Department of Mechanical and Aerospace Engineering

University of Strathclyde Engineering

MSc. Thesis

Investigating the use of MATLAB/SIMULIK and LabVIEW in Microgrid Modelling and Simulation

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A thesis submitted in partial fulfilment for the requirement of the degree

Master of Science

Sustainable Engineering: Renewable Energy Systems and the Environment

2017

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Signed: Mahmoud Laban Date: 25/08/201

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Abstract

Energy sufficiency has become one of the basic needs for civilizations to thrive; the Microgrid is a solution that can provide energy abundance for inaccessible energy demand locations, and provide higher energy security, reliability and power quality for accessible energy demand locations; in addition, Microgrids can help overcoming the centralized grid limitations on Renewable Energy capacity; hence, allow more exploitation of naturally abundant renewable energy sources, which may aid in national scale demand reduction for combustion and nuclear fuels. The high cost and complexity of Microgrid projects can make them difficult to justify by business investors; also, can make them relatively less attractive for end-users. Microgrid design requires a combination of various disciplines, to breed a comprehensive and adequate feasibility analysis. The presence of powerful simulation tools is crucial, to undertake reasonable analysis and accordingly establish a strong business case for a new proposed Microgrid installation.

This research investigates the role of modelling and simulation in Microgrid design, and the use of LabVIEW and MATLAB+SIMULINK, for modelling a proposed Microgrid and simulating its performance.

This project has successfully established a solid Microgrid modelling foundation in MATLAB+SIMULINK that can be enhanced in the future, and used to test and assess the performance of control algorithms. The analysis and literature review covers a range of methods that could be used to construct a Microgrid test environment, while focusing predominantly on Microgrid control and Supply-Demand management, and providing a comprehensive summary explanation of Microgrids in terms of structure, purpose, objectives, expected benefits, challenges, and the methods used for Supply-Demand Management and Control.

Acknowledgments

Having accomplished this project successfully, I would like to thank God for granting me the will power and strength, to endure this intense year that has incredibly boosted all my personal skills, and transformed me to a better person. I would like to sincerely, and greatly thank all my teachers, and emphasize on expressing my tremendous gratitude and appreciation. Special and genuine thanks for Professor Joe Clarke, Professor Paul Tuohy, and Professor Nick Kelly, for they have greatly added to me on both, the personal and professional levels; thank you, it has been a great honour and pleasure being taught by you. Now that I have been given that great honour of completing this degree, I have been burdened with a higher moral responsibility to reimburse what I have learned. I would like to thank my parents and sister and wish to earn their respect and let them be proud of me.

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1. Overview

1.1. Introduction

The current existing centralized conventional electric power systems fundamentally consist of centralized electricity generation sources, Transmission and distribution networks T&Ds, and energy demand users (consumers); users can be classified into either residential, commercial or industrial. This national scale centralized structural is often referred to as the "Main Grid" or "Utility Grid". The Electricity Transmission and Distribution Networks are responsible for delivering electricity from centralized energy generation sources to the end users.

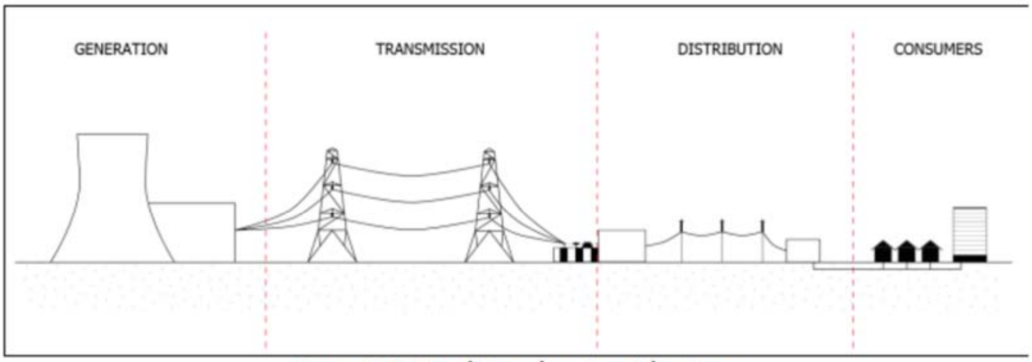


Figure 2-1: Traditional main grid set-up

Figure 1 - schematic of the traditional model of centralised generation (Energy, XERO. 2016)

That centralized process incurs considerable amount of energy losses, caused by heat dissipation, relative to the long electricity travel distance between sources and destinations; besides, some destinations may be unreachable for the main centralized grid, or could exist in remote inaccessible locations; such as in, military applications and temporary deployments that may require flexible mobility; in addition, some critical applications may need a secondary supply of electricity, to provide higher energy security. To address those issues and establish a bigger potential for further performance optimization, a new approach has emerged that if implemented on a large scale, could relatively improve the entire energy system's performance; The "Microgrids", which can be described as locally controlled decentralized energy generation of smaller scale grid structures that are capable of functioning either autonomously, or in an interrelationship with the main grid.

1.2. Objective

Microgrid systems encompass a wide range of technical and economic variabilities. That fact reflects in a high degree of uncertainty during the design and proposal phases of the project, which makes investment in Microgrid projects very risky, and likely to result in high cost estimations, aiming to reduce the business risks; that may lead to less appealing proposals for consumers. The uncertainty of design can also lead to high likelihood of unexpected performance and long-term costs after implementation. Modelling and Simulation can present a considerably effective method, for reducing the amount of uncertainty during Microgrid design and planning; in addition, can increase precision in short and long-term costs estimations.

