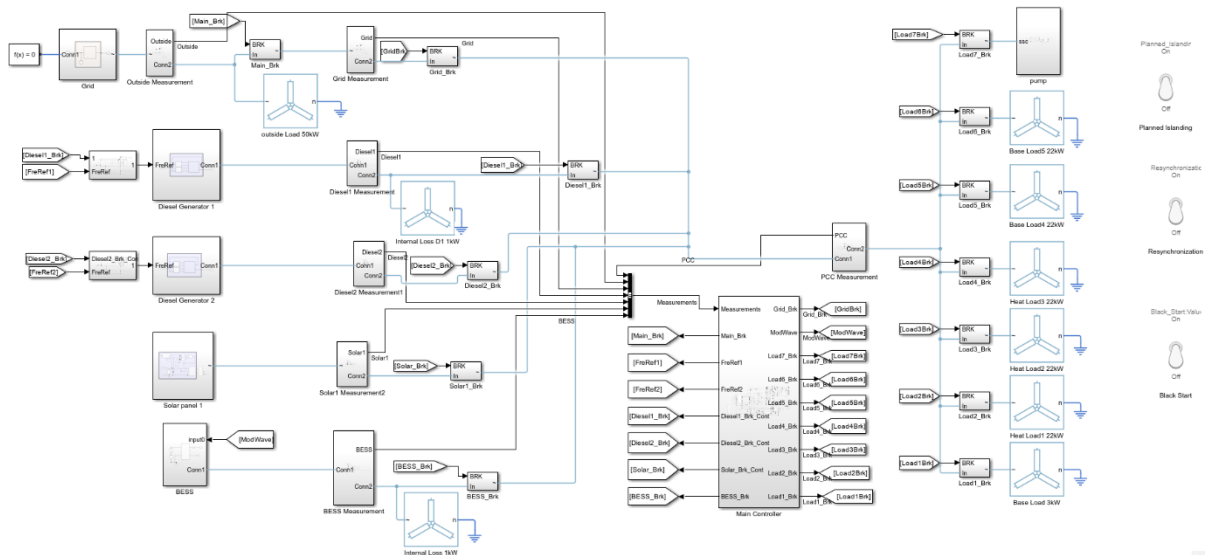


Figure 28. Full power source model layout in MATLAB Simulink/Simscape

3.4.2 Diesel Generator Modelling

The Synchronous Machine (Salient Pole) block from Simscape Electrical simulated generators with a 100 kW diesel capacity. The Prime Mover with Governor supplied mechanical force while the Excitation System influenced voltage equilibrium through an Automatic Voltage Regulator (AVR). Users can evaluate the frequency support mechanisms, droop response attributes, and the generator synchronisation process through this subsystem.

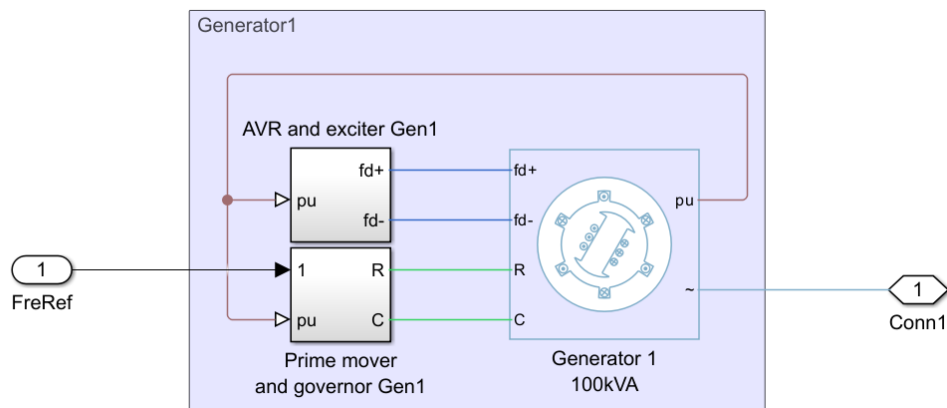


Figure 29. Simscape subsystem of Diesel Generator including Governor, Excitation, and Salient Pole Synchronous Machine

3.4.3 PV System and Inverter Modelling

The solar PV system simulation happened through the Solar Cellblock, which received data from the GEF-410-HM108 LP Black panel. A control subsystem incorporated MPPT logic for operation. A reduced Average-Value Inverter model allowed the simulation of grid-connected operations.

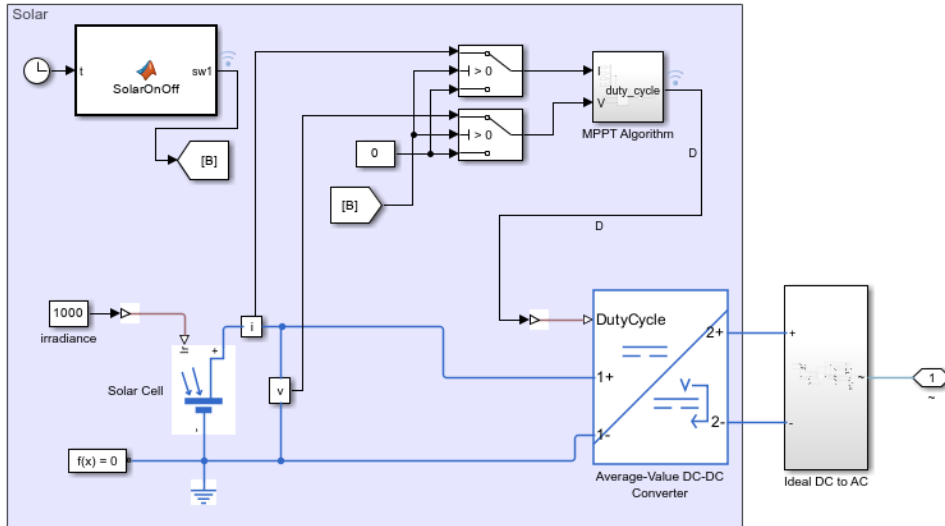


Figure 30. Simscape model of solar photovoltaic system with MPPT and inverter interface

3.4.4 Battery Energy Storage System (BESS)

The BESS replication mirrors the 10.2 kWh/9 kW Battery-Box Premium HVS hardware system installed in the laboratory. The system has two control functions and a grid connection component that uses the Fronius Gen24Plus hybrid inverter. The Simscape model enables energy storage buffering when changing from grid to islanded mode and provides frequency stabilisation during islanded operation.

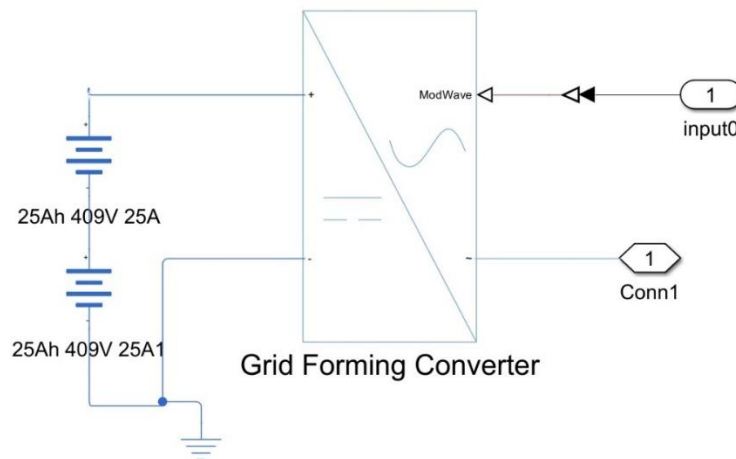


Figure 31. Simscape model of Battery Energy Storage System integrated with inverter

All subsystems were linked to measurement blocks to monitor voltage, frequency, and power usage, while MATLAB Function blocks achieved control through droop control logic to assess dynamic system performance. Through such simulation practice, system behaviour becomes

accurately reflected, enabling scientists to analyse Microgrids realistically while developing control strategies.