The core objectives of this research can be summarised as:

- Investigating the role of Modelling and Simulation in Microgrid specification design.
- Investigating the role of Modelling and Simulation in testing and optimizing control strategies and algorithms.
- Investigating the role of control and automation in Demand side management and predictive control.
- Investigating the use of both LabVIEW and MATLAB+SIMULINK, in modelling and simulation, and how they could be used in establishing a Microgrid test environment.
- Establishing a simulation test model, using MATLAB+SIMULINK, that can be used as a foundation for future research and work development towards a Microgrid test environment.

This work is expected to inspire future work for developing a solid Microgrid test long-lasting platform for academic use.

1.3. Methodology

A thorough analysis and study have been undertaken for a range of up to date research papers, master's theses, academic and industrial case studies, and relevant commercial products. Products that have been reviewed include: modelling and analysis products (LabVIEW, SIMULINK), and state of the art industrial Microgrid automation products (DCS and SCADA systems).

<u>The research went through several phases:</u>

- Identifying and demonstrating Microgrids fundamental features, aims and objectives, challenges and complexities.

- Exclusive focus on investigating Supply-Demand Management, and Load Shaping strategies and methods, while reviewing the most recent case studies in Scotland. (Ex: Nines and Origin Projects)

- Studying the role of control and automation in Active Demand Management, while reviewing the current market automation commercial products, and their related case studies.

- Studying and evaluating the use of LabVIEW and MATLAB+SIMULINK as Microgrid modelling and simulation tools , while comparing between both, and presenting case studies of their applications.

- MATLAB+SIMULINK has then been used to develop and test a full Microgrid model that consists of the most commonly used Microgrid components: Solar PV farm, Wind Turbine, Backup Diesel Generator, connection to the main grid, Battery Storage, and a dynamic variable load to simulate a variable residential community Microgrid. The model was designed to be used for linear simulations, using phasor equations, at a fixed frequency, to calculate the power generation and load consumption over time; without computing the differential equations of power quality and detailed wave form behaviours.

- The model can be used to identify the ideal specifications for a Microgrid local generation and storage capacity, within given load profile, and weather data; it can also be used for testing control algorithms, to determine the optimum control strategy that provides the best cost performance, and optimal utilization of renewables and storage; furthermore, it can be used for assessing the expected outcomes of applying certain predictive control algorithms before applying to an installation.

2. Microgrids demonstration

2.1. Definition and main Characteristics

Depending on the requirements and objectives, a Microgrid may be designed to operate in either a solely isolated mode (Islanded Mode), permanently wired to the grid mode (Private Wire Mode), or a dual operation mode where a control algorithm is responsible for connecting/disconnecting the Microgrid from the main grid to function in either mentioned modes (True Microgrids).
Motivated by the recent increased interest in Microgrid development in Scotland, a report (Energy, XERO. 2016) was produced by Xero Energy Limited (XE); on behalf of Highlands and Islands Enterprise (HIE), and Scottish Government, aiming to provide a high-level guidance for Microgrids; it states that:

> The term Microgrid can be used to denote a small, usually privately owned and operated, grid irrespective of its actual connection arrangements with the main (public) grid – this includes 'private wire' systems which are permanently connected to the main grid and island systems which are never connected to the main grid. In addition, there are Microgrids that can operate in both modes (connected to and islanded from the main grid) – this latter more flexible Microgrid is the internationally recognised definition of a Microgrid, termed a true Microgrid hereafter (Energy, X. 2016).

The term True Microgrids is a term used, particularly in the UK, to describe Microgrids that can connect and disconnect from the main grid, when required, and operate either dependent on, or independent from the main grid. True Microgrids provide higher energy security for users, as they can operate in absence of the main grid by switching between two available power sources; thus, as well, the opportunity to optimize power quality by choosing the most favourable power source based on load preference. Those benefits can be tangible when operating critical or sensitive loads, such as hospitals and certain industrial facilities. Similarly, the switching feature can act to mitigate risks of encountering acute faults and failures, or hazardous voltage fluctuations and harmonics; hence, preventing damage to equipment or people which, increases the system's reliability. On the other hand, Private wired systems are permanently connected to the grid whilst the local generation is either used locally or exported to the main grid; mainly for economical optimization.

Microgrids are fundamentally small in scale, such as that the load is usually a domestic community, residential island, commercial estate, military deployment or industrial site. One of the main features that associates the Microgrids small-scale structure is the amplified capability to coordinate the local load and local energy generation, to operate together in correspondence. Microgrids are often referred to as Smart grids, to demonstrate their ability of actively managing Supply-Demand interaction, and different modes of operation. Active management is realized using state of the art automated control systems and information technologies, providing real-time control that can be enhanced incorporating advanced predictive control algorithms. Microgrid control may aim to optimize the energy and cost performance of the energy system, using Load/Demand Shaping strategies. Microgrid Active management and control will be discussed later in a dedicated section.

In theory, multiple interconnected Microgrids may be designed to exchange information and/or trade electricity, in isolation from the main grid, to offer even higher redundancy for electricity supply; thus, higher electricity market competitiveness and energy security. Interconnections between two main conventional national scale grids are not considered Microgrids.

Points of Common Coupling (PCCs) are used to connect/disconnect from the grid and segregate parts of an electric system; PCC is a term recognized in the UK electricity industry as, the point of connection with the main grid; that point can be circuit breakers or any means of connecting/disconnecting between different systems and they are used to define the boundaries between systems and system owners. (Energy, X. 2016)
PCCs are used to switch between the Microgrids modes of operation for either compulsory reasons; such as, disturbances and faults, maintenance; or for performance optimization preference. The switching mechanism is ideally automated by an advanced control system and handled by robust protection components to ensure a safe, reliable and seamless transition. (Fig.2)

In any Microgrid design, local generation may either be scattered among different locations or integrated together in one unit. Grouping local generation together tends to reduce capital and running costs.

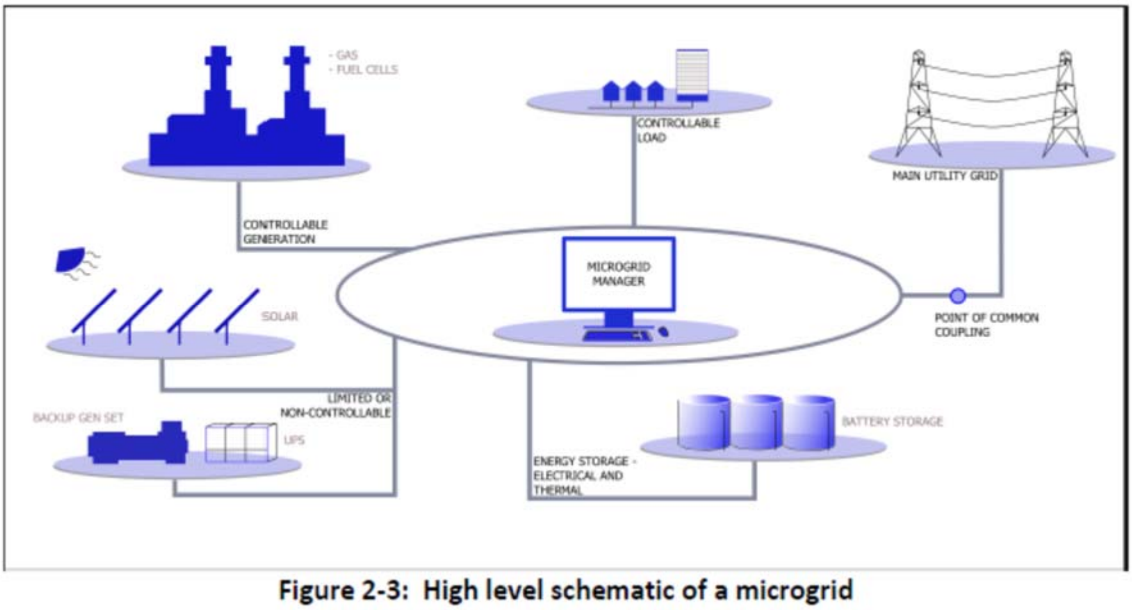


Figure 2 - High level schematic of a Microgrid (Energy, XERO. 2016)

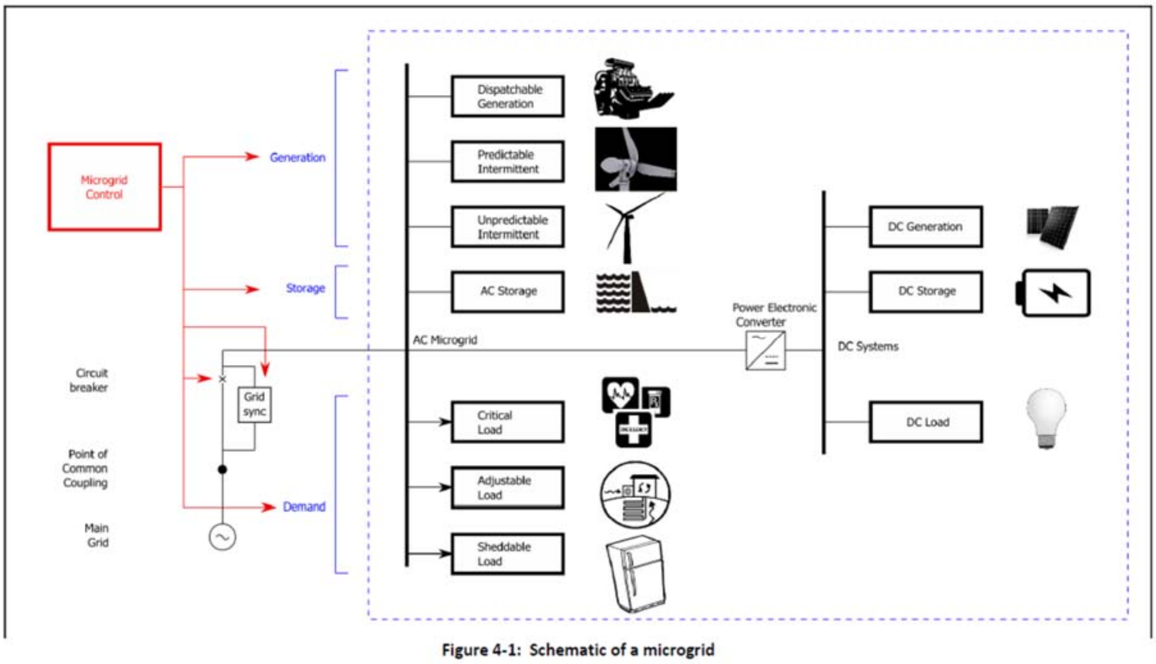


Figure 3 - Detailed level schematic of a Microgrid (Energy, XERO. 2016)

2.2. Microgrid Objectives

Microgrids don't just aim at reducing the large distance transmission energy losses, or just at providing sustainable and reliable power for remote areas; in fact, there could be plentiful further purposes and benefits associated with them. For instance, one of the most significant potential benefits is decentralizing energy generation which can allow extra penetration of intermittent renewable energy sources, to the energy network, beyond the main grid constraints, which would expectedly increase the exploitation of abundant renewable sources. The main grid penetration by renewables is limited, due to the intermittent and non-dispatchable nature of renewable energy sources; that impacts the grid stability, and power quality, if the penetration capacity upsurges beyond a certain level.