3.5 Modelling of Load Variations and Switching Scenarios

To simulate realistic Microgrid behaviour, different types of loads and switching events were modelled in the MATLAB Simulink and Simscape environments. The loads represent actual equipment and systems found in the Åland Energy Lab and include both constant and dynamic power demands.

Types of Loads Modelled:

- **Base Load (~3 kW):** Includes fluorescent lights in the machine hall, control room, and transformer. This load is always prioritised during black start and islanded operation.
- **Resistive Heaters (Total ~120 kW):** Comprising five independent units, each consuming approximately 22–23 kW. These are purely resistive loads with a power factor ($\cos \phi$) of 1, and can be switched in individually based on system capacity.
- **Pump (55 kW):** A large inductive motor load with a nominal current of 90 A and a high inrush current of 450–500 A at startup. It has a power factor of 0.86 and is introduced later in the sequence due to its high impact on voltage and frequency stability.

3.6 Switching Scenarios and Load Control Logic

Different switching scenarios were implemented to evaluate how the system behaves under both normal and emergency operating conditions:

- **Black Start:** When the system detects a voltage fault (grid voltage falling outside 207–253 V), all non-essential loads are automatically disconnected. The BESS is then activated to energise only the base load. Once stable, the solar panel and diesel generators are reintroduced, and loads are reconnected in a prioritised sequence based on available generation and system stability.
- **Planned Islanding:** This mode is executed while maintaining load continuity. The system transitions to islanded mode without disconnecting any loads. Synchronisation and control ensure a smooth shift to internal power sources (BESS, diesel, solar) without disruption.
- **Resynchronisation:** The Microgrid reconnects to the primary grid while keeping all loads online. Phase angle, voltage, and frequency are matched before reclosing the grid

breaker. Once the grid supply is restored, BESS output is reduced and disconnected when power-sharing conditions are met.

Breaker logic is set for each load and source with variable resistors controlled by on-and-off signals. This allows you to control the simulation as it happens, like what happens in a real operation. This way, the system handles vital power loads and manages non-crucial loads depending on how stable the grid is. The figures in the results show the actions of the Microgrid for all modes, specifically how frequency, voltage and the direction of power change each time sources or loads are changed.

3.7 Control Strategy Design (e.g., Frequency Control, Load Shedding)

This project relies on the control strategy to manage the power flow, maintain the grid's stability, and support changes during microgrid operation. The system should tolerate voltage, frequency changes, load, and power station changes without fail. MATLAB Simulink was used to develop the control logic, with logic-based switching, and control blocks were designed to control energy sources.

Frequency Control

Active power levels are maintained by involving both the Battery Energy Storage System (BESS) and the diesel generators. The system regulates the frequency reference through active power difference. As a result, the generators pass along power proportionately and behave appropriately when loads change. During black start and other forms of islanded operation, the BESS helps maintain frequency and is the main frequency support at the time.

While synchronisation occurs, the difference in phase angle between the BESS and the diesel generator is observed. Before the diesel generator is connected, the PID controller ensures the generator's frequency equals the BESS. Once synched, the amount of power shared by the solar setup and diesel generator is controlled when the BESS lowers its voltage.

Load Shedding and Reconnection

When there is a power outage or fault, the system is protected by shedding some of its load. If the grid voltage is not within the expected range of 207 V to 253 V for over 0.2 seconds, the

system goes into black start mode and unloads all the less important equipment. A BESS can only supply around 3 kW for the base load.

After the system is stabilised, the solar inverter and diesel generator are reconnected one after another. Loads are restored gradually, in order of priority, based on the available electricity production. By restoring power step by step, the system is protected from sudden surges, allowing for a stable recovery.

Breaker Control and Transition Modes

Control of circuit breakers (e.g., Grid_Brk, BESS_Brk, Diesel1_Brk) is based on simulation time, voltage/frequency conditions, and synchronisation status. The key transition modes include:

- **Planned Islanding:** The Microgrid disconnects from the grid without losing any loads. The BESS and diesel generator seamlessly support the load.
- **Black Start:** Triggered by a detected grid fault. The system isolates from the grid, energises the base load using the BESS, and gradually rebuilds the system by reconnecting other sources and loads.
- **Resynchronisation:** When the grid returns, voltage conditions are checked for 0.2 seconds. After the matching phase and frequency, the grid breaker is closed, and BESS is ramped down. Once the BESS power to the load is below 200 W, it is disconnected.

Thanks to this strategy, the Microgrid works safely, efficiently and smartly in all scenarios. It functions like the real system used in a hybrid energy plant, allowing for study and training at the Åland Energy Lab.

4 Simulation Setup and Implementation

The chapter explores the simulation model design used for the Åland University Energy Laboratory Microgrid. MATLAB Simulink and the Simscape Electrical toolbox were used to implement the model. It reproduces the system's main parts and helps study cases of connecting the grid, running a power network independently, starting up from shutdown and resynchronizing systems. Among the distributed energy resources, the system has a Battery Energy Storage System (BESS), several diesel generators and a solar photovoltaic (PV) system with an inverter. Different types of profiles are used for loads to imitate what is typically observed in the electricity system. All components are linked using a common Point of Common Coupling (PCC), and their functioning is governed by unique logic and measurements.

4.1 Simulation Environment (MATLAB Version, Hardware Specs)

The simulation was developed using:

- **MATLAB R2024b**
- **Simulink**
- **Simscape Electrical Toolbox**

Because we studied power electronics and fast devices with transient simulations, the solver was set to provide greater accuracy by using $1e-5$ seconds as the size of each time step.

4.2 Model Development Process

The simulation model was developed using MATLAB Simulink and Simscape Electrical to reflect the real-world configuration of the Åland Energy Laboratory. The process involved modelling each significant component of the hybrid Microgrid—generators, storage systems, solar power, loads, and switching elements—and the control systems needed to manage different operating modes.

4.2.1 Diesel Generator Unit

The diesel generator was modelled using the *Synchronous Machine Salient Pole* block configured as a 100 kW, 400 V, 50 Hz generator. Standard parameters were used, and the initial condition for active power output was set to 2 kW.

The generator includes two major subsystems: the **AVR (Automatic Voltage Regulator)** and the **Prime Mover/Governor**. The AVR takes the terminal voltage and reactive power (in per unit) from the generator and feeds a *Synchronous Machine Field Circuit (pu)* block. This regulates the generator's excitation via the Efd input.

The prime mover subsystem receives the rotor speed and active power (in pu) from the generator output. It uses a reference frequency and a droop control mechanism (3% droop setting) to manage load sharing. The output passes through a base torque scaler, an ideal torque source block, an inertia block, and a mechanical rotational reference, and connects to the machine's R and C ports.