This chapter intends to highlight the most significant identified purposes for Microgrid usage.

2.2.1. Environmental

Certain renewable energy sources conceivably produce negligible Green House Gaseous (GHG) emissions, compared to fossil fuels generation; hence, maximizing renewable sources penetration to the energy network can have substantial positive impact on reducing GHG emissions; in addition, due to their abundance, Renewable energy sources can significantly reduce electricity market cost, therefore, contribute in ending fuel poverty.

2.2.2. Energy Demand Reduction

Furthermore; demand reduction (from the main grid), up to self-sufficiency, can be achieved in a Microgrid, if distributed generation is consumed locally; hence, reduce the need for central dispatch generation from the main grid. Assuming central generation is more fossil fuel based than distributed generation is (due to main grid renewables limitation), increasing the percentage of distributed generation would theoretically result in less GHG emissions.

2.2.3. Increasing supply

Designing the main grid infrastructure to accommodate bi-directional flow of electricity can enlarge the significance of, and maximize the benefits from Microgrids; thus, encourage further development and proliferation of Microgrids. The Microgrid can feed power to the main grid, so that in periods of local demand saturation, excess energy generation can be exported to the main grid to be distributed among other network users; similarly, the infrastructure can be designed so that the electricity can also be traded directly among nearby interconnected Microgrids, by that, renewable energy exploitation can be maximized to the full potential and the exported energy would contribute in reducing the required main grid central generation, in addition to introducing electricity price competition hence promoting sustainable electricity market prices.

2.2.4. Accessibility and Security

Energy security can be defined as the redundancy of energy supply.
The distinctive feature between a True Microgrid and a Private Wire Microgrid is the ability to switch to Islanded mode when needed (only exists in True Microgrids); this feature is required when higher energy security is needed, which can be the case for critical and sensitive applications. The common fundamental feature that characterizes both types is the ability of locally generating electricity and exporting the surplus to main grid; it would be plausible to conclude that, in some cases, a True micro grid may be needed only for the purpose of providing higher energy security, or exchanging renewable generation locally; thus; not necessarily incorporate the ability of exporting power to the grid.
Islanded Microgrids that operate autonomously and independently from the grid can deliver great benefits and provide reliable energy access, for areas where the connection to the main grid isn't economically or technically feasible, due to large distance (remote and rural areas).

2.2.5. Reliability, Resilience and Power Quality

True Grids that can switch between grid connected and islanded modes of operation could also improve energy reliability and resilience, by availing a secondary energy supply to serve in situations of main grids faults, failures, or blackouts; they can also improve power quality and energy performance; Power Quality may be defined as better compatibility between the generation sources and the loads (Von Meier, Alexandra 2006).

When enhanced with predictive control, a True Microgrid can attain high levels of reliability and resilience; resilience can be defined as the ability to recover from faults and failures while minimizing their implications on power quality and performance. In systems where certain failures and faults are inevitable or of high probability, high resilience is paramount.

The national infrastructure advisory council of the US defines the infrastructure resilience as:

> The ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event (Fall, E., 2009).

2.2.6. Distributing Generation

Microgrids are principally predicated on local energy generation, preferably and not essentially, renewable energy sources. As mentioned earlier, Distributed generation is associated with several potential benefits that serve the entire energy network.
In the UK Energy network, more distributed generation, including renewable generation, is being added recently in an increasing pace, which is establishing a stronger foundation for Microgrid projects replication. Distributed generation is not limited to renewables; it may as well utilize conventional combustion engines, and advanced and efficient micro generation sources such as:

- **Microturbines**: Advanced compact design of conventional gas turbines that can be used in small scale applications and incorporate state of art technologies such as air bearings, foil bearings, and waste heat capture, which contributes in their high efficiency. Microturbines have been recently developed to operate for up to 500 KW power output and inhabit a chassis that is as small as a hand. They are remarkably efficient, echo friendly, and produce trivial noises during operation, which makes them ideal for domestic applications and particularly Microgrids. (Capehart, B.L. and Engineering, 2016)

- **Sterling Engines:** Engines that use thermodynamics, unlike Internal Combustion Engines that use fuel combustion, to drive a piston engine that generates electricity. They are commonly used for small scale applications and are very suitable for domestic use.

- **Combined, Heat and Power (CHP) and Combined Cooling Heating and Power (CCHP):** The technology itself was initially developed for utilizing waste heat from large power generation (ex: Gas turbine combustion process) to generate more power using a Steam turbine, or to provide low grade heat to nearby facilities (See District Heating), that low grade heat can be used to withdraw heat, using a refrigeration cycle, for cooling applications. Similarly, Individual compact units were designed, for smaller scale domestic use, typically capturing waste heat from local heat generators (Ex: Gas Boiler), and use it for generating electricity using a Stirling Engine.

- **Small scale hydro**

Augmented utilization of such advanced efficient microgeneration technologies can imaginably have amplified benefits on a national scale; Furthermore, For the individual consumer; generating electricity locally can have cost benefits by trading electricity with electricity supplier to be redistributed among other users (Fig. 4).