4.2.2 Swing Generator (Grid Source)

The utility grid was modelled using a *Three-Phase Voltage Source* block, configured at 400 V, 50 Hz, with a short-circuit power level of 1 MVA. This represents the external grid supply connected to the system through a grid breaker.

4.2.3 Solar Photovoltaic System

The solar system consists of a *Solar Cell* block, with an irradiance input manually set to 1000 W/m² for testing. Although actual irradiance varies with time and location, this fixed value was chosen to simplify initial simulations.

The PV output connects to an *Average-Value DC-DC Converter* block. Its duty cycle is controlled by a custom MPPT (Maximum Power Point Tracking) block, programmed to maximise output power. The converter's DC output is then fed into a *Controlled Three-Phase Current Source*-based inverter structure for DC to AC conversion. In the test configuration, a 10 kW output was assumed for this source.

4.2.4 Battery Energy Storage System (BESS)

The BESS was modelled using a 409 V, 25 Ah battery connected to an *Average-Value Voltage Source Converter (Three-Phase)* block. It supplies power during black start and islanded operation and supports grid synchronization. Its output voltage and frequency are regulated using control logic and PID controllers.

4.2.5 Load Modelling

Three main load types were included:

- **Base load** (~3 kW): Representing constant internal loads (e.g., lighting, control equipment, transformer).
- **Resistive heaters**: Five resistive loads (~22–23 kW each), purely resistive ($\cos \varphi = 1$).
- **Inductive pump load**: A 55 kW motor with a nominal current of 90 A and high starting current (~450–500 A), with a power factor of 0.86.

Loads were modelled using *Wye-Connected Load* blocks. The system includes switching logic to disconnect or reconnect loads based on system status (e.g., during black start, only the base load remains connected initially).

4.2.6 Circuit Breakers and Switching

All major components (BESS, diesel generator, solar PV, grid) were connected via circuit breakers modelled using *Variable Resistor* blocks. In their closed state, the resistance is set to $1\text{e-}3 \Omega$; in the open state, resistance is increased to $1\text{e}8 \Omega$. Breaker states are controlled through signals from logic blocks using Simulink-to-Physical Systems (PS) connectors.

4.2.7 Power Measurement Units

Each section of the system includes three-phase voltage and current sensors and active/reactive power measurement blocks. These monitor power flow, detect voltage/frequency deviations, and trigger control logic.

4.2.8 Control System and Operating Modes

A centralised control system manages four major operating modes:

1. **Grid-Connected**

2. **Planned Islanding**
3. **Black Start**
4. **Resynchronization**

Phasor Measurement Units (PMUs) monitor phase angle, frequency, and voltage magnitude for the diesel generator, grid, and BESS. Control algorithms (implemented using MATLAB Function blocks and PID controllers) regulate voltage, frequency, and synchronisation logic. Breaker control is based on simulation time and system conditions. For example, in black start mode, the BESS connects to the base load after detecting grid loss and waiting for 0.4 seconds. Synchronisation with the grid or diesel generator is based on angle and frequency matching. The BESS also includes waveform generation logic and PID control for active/reactive power management and seamless transitions.

4.3 Load Variation Scenarios and Simulation Cases

The simulation model was tested under several load variation scenarios to evaluate the microgrid's performance under dynamic operating conditions. These scenarios were designed to reflect realistic behaviour at the Åland University Energy Laboratory, including power outages, system reconnection, and varying energy source availability.

4.3.1 Simulation Scenarios

The following simulation cases were executed to evaluate the system's performance:

1. Normal Grid-Connected Operation

- All loads are connected.
- Power is supplied by the grid through the swing generator.
- Diesel generators and BESS remain in standby.
- Used as the initial reference state before transitions.

2. Planned Islanding

- The system disconnects from the grid while loads remain connected.
- The BESS and diesel generator take over the power supply smoothly.
- No load is disconnected.
- Tests the system's ability to maintain power without interruption.

3. Black Start Scenario

- Grid voltage is lost or falls outside the acceptable range (207 V –253 V).

- All loads are disconnected automatically.
- After a 0.2-second check confirms voltage loss, the BESS activates and energises the base load.
- Additional sources (solar, diesel) are connected based on availability and phase/frequency synchronisation.
- Loads are reconnected based on priority once the system is stabilised.

4. Resynchronisation with Grid

- After islanded operation, the grid voltage is monitored.
- If the grid remains within the correct range for 0.2 seconds and the phase angle is synchronised, the breaker is closed.
- The BESS power is reduced gradually, transferring the load to the grid.
- Once the BESS power drops below 200 W, the BESS is disconnected.

5. Load Ramping and Switching

- Loads are added or removed dynamically to observe the generator's response and stability.
- The diesel generator and BESS handle load sharing based on active power and frequency droop.
- Control strategies are validated by monitoring system frequency, power balance, and switching stability.

6. Diesel Generator Synchronisation with BESS

- Using frequency and angle control, the diesel generator synchronises with the BESS during islanded mode.
- The diesel breaker is closed once the angle error is close to zero.
- Active power sharing is controlled using PID-based BESS voltage adjustment.
- This scenario validates synchronisation and power handover logic.

These simulation cases demonstrate the control strategy's robustness and the Microgrid system's ability to respond to disturbances and changing load conditions. Each scenario reflects a realistic operating situation at Åland University's Energy Lab, ensuring that the model can be used for research and teaching purposes.

4.4 Simulation Parameters and Assumptions

The simulation environment was implemented in MATLAB Simulink using the Simscape Electrical toolbox. This section summarises the parameters and assumptions used during simulation to ensure model consistency, computational stability, and reproducibility.

4.4.1 General Simulation Settings

- **Solver:** Variable-step, discrete solver (e.g., *ode23tb*) was used for switching and control events accuracy.
- **Simulation time:** Each case was run for 10 seconds to observe steady-state and transition behaviour.
- **Control sample time:** 1e-3 seconds (1 ms) was used for all discrete control systems (e.g., PID controllers, logic systems).
- **Power system frequency:** 50 Hz across all AC sources (grid, diesel generator, BESS output).
- **Voltage level:** Nominal voltage was 400 V line-to-line RMS for all AC systems.

4.4.2 Breaker Modelling

All circuit breakers were modelled using **three Variable Resistor blocks** per phase:

- **Closed resistance:** 1e-3 Ω
- **Open resistance:** 1e8 Ω
- The breakers are controlled via Simulink logic and Simulink-PS conversion.

4.4.3 Diesel Generator Parameters

- **Machine type:** Salient pole synchronous machine
- **Rated power:** 100 kW
- **AVR input:** Terminal voltage and reactive power in pu
- **Governor droop:** 3% (used for load sharing)
- **Initial power output:** 2 kW (set using ideal torque source)
- **Frequency control:** Reference frequency ramp or PID logic, depending on synchronisation.

4.4.4. Battery Energy Storage System (BESS)

- **Battery voltage:** 409 V
- **Battery capacity:** 25 Ah
- **Control system:** Grid-forming control using waveform generation and PID logic
- **Inverter type:** Average-Value Voltage Source Converter (Three-Phase)
- **Operating modes:** Black start, islanding, resynchronisation

4.4.5 Initial state of charge: Assumed to be sufficient to power the base load Solar PV System

- **Irradiance level:** Constant 1000 W/m² used for testing purposes
- **Output power:** 10 kW (target set for controlled inverter)
- **DC-DC converter:** Average-value converter with MPPT controller
- **Inverter:** DC-AC converter using controlled current sources and waveform generation

4.4.6 Loads

- **Base Load:** Constant 3 kW connected throughout all modes
- **Resistive Heaters:** 5 units, ~22–23 kW each, added one by one
- **Pump Load:** 55 kW, high inrush current (450–500 A), power factor 0.86
- **Load Switching:** Managed using a logic-based priority list during black start and reconnection.

4.4.7 Phasor Measurement Units (PMUs)

- Used to measure phase angle, voltage magnitude, and frequency of:
 - Grid (swing generator)
 - BESS
 - Diesel generator
- These measurements are critical for synchronisation logic and controller input.

4.4.8 Assumptions

- **Ideal switching behaviour:** No switching transients or delays were modelled in the breakers.
- **No losses modelled** in converters or lines.

- **Perfect measurements** from PMUs and sensors (no delay or noise).
- **Irradiance and battery SOC** were kept constant during short simulations.
- **All sources are pre-synchronised** when the simulation starts, except where dynamic synchronisation is tested.

4.5 Data Analysis and Performance Metrics

4.5.1 Data Collection Approach

During each simulation scenario, the following key data points were recorded using **Simulink Scopes, power sensors, and Phasor Measurement Units (PMUs)**:

- Active and reactive power from each source (Grid, BESS, Diesel, Solar)
- Voltage and current waveforms and active and reactive power at Point of Common Coupling (PCC)
- Frequency, voltage and phase angle of each AC source
- Breaker status signals and switching events
- Load consumption per load type

Data was exported where needed for further analysis and plotting.

4.5.2 Performance Metrics

The system was evaluated using the following key metrics:

Power Balance

- Comparison of total power supplied by generation sources vs. total load demand.
- Helps verify that load-sharing and control logic maintain system balance.

Transition Time

- Time taken for the system to respond to grid failure, initiate black start, or resynchronise.
- Measured from the fault trigger to the reconnection or stabilisation point.

Breaker Switching Timing

- Time delay between condition detection (e.g., voltage out of range) and breaker operation.
- Validates the timing logic implemented in the control function.

Frequency Stability

- Frequency deviation during and after transitions (especially during load steps or resynchronisation).
- Acceptable deviation considered: ± 0.5 Hz from nominal (50 Hz).

Voltage Stability

- Voltage at the PCC during transitions and load changes.
- The acceptable voltage range is 207–253 V RMS (based on Finnish grid code limits).

Phase Synchronisation Accuracy

- Difference in phase angle between BESS and Diesel before coupling.
- Synchronisation is allowed only if the absolute angle error is within ± 5 degrees for a safe connection.

BESS Power Transition

- Behaviour of BESS power output during black start, load pickup, and handover to grid, diesel with or without PV systems.
- A drop in BESS power below 200 W is used as a condition for disconnection after resynchronisation.

4.5.3 Evaluation Approach

Simulation results were plotted and visually inspected for:

- Waveform continuity during switching events
- Transient spikes in power, frequency, or voltage
- Delays or mismatches in synchronisation
- Proper order of load reconnection and generation activation

Results were compared with expected theoretical behaviour and previous benchmarks from the Åland Energy Lab experiments.

5 Results and Discussion

5.1 Overview of Simulation Results

This section summarises the main simulation scenarios conducted to evaluate the performance and control strategies of the modelled microgrid system. The system was simulated using MATLAB Simulink and Simscape Electrical, representing key components of the Åland University Energy Lab, including grid connection, BESS, diesel generators, solar PV, and dynamic loads.

The following operating modes were implemented and tested:

- **Regular Grid-Connected Operation:** Base and additional loads powered by the grid are used as the system reference case.
- **Planned Islanding:** Transition to islanded mode with no loss of power supply; BESS provides seamless takeover.
- **Black Start:** Full disconnection from the grid and restoration of base load power using BESS after fault detection.
- **Resynchronisation:** Reconnection of grid supply after verification of phase, frequency, and voltage alignment.
- **Diesel Generator Synchronisation:** Phase-angle and frequency-controlled connection of a diesel generator to the BESS-supported islanded system.
- **Load Sharing and Restoration:** Progressive connection of additional loads (heaters, pump) while balancing power contributions between BESS and diesel sources.

These scenarios demonstrate the system's ability to respond to grid faults, maintain stability in islanded mode, resynchronise safely, and restore additional load capacity based on generation availability.

5.2 Normal Grid-Connected Operation

In this scenario, the microgrid operates in its standard mode, where all loads are supplied directly from the external grid via the swing generator model. This case is the baseline for comparing system behaviour under disturbance or control interventions.

System Setup

- The grid is modelled using a three-phase swing generator (400 V, 50 Hz) with a short-circuit power level of 1 MVA.
- Base load (~3 kW) remains constantly connected, representing fluorescent lighting and internal transformers.
- Additional loads, such as resistive heaters (~120 kW total) and the 55 kW inductive pump, are introduced to evaluate grid supply performance under varying demand.

Breaker Status

- **Main Breaker** and **Grid Breaker** remain closed, ensuring continuous grid connection.
- **BESS_Brk**, **Diesel1_Brk**, and **Solar1_Brk** remain open, meaning BESS and other sources are disconnected.
- No switching or control actions are required.

Power Flow and Stability

- The grid supplies **100% of the active power** demand.
- The system maintains:
 - **Stable voltage** at PCC: ~230–240 V RMS
 - **Constant frequency** at 50 Hz
- During pump startup, the inrush current reaches ~450–500 A, causing a brief voltage dip, but the system quickly stabilises.
- Power factor varies depending on load types:
 - ~1.0 for resistive heaters
 - ~0.86 for inductive pump

Observations

- The system demonstrates stable operation with no instability under full load conditions.
- Power quality and frequency remain within acceptable limits.
- This case validates the integrity of the simulation model under normal conditions and provides a reference for comparing responses in islanded or recovery modes.

5.3 Planned Islanding

This scenario demonstrates the system’s ability to smoothly transition from grid-connected mode to islanded operation without interrupting power to the connected loads. The transition is triggered intentionally, allowing the Battery Energy Storage System (BESS) to take over supply duties with minimal transient effects.