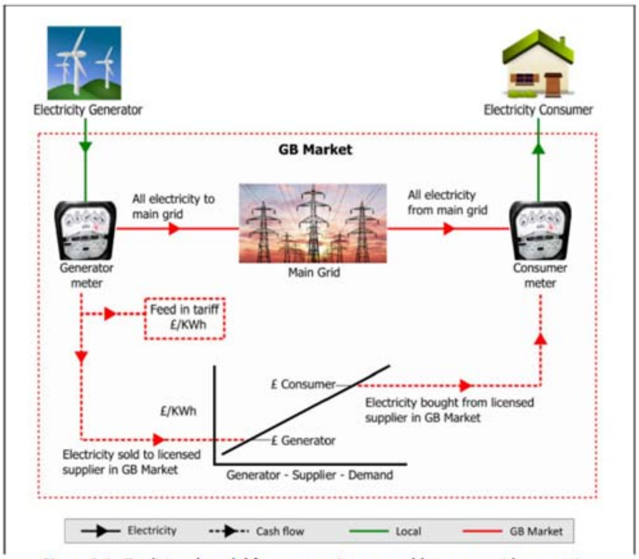


Figure 5-1: Traditional model for community renewable energy grid connection

Figure 4 - Traditional model for community trade connection (Energy, XERO. 2016)

2.2.7. Enhanced controllability

The small-scale feature of the Microgrid, when combined with sophisticated local control, conceivably enables a higher resolution of system live monitoring and data collection, which can significantly improve the operation efficacy and system's performance. Data acquisition and Information Technologies can then be as well used to enhance real-time control judgment, and long-term decision making, for system's operators and business owners, which suggest great improvements in short and long-term system's performance. Furthermore; real-time control can be optimized and facilitated by exchanging high-resolution data and information between consumers and operators. Control systems and the interaction between consumers and operators will be discussed later; Active Demand management is also going to be discussed in details later in dedicated sections.

2.3. Considerations and challenges

2.3.1. Renewable Energy Intermittence

Renewable Energy Sources are intermittent and non-dispatchable, which means that they are not continuously available, and can't respond to large fluctuations in demand; thus, require energy storage. Energy Storage is expensive and may be inefficient. Grid stability can be a problem when increasing intermittent non-dispatchable supply, which is a fundamental feature of renewable energy sources.

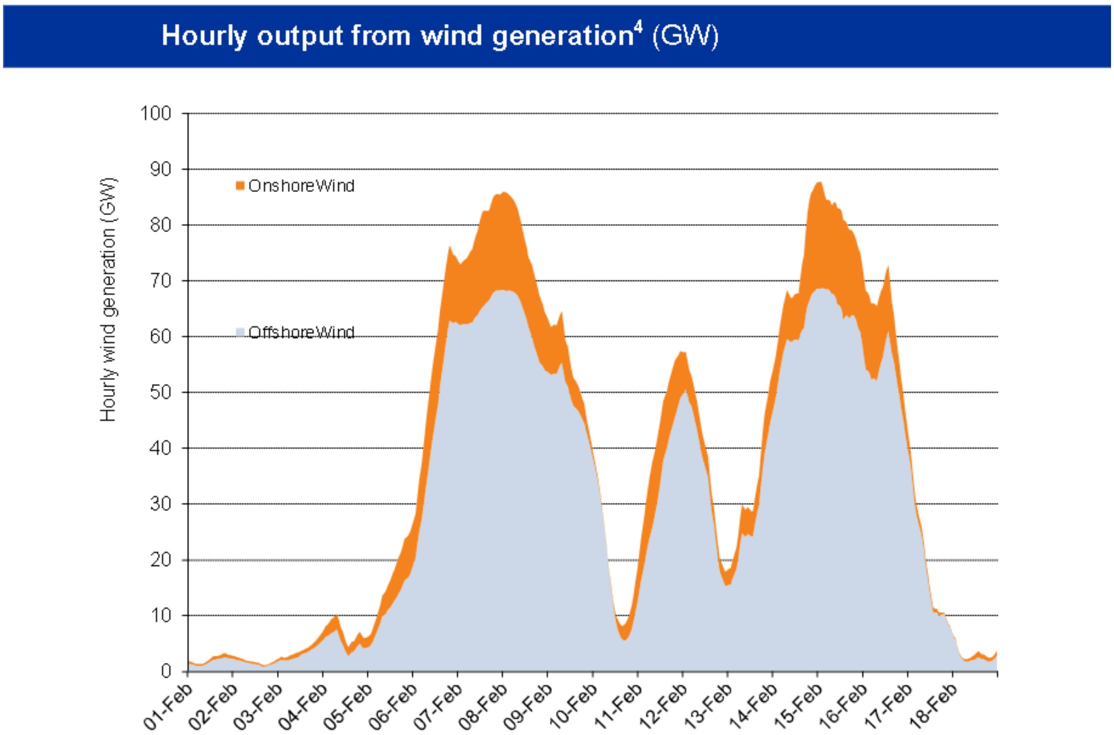


Figure 5 - Intermittency of Wind generation; from Technical constraints on renewable generation report, by committee of climate change in the UK. (CCC, 2011)

2.3.2. Power quality and synchronization risks

Having an interconnection between two energy networks with difference power sources requires additional protective equipment, and enhanced control, to ensure careful synchronization between both systems, to avoid system failure, and to avoid damage to equipment. According to the (Energy, XERO., 2016), In the UK, the National grid operators are responsible of maintaining the system's frequency within the prescribed normal operating limits which are 49.5Hz and 50.5Hz.

Integrating Bi-directional electricity flow functionality can be costly and technically challenging; Accommodating this functionality on a wide scale can jeopardize the power quality in the main grid; thus; require relatively extensive infrastructure upgrade that is proportional to the scale of implementation, to ensure exported power compatibility and maintain grid stability.