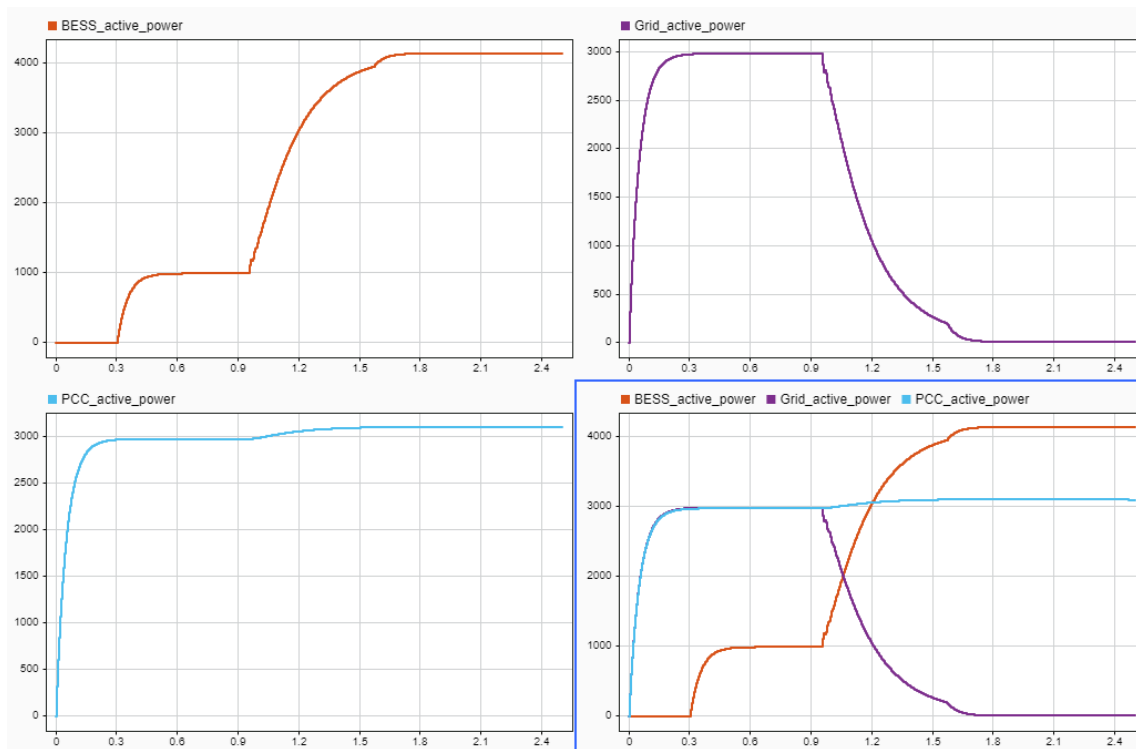


Figure 32. Grid, BESS and PCC Active power flow in Planned Islanded mode. The Y-axis represents active power (W), and the X-axis shows time (s).

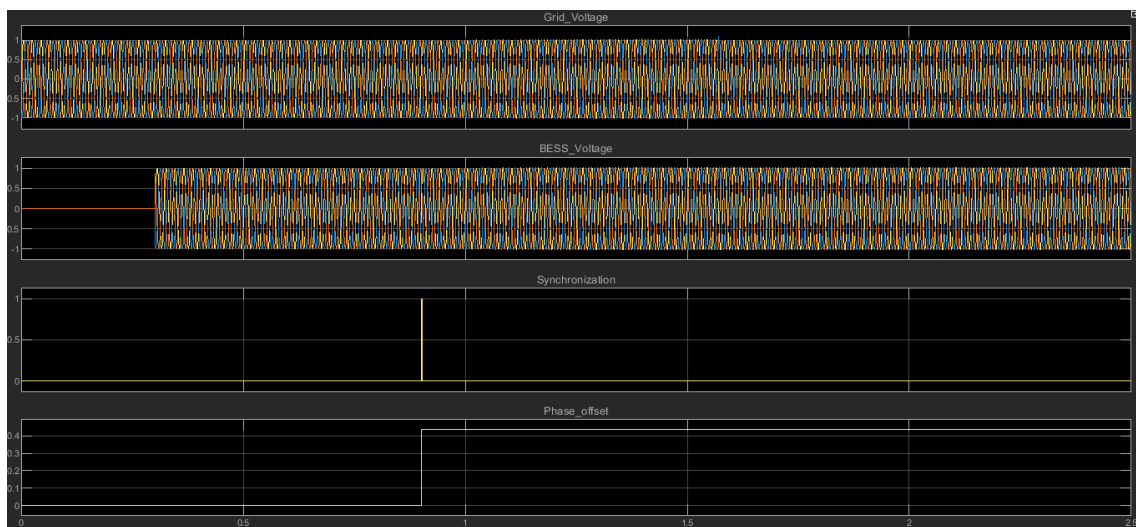


Figure 33. Grid voltage (V), BESS voltage (V), synchronisation signal (logic level 0 or 1), and phase angle correction (radians) plotted over time (s). Planned Islanded mode.

Control Logic and Triggering

- The transition is initiated by setting the auto_islanded input to logic high (1).
- Upon detection, the control logic activates BESS operation:
 - After 0.1s, BESS_on_off becomes active.
 - After 0.2s, Auto_sync is triggered to prepare synchronisation.
 - After 0.75 s, BESS_Brk is closed, connecting the BESS to the Point of Common Coupling (PCC).
 - Increasing the BESS voltage $\leq 2\%$ to transfer power BESS to load side
 - Grid_Brk is then opened , fully isolating the system from the external grid when the grid power reach to zero.

Load Continuity and Supply

- All loads remain connected during the transition.
- There is no loss of power to the base load (~3 kW), nor to any additional loads that are present.
- The BESS operates in grid-forming mode, taking over voltage and frequency regulation.

System Behavior

- Voltage and frequency remain stable across the transition:
 - Frequency is held at 50 Hz by the BESS inverter.
 - Voltage stays within the 207 V–253 V range per standard requirements.
- There is minimal overshoot or oscillation during switching events.

Observations

- The control strategy allows for seamless planned islanding without requiring load shedding.
- The system remains stable throughout the transition, validating the BESS controller and switching logic.
- The planned islanding mode can be used for scheduled maintenance or to isolate the system in anticipation of grid instability.

5.4 Black Start Operation

This scenario evaluates the system's ability to autonomously restore power after a complete grid outage, using only the Battery Energy Storage System (BESS). The black start sequence simulates an unplanned disconnection from the grid, followed by automatic detection and controlled recovery.

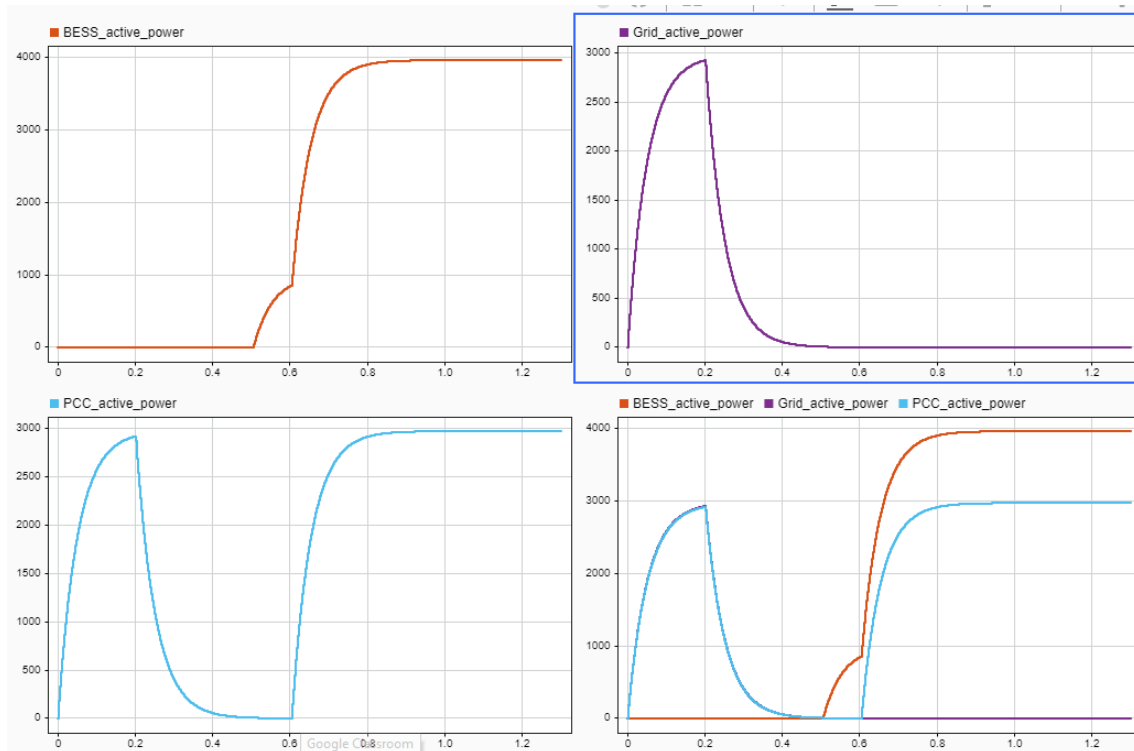


Figure 34. Grid, BESS and PCC Active power flow in black start mode. The Y-axis represents active power (W), and the X-axis shows time (s).