2.3.3. Management and regulations

The entity that regulates and licenses the UK main grid is, The Office of Gas and Electricity Markets (Ofgem). The (Energy, XERO. 2016) report reviewed the regulatory aspects of Microgrid installations in the UK (See fig.6); such as, licensing, exemptions and liabilities; the research identified different parties involved in the UK energy network framework as follows:

- Centralized Generation owners – Owned and licensed separately
- Smaller Distributed generation owners – Include individual end-users with small generation and Microgrid owners (Exemptions can apply up to 100 MW)
- Transmission and Distribution Operators
    - Distribution Network Operators (DNOs)
    - Independent Distribution Network Operators (IDNOs)
    - Transmission owners – Onshore and Offshore
    - National Electricity Transmission System Operator (Ensures real time supply-load matching)
    - Elexon – Settles the Electricity metering
    - Mere Consumers

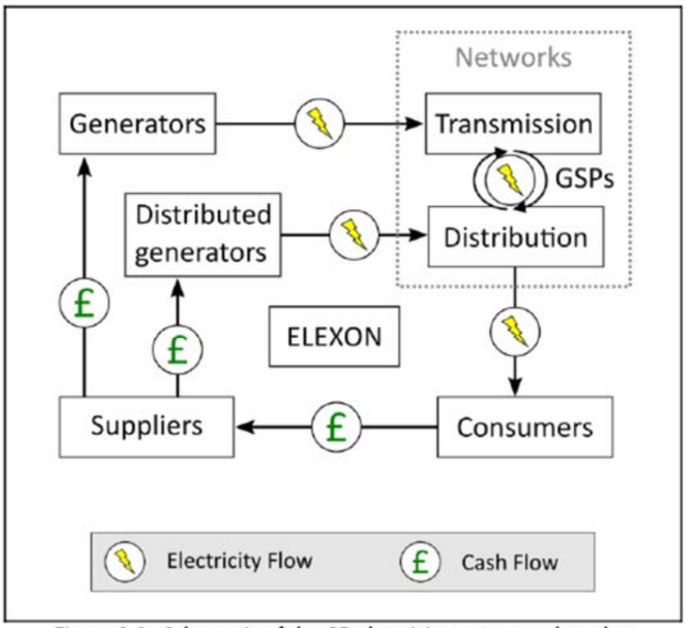


Figure 2-2: Schematic of the GB electricity system and market

Figure 6 - Schematic of the GB electricity system and market (Energy, XERO. 2016)

The interface between different energy networks must consider the segregation between various owners and operators; Microgrid installation increases the number of interfaces between systems (increased parties), which requires additional infrastructure, and electrical facilities; such as, Substations, monitoring and metering devices, and Switchgear, to handle the connection/disconnection operations. This process needs to be governed with high competency and aid of sophisticated industrial control systems that can provide high level of Fault-Tolerance and integrity, to ensure acceptable levels of performance safety and reliability while reserving the legal rights and interests of all parties. Microgrid proliferation is expected to relatively increase the number of parties involved in the energy market. Significantly increasing the number of parties involved and system owners can conduct a considerable amount of chaos, in terms of regulations, rights and obligations, if not well managed; also, can magnify the burden and cost on authorities.

2.3.4. Increased costs

Additional infrastructure, equipment and complexity mean higher cost; to relate, Microgrids introduce higher complexity and risks than the average conventional setup. Additional infrastructure and control conditions are not only required in multi-mode Microgrids; Island Microgrids also require additional infrastructure to ensure appropriate Supply-Demand matching, and to be able meet the highest peak demand without disrupting the power quality of the network.
Designing reliable and efficient control systems impacts both capital and running costs; while the capital cost is elevated due to the requirement of additional control equipment, and systems engineering, running costs as well are elevated corresponding to energy losses due to inefficient energy performance, which is correlative to the Control system's performance. Moreover, Additional costs can be incurred due to upgrading an existing running system; an example of that would be replacing an existing conventional small community grid connection, into a True Microgrid or a Private Wire Microgrid; another example would be converting an Island Microgrid into a True or Private Wire Microgrid.

When the function of switching to Islanded mode is not required, which would be the case if the level of energy security in the main grid is highly satisfactory for the target application and happens to be the prevalent situation in Scotland, economical preference would tilt towards Private wire Microgrid over True Microgrids; However, there are some remote/rural communities in Scotland that may benefit from Islanded Microgrids, due to lack of access to the main grid.

The (Energy, XERO. 2016) report questions the benefits of implementing Microgrids in Scotland, considering its cost and complexity. That is since, the high security level of main grid energy supply in Scotland, and the availability of cost effective and less complex solutions such as backup generators; The report states that the only currently operational True Microgrid is at the Centre for Alternative Technology (CAT), in Wales.

2.3.5. Consumer Desirability

Consumers acceptance is a decisive factor in Microgrid success potential; However, adding complexities, responsibilities, or liabilities, may reduce consumers appreciation for Microgrid solutions. To overcome that, Benefits and added values need to be demonstrated, effectively and clearly, to consumers to gain their acceptance.

Poor system design (inconvenient Load shaping, inefficient control…. etc) can have a negative impact on consumer's comfort and satisfaction, which can vandalize future marketing efforts. Microgrid simulation, the primary focus of this research, can increase Microgrid design optimization, which may help producing more cost effective, and better performing, solutions.

3. Active Management and Load shaping

3.1.Supply-Demand matching

Overall any energy system, Energy demand fluctuates over time, in response to consumer's consumption fluctuations. Energy supply needs to always match the fluctuating load, which requires high flexibility and responsiveness of generation sources to overcome these fluctuations. That requirement emphasizes the need for dispatchable, responsive, and permanently available, energy sources, and restricts the growth of renewable energy penetration capacity to the main grid.

The quality of Supply/Demand matching process may be defined as, the harmony between energy generation and demand. Optimizing the Supply-Demand matching process helps in maintaining satisfactory power quality and reliability, in addition to reducing the risk of blackouts and system collapses that may occur in case of failure in Supply-Demand matching; Optimization can be done either by improving energy generation responsiveness or by Demand Management.

Particularly; Supply-demand matching can be challenging in Island mode operation if the local generation is predicated on intermittent renewable energy sources.

3.2. Load/Demand shaping and management

Load/Demand Management can be perceived as, adjusting consumer demand pattern to match the desired ideal energy generation profile and maintain adequate performance. Load management has a very high potential in Microgrid applications due to, as discussed before, its small scale and “Enhanced Controllability”. Load/Demand management attempts to reshape the load pattern, and is often referred to as “Load Shaping” or “Load shifting”. Load/Demand shaping have several approaches and, if well designed, can deliver significant improvements to the energy system performance; however, implementing it is very challenging.

Demand/Load Shaping primarily aims at reducing the magnitude of demand fluctuations, by adjusting consumer loads, to maintain minimum overall demand peaks (Peak Shaving). Peak shaving can have various benefits on the system’s performance, by increasing its stability and reliability; hence, allowing it to accommodate more renewable generation. High peak demand can cause surges in electricity market cost, in addition to relatively increasing the difficulty of Supply-Demand matching, which then requires more availability of dispatchable energy generation sources (Most commonly nuclear and fossil fuels), making it more challenging to increase renewable generation capacity, which is intermittent, non-dispatchable, and much less responsive unless associated with large capacity energy storage ; however, energy storage as discussed is high in cost, which can nullify the cost benefits of renewable energy usage. Some means of Load management and shaping are going to be discussed in the flowing sections.

3.2.1. Load shaping by interaction with consumer

Energy Demand can be managed by coordinating with consumers; that can be achieved using advanced distributed control and information technologies to provide the consumer with weather and cost forecast data that could help them optimize their consumption and energy usage; additionally, the user can be allowed to actively interact with the control system, by logging information that is helpful for operation and control; this strategy will be discussed later in a further section (See Origin Project).

If Consumers could cut down their usage and improve the efficiency of their overall consumption, not only their bills, but also, the overall energy demand would relatively be reduced while helping reduce the system peak demand (peak shaving); hence, maintaining higher stability. In theory, reducing the overall energy demand would reduce the average price of electricity in the electricity market.

Managing end-user consumption can’t easily be done, and would require clear demonstration of expected outcomes for consumers, to encourage them to engage with the energy process, or pursue any behavioural or lifestyle changes; however, consumer adaptation to behavioural changes cannot be predicted nor guaranteed.

3.2.2. Active management and predictive control

As mentioned in the previous section, control systems can incorporate communication and information technologies that can be used to improve consumers interaction with the energy system; moreover, a Microgrid system's performance can be enhanced by actively managing local generation and battery storage effectively, to ensure optimal exploitation of renewables and minimal depreciation of energy storage facilities. That can be done by utilizing high level resolution live data monitoring, and facilitating the interaction between users, system operators, and controls. Controls can employ complex predictive control algorithms based on weather and load forecasting to perform the most appropriate decisions; hence, produce an optimal energy performance and end-user satisfaction. Automated control could also act to shed down non- critical loads at appropriate times. Likewise load management by customer interaction; Predictive control management can be as challenging; control algorithms can be very complex and require accurate input data to function as desirable; in addition, the input data which is most commonly the predicted load profile, and weather forecast, can never be of guaranteed accuracy. That is why predictive control is constrained in terms of expected level of optimization. Predictive control will be discussed later in this paper.

3.2.3. Load shaping by thermal storage

As discussed, Demand Management aims at optimizing the system's performance; hence, reducing the usage of expensive energy storage (Commonly Battery storage). If that is successfully implemented, can aid in increasing renewables utilization, by relatively adjusting consumer demands to accommodate intermittent renewables availability. One of the remarkable methods of Load shaping is: actively managing thermal storage (Water heating tanks) at consumer premises to store energy in the form of heat, instead of using expensive electric battery storage; primarily, to sink as much energy as possible during periods of renewables availability, or periods of low electricity cost, in case of operating in main grid connected mode.

Thermal storage differs from other types of energy storage in the fact that the stored energy, which is in heat form, can't be converted back to electricity; electricity is converted into heat energy, using water heating, and stored in tanks such that it can be used over extended periods of time by consumers; hence, it can be portrayed as a way of stretching the consumer heat demand on a longer period, rather than a form of long-duration energy storage.

The major challenge associated with Thermal Storage is the volatile nature of heat energy, which is due to the second law of thermodynamics, which states that entropy can only increase over time, leading to dissipation of heat and energy loss regardless of the storage medium. That nature causes inevitable dissipation of heat of which rate and magnitude are impossible to predict accurately; In addition, Heat transfer has a very slow response rate from a Control perspective, compared to any other form of energy transfer (Such as pressure, flow, electricity ..etc). These facts make attempting to actively manage, and control, Thermal Storage notably challenging, and likely to incur large amount of heat/energy losses and dissipation, which can cause tangible inefficient overall energy performance. Furthermore, if the dissipated heat results in undesired space heating; it may also collide with consumer needs and comfort.

Nevertheless, locating thermal storage at consumer premises, can constraint these loses into the consumers living space, while allowing the utilization of these losses in space heating; that would clearly have less applicability during periods that don't require significant heating, such as summer time. Utilizing Thermal storage for space heating can be counter-productive, if it takes effect unintentionally due to ineffective controls.