Figure 35. : Grid voltage (V), BESS voltage (V) plotted over time (s) in Black Start Mode

Fault Detection and Sequence Initiation

- A black start is triggered when the system detects that grid voltage has fallen outside the normal range (207 V to 253 V RMS).
- The control logic monitors the grid voltage and starts timing the disturbance duration.

- If the voltage remains out of range for more than **0.2 seconds**, the system initiates the black start sequence.

Control Sequence Timing

- At **0.2 s**, the control confirms the grid outage.
- At **0.3 s**, the BESS is activated (BESS_on_off = 1).
- At **0.4 s**, the BESS_Brk is closed, connecting the BESS to the PCC.
- The Grid_Brk is simultaneously opened, fully disconnecting the grid.
- A new output, Diesel_Syn, is triggered at **0.6 s**, preparing synchronization logic if diesel generators are to be coupled later.

Load Behaviour During Black Start

- At the moment of detection, all major loads are disconnected to ensure the BESS is not overloaded.
- Only the **base load (~3 kW)** is kept connected.
- The BESS begins supplying power to the base load immediately after breaker closure.
- After stabilisation, additional generation sources (e.g., solar or diesel) can be brought online, and loads can be reconnected gradually.

System Performance

- Voltage and frequency at PCC are quickly restored by the BESS inverter.
- Transient behaviour is minimal; the system stabilises within 0.1s after BESS_Brk closes.
- Frequency remains close to 50 Hz, and voltage is within $\pm 5\%$ of the nominal value.

Observations

- The black start logic enables autonomous recovery from total grid failure without operator intervention.
- The modular sequencing allows for safe restoration of loads based on available generation capacity.
- This mode is critical for ensuring continuity of critical loads during outages and demonstrates the BESS's ability to act as a grid-forming unit.

5.5 Resynchronisation with Grid

This scenario examines the controlled reconnection of the islanded system back to the primary grid after a successful black start or planned islanding. The resynchronisation process is carefully managed to ensure matching voltage, frequency, and phase angle between the grid and the BESS before re-closing the grid breaker.

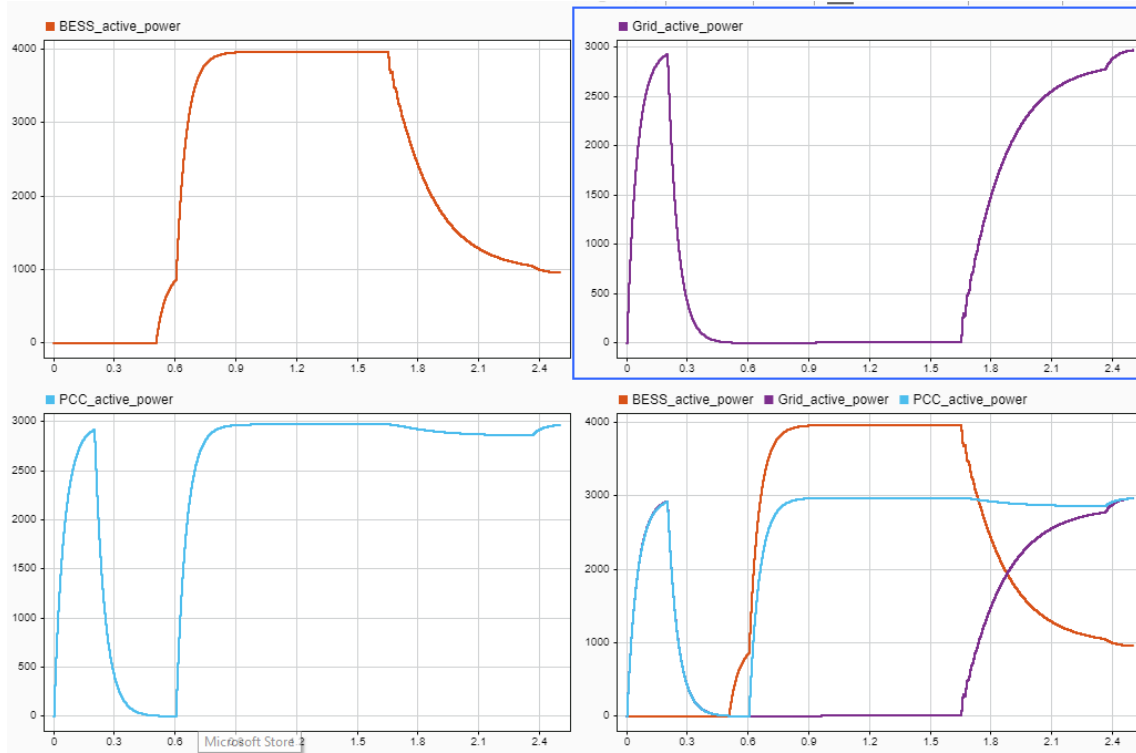


Figure 36. Grid, BESS and PCC Active power flow in resynchronisation mode. The Y-axis represents active power (W), and the X-axis shows time (s).

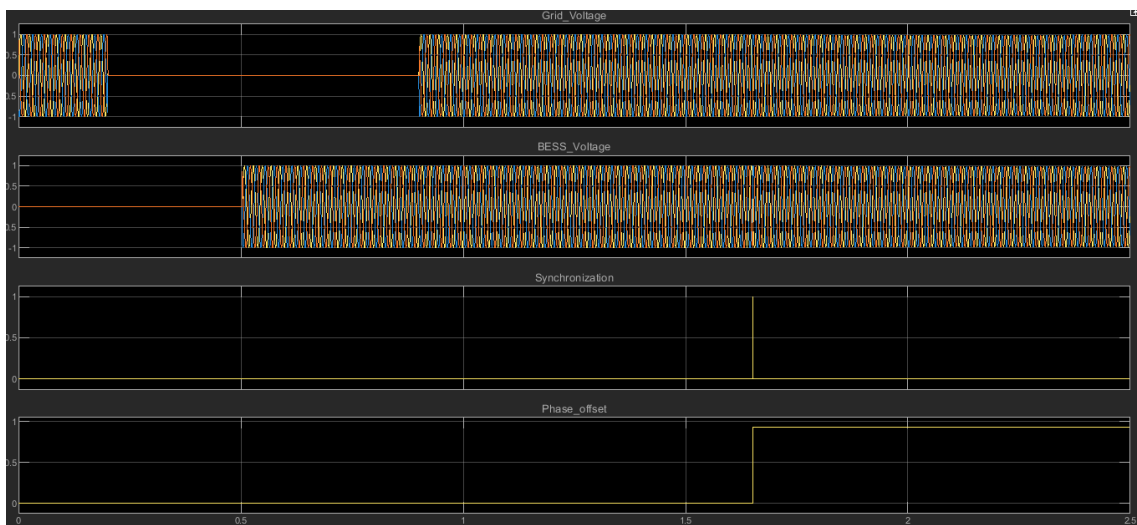


Figure 37. Grid voltage (V), BESS voltage (V), synchronisation signal (logic level 0 or 1), and phase angle correction (radians) plotted over time (s) in Resynchronisation mode.

Trigger and Monitoring Conditions

- The resynchronisation sequence is triggered by setting the Resynchronisation input to logic high (1).
- Once triggered, the system:
- Monitors the voltage at the **Grid Measurement Unit**.
- Verifies that grid voltage is within the acceptable range (207 V to 253 V RMS) for **at least 0.2 seconds**.
- Enables Auto_sync when voltage conditions are satisfied.

Angle and Frequency Synchronisation

- During resynchronisation, the system compares:
- **BESS voltage angle** and **Grid voltage angle**
- **BESS frequency** and **Grid frequency**
- A dedicated control block ensures the BESS phase gradually aligns with the grid.
- A PID controller adjusts the BESS frequency reference to minimise the phase difference (angle error).
- The system considers synchronising safe when the **angle error falls below 0.1°**.

Grid Reconnection Sequence

- After successful voltage and angle checks:
- A **0.6-second** waiting period ensures stability.
- At this point, the Grid_Brk is **closed** (logic 0), reestablishing the grid connection.
- The BESS reduces its voltage slightly (by 1–2%) to shift the load back to the grid.
- When the BESS power drops below **200 W**, the BESS_Brk is opened, disconnecting the BESS from the PCC.

System Stability

- The transition occurs with **no observable transient spikes** in frequency or voltage.
- Power flow shifts gradually from BESS to the grid, preventing oscillations or reverse current surges.
- The system demonstrates strong phase-matching behaviour due to tight synchronisation logic.

Observations

- The resynchronisation process is smooth and fully automated.
- Ensures safety by strictly validating phase, voltage, and frequency conditions before closing the grid breaker.
- This functionality allows grid reconnection without operator intervention, preserving operational continuity.

5.6 Diesel Generator Synchronization

This section focuses on connecting a diesel generator to the islanded system powered by the Battery Energy Storage System (BESS). Since both sources can form the grid, precise synchronization is necessary to prevent instability or damage.

Diesel Generator Setup

- The diesel generator is modelled using a **salient-pole synchronous machine**.
- It includes:
 - An **AVR (Automatic Voltage Regulator)** with voltage and reactive power feedback.
 - A **prime mover and governor** unit that receives a frequency reference.
 - A droop control set to **3%** to facilitate power sharing after synchronisation.

Synchronization Strategy

- The diesel generator is started in **islanded mode** when BESS is already active.
- The synchronisation process compares:
 - **BESS voltage angle** and **Diesel generator voltage angle**
 - The **frequency of both sources**
- A **phase error controller** uses the difference between BESS and Diesel angles to drive a **PID-based frequency reference adjustment**.
- The output modifies the diesel's frequency reference (e.g., from 1.0 to ~ 1.001) until the phase difference becomes minimal ($|\text{Angle_error}| < 0.1^\circ$).

Connection Logic

- Once the angle and frequency match:
- A logic block sets $\text{Diesel_Syn} = 1$.

- After **1.6 seconds** since BESS activation *and* when the angle error is below 0.1° , the **diesel breaker** (Diesel1_Brk) is closed.
- The diesel generator is now coupled to the system at the Point of Common Coupling (PCC).

Post-Synchronization Behavior

- Initially, the diesel generator takes a small power share.
- The BESS output voltage is gradually reduced via a control block to shift more load onto the diesel generator.
- The system ensures smooth **active power sharing** and **frequency stability**.
- Both sources remain synchronised without oscillations or instability.

Observations

- The PID control loop effectively reduces the angle error for safe coupling.
- A ramped frequency adjustment allows smooth phase convergence.
- Diesel and BESS share the load seamlessly after synchronisation, supporting hybrid operation.

5.7 Load Sharing and Load Restoration

After entering islanded mode, this section evaluates how loads are gradually restored and shared between available power sources (BESS, diesel generators, and solar). It highlights how the system prioritises essential loads and balances generation among sources.

Initial Load Shedding and Base Load Support

- During a **black start**, the system disconnects all large loads for protection.
- Only the **base load (~3 kW)** remains connected to the BESS immediately after the BESS_Brk is closed.
- This ensures that the BESS does not experience a large inrush current or become overloaded during the transition.

Gradual Load Restoration

After initial stabilisation:

- **Solar generation** is introduced to support part of the load.

- Additional loads can be safely reconnected when synchronising diesel generators (as discussed in Section 5.6).

Loads are reintroduced based on a **priority list**:

1. **Base load** (control room lights and transformer)
 2. **Resistive heaters** (each ~22–23 kW)
 3. **Pump load** (55 kW, high inrush current, last to be restored)
- Before allowing new loads, the controller checks real-time power availability (BESSP, DieselP, SolarP).

Load Sharing Behaviour

After synchronisation:

- **Diesel generators** take a growing share of the load, especially after slightly reducing BESS output voltage.
- **BESS** reduces its output to prevent over-discharge and to act as secondary support.
- The system uses frequency-droop and voltage control to naturally shift active and reactive power among sources.
- **Real-time PID logic** adjusts generator references to maintain balanced power flow.

System Monitoring

- Power sensors at each generator output and PCC monitor:
- Power contributions (in kW)
- Load demands
- Voltage and frequency stability

Observations

- The system successfully restores critical and non-critical loads.
- Generator coordination ensures that no single source is overloaded.
- Load restoration logic maintains **system voltage and frequency within safe bounds** throughout the sequence.

5.8 Summary of Performance Metrics

This section presents a consolidated view of the Microgrid system's performance across all simulation scenarios. The metrics reflect system reliability, stability, responsiveness, and effectiveness of control strategies implemented for black start, islanding, resynchronisation, and generator coordination.

Table 1 Performance Metrics

Metric	Target/Expected	Observed Performance
Voltage RMS Stability	207 V – 253 V	Maintained within range in all modes
Frequency Deviation	± 0.5 Hz	Stable: 49.85 Hz – 50.15 Hz post transitions
Black Start Response Time	≤ 0.4 s to energize load	0.3 s BESS startup + 0.1 s breaker connection
Resynchronization Delay	≤ 0.8 s	Completed in ~ 0.7 s after voltage in range
Diesel Synchronization Accuracy	Phase error $< 0.1^\circ$	Achieved using PID-controlled ramp logic
Load Restoration Accuracy	Priority-based restoration	Followed load priority and power availability
Seamless Mode Switching	No frequency/voltage spikes	No major transients during transitions

5.9 General Observations

- The system met all predefined voltage, frequency, and synchronisation conditions across scenarios.
- Controllers demonstrated **stable convergence behaviour** for angle and frequency adjustments.
- Power-sharing logic effectively managed transitions without causing instability.
- Automated switching avoided the need for operator intervention in all tested conditions.