4. Microgrid Case Studies:

Due to the discussed expected outcomes and benefits of Microgrid projects, they are increasingly becoming popular worldwide, as their core technologies are advancing, and their underlying technical and cost challenges are being alleviated.

4.1.True Microgrid case studies

As mentioned citing the (Energy, XERO. 2016) report, the only True Microgrid known functioning till the date of the report, is the Centre for Alternative Technology (CAT), in Wales; however, there are numerous communities that are designed to run on backup energy supply in case of failure of the main grid connection. As discussed before, that is useful in applications that require higher energy security due to safety or economic reasons; such, as hospitals, sensitive industries, and critical loads that require higher reliability of power supply

4.2.Island Microgrid case studies

Isle of Eigg:

A residential community that maintains ownership of its Islanded grid; the community manages and maintains the Microgrid. It is a permanently Islanded Microgrid with no connection to the main grid; before establishing the Microgrid system, the Island used to run on costly diesel generators.

According to (xx cite) the Island runs on three hydro generators, four small wind turbines and PV Panels. The system combines three different sources of renewables (wind, solar and hydro) to ensure consistency of supply during the intermittency of each. Which leads to the minimum requirement of the fossil fuel based backup generator.

4.3. Demand Management case studies

Orkney, the UK's first Smart grid (S.S.E, 2017); was developed in incorporation with University of Strathclyde designed to perform as Smart grid by actively managing the energy generation to match the demand using real time control. Other instances in Scotland that utilize microgeneration are Isle of Lewis, Isle of Rum, Isle of Muck

The two most remarkable projects that are currently under development are the NINES and Origin projects:

4.3.1. Shetland's NINES Project

Shetland incorporates a fully Islanded and privately owned Microgrid', as shown in figure 7, the system is an actively managed system that utilizes a district heating scheme, large scale centralized battery storage system, microturbines, wind turbines and thermal water storage demand side management system that will be discussed later.

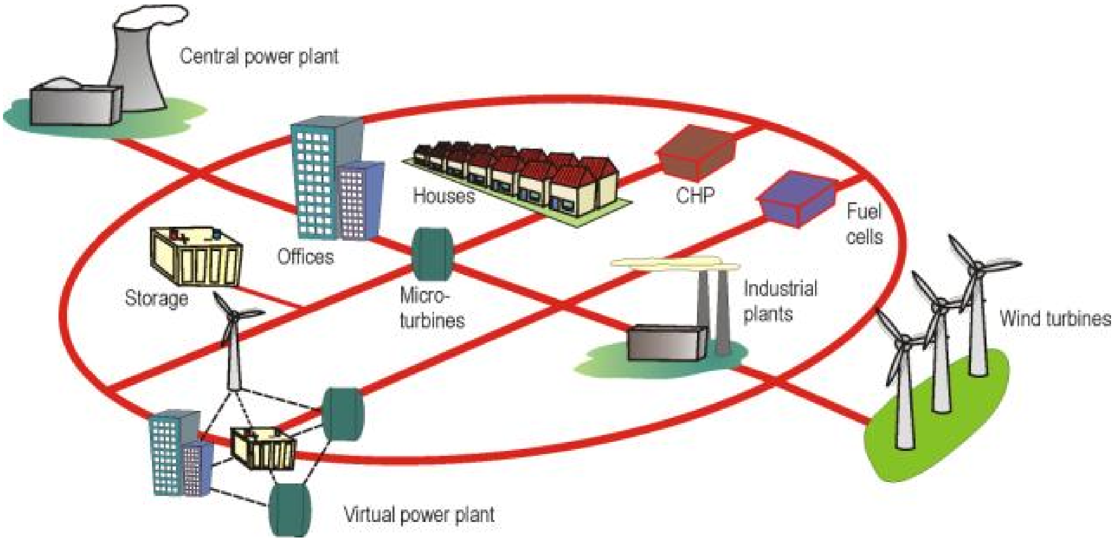


Figure 7 - Shetland's nine project development plan schematic (SSE, 2017)

The project is already running, but further development is ongoing to enhance active management and the Thermal Storage demand management system.

The NINES Project intends to actively manage up to 5.5MW capacity, in the form of distributed storage heaters, and immersion water cylinders, in up to 734 homes, in addition to a 4MW electrical boiler used for a centralized Non-domestic thermal Storage facility that can store up to 130MWh of hot water (S.S.E, 2017).

The project aims to use predictive control, based on weather and demand forecasts, to utilize the distributed and centralized Thermal Storage for the best system performance. Briefly, energy would be stored in excess during periods of renewables availability, or prior to a predicted shortage of supply, to be used over extended periods of time. Due to the volatile nature of thermal energy, storing large amounts of energy in the form of heat would relatively require additional insulation to contain the energy stored with minimum amount of dissipation and heat loss.

Some positive customer feedbacks indicate that the ongoing project is getting closer to its desired outcomes.

4.3.2. The origin Project

As described earlier; Demand Management aims at adjusting consumer demand patterns to match the desired ideal energy generation profile, and maintain adequate performance. The origin project “Orchestration of Renewable Integrated Generation in Neighbourhoods” (Gerard, P. et al., 2015) aims at maximizing the share of local renewable energy generation in overall consumer consumption, and consequently minimizing the energy needed from the main grid, by stretching consumer demands to meet highest renewable sources availability. The project aims to achieve its desired improvements by utilizing Solar Water Heating, and Thermal Storage, interacting with consumers, applying predictive