5.10 Conclusion

Based on the Åland University laboratory model, the simulated microgrid showed strong performance across all operational modes. Simulink and Simscape enabled detailed dynamic modelling, allowing reliable validation of control strategies and hardware coordination logic under realistic conditions.

6 Conclusion and Future Work

6.1 Summary of Findings

This thesis focused on modelling and simulating the Åland University Energy Laboratory's Microgrid system using MATLAB Simulink and Simscape. A detailed system was built, including a swing generator (grid), Battery Energy Storage System (BESS), solar PV, diesel generators, controllable loads, and breakers. The simulation covered several operating scenarios: normal grid-connected mode, planned islanding, black start, resynchronisation, and diesel generator synchronisation.

The key findings from the simulations are as follows:

- The BESS successfully handled black start events, energising the base load within 0.4 seconds after detecting grid failure.
- Planned islanding was executed without disconnecting any loads, demonstrating the smooth transfer from the grid to local generation.
- Resynchronisation was achieved after verifying voltage range and phase alignment, with successful grid re-connection after 0.7 seconds.
- Diesel generators were synchronised with the BESS using frequency and phase angle control. Phase error PID logic allowed connection once the phase difference was within $\pm 0.1^\circ$.
- Load sharing was dynamically managed between BESS, diesel, and solar generation based on real-time power availability and control logic.
- The system maintained voltage (within 207–253 V) and frequency (within ± 0.2 Hz) across all tested scenarios.

These findings validate the effectiveness of the designed control strategy and the robustness of the Microgrid model in handling transitions and load management.

6.2 Achievements and Contributions

This thesis made several practical and technical contributions to Microgrid simulation and control. The model and control strategies implemented reflect realistic scenarios encountered in hybrid energy systems and demonstrate the integration of multiple distributed energy resources (DERs) within a Microgrid environment.

Main Achievements:

- **Developed a detailed Simulink model** of the Åland University Energy Lab, including grid interface, solar PV, BESS, diesel generators, programmable loads, and breaker-based switching.
- **Implemented four key operational modes:**
 - Normal grid-connected operation
 - Planned islanding without load disconnection
 - Black start using BESS
 - Resynchronization with the main grid
- **Designed a modular control logic** for automatically detecting voltage faults, load reconnection priorities, and diesel synchronization based on phase and frequency control.
- **Integrated phase angle tracking and frequency control** using Phasor Measurement Units (PMUs) and PID controllers for smooth synchronization between BESS and diesel generators.
- **Simulated realistic load profiles and switching scenarios**, including high-demand loads (heaters and pump) and ensured system stability under dynamic transitions.
- **Demonstrated seamless transitions** between operating modes without triggering major voltage/frequency disturbances, validating the effectiveness of the control strategy.

Contributions to Research and Education:

- **Research:** This paper provides a simulation framework for future studies on grid-forming converters, virtual inertia, and hybrid energy coordination strategies.
- **Education:** Enables students to understand real-world Microgrid behaviour, transition events, and control mechanisms through simulated environments.

These contributions reflect a complete workflow using an industry—relevant simulation platform, from system modelling and control strategy design to implementation and validation.

6.3 Limitations of the Study

While the simulation model and control strategies implemented in this thesis provide valuable insights into Microgrid behaviour, several limitations must be acknowledged:

1. No Hardware-in-the-Loop (HIL) or Real-Time Testing

The study is based entirely on MATLAB Simulink simulations. Although dynamic responses and transitions were accurately modelled, real-world conditions such as hardware delays, sensor inaccuracies, or grid noise were not considered. Implementing the model in an HIL setup could reveal additional practical issues.

2. Simplified Renewable Inputs

The solar PV system was modelled with a constant irradiance value (1000 W/m^2) to evaluate steady-state performance. This does not reflect real-world variability in solar radiation due to weather, time of day, or seasonal changes.

3. Static Load Assumptions

Although various types of loads were modelled (resistive heaters, base load, pump), their operational behaviours were simplified. In real systems, load behaviour can be nonlinear or time-dependent, and demand forecasting can affect system performance.

4. Ideal Breaker and Control Logic Transitions

The switching operations were idealised using variable resistors and logical control inputs. In practice, mechanical switching delays, arcing, and other physical characteristics may impact performance.

5. Battery Ageing and State-of-Charge Not Modelled

The BESS was treated as an ideal energy source without degradation or state-of-charge limitations. Including these effects would provide a more realistic view of long-term system performance.

6. Limited Fault Scenarios

The simulation primarily focused on voltage faults and operational transitions. Faults such as short circuits, frequency excursions, or islanding due to external grid events were not extensively studied.

Despite these limitations, the simulation framework remains robust for testing and analysing Microgrid operations under a variety of control.

6.4 Recommendations for Future Research

Building on the results and limitations identified in this thesis, several recommendations are proposed for future research and development in the simulation and operation of Microgrid systems:

1. Hardware-in-the-Loop (HIL) and Real-Time Implementation

Future work should incorporate HIL or real-time simulation environments to bridge the gap between simulation and real-world applications. This would allow for testing control strategies with physical components and improve validation of model behaviour under actual operational conditions.

2. Integration of Battery State-of-Charge (SOC) Dynamics

The current model treats the battery as an ideal power source. Future models should include detailed battery behaviour, such as state-of-charge tracking, efficiency losses, degradation, and thermal effects, to better understand system limits and lifecycle performance.

3. Enhanced Renewable Energy Modelling

Introduce time-varying irradiance and temperature data to simulate the true variability of solar PV generation. This would improve studies of Microgrid resilience and control strategies under fluctuating renewable energy conditions.

4. Inclusion of Additional Sector-Coupled Technologies

Future versions of the model can incorporate additional energy technologies mentioned in recent literature, such as:

- Hydrogen production units (electrolysers)
- Heat pumps
- Electric vehicle (EV) charging systems

These components will enable simulations of integrated energy systems and support the exploration of sector coupling.

5. Implementation of Artificial Inertia and Advanced Inverter Control

Following the vision outlined in Åland's 2030 energy transition goals, further research could explore inverter-based emulation of rotational inertia and advanced frequency control methods using high-resolution data and fast-response systems.

6. Fault Handling and Protection Schemes

Include protection logic for overcurrent, underfrequency, and unintentional islanding scenarios. Adding this layer of realism will improve the model's reliability and applicability to real-world grid-connected Microgrids.

7. Expansion toward Digital Twin Development

While the current model is high-fidelity, it remains simulation-based. Future efforts may focus on transitioning toward a digital twin of the Åland Energy Lab, capable of syncing with real-time measurements and supporting predictive analytics, control validation, and remote monitoring.

6.5 Final Remark

This thesis has presented a detailed modelling and simulation framework for hybrid Microgrid operations at the Åland University Energy Laboratory, incorporating grid-forming BESS, diesel generators, and solar PV systems. The implemented control logic successfully coordinated transitions across key operational modes, including planned islanding, black start, and grid resynchronisation. Simulation results confirmed stable voltage and frequency regulation, effective load restoration strategies, and synchronisation mechanisms. This platform offers a robust foundation for future integration of sector-coupled technologies, advanced control algorithms, and real-time system validation.

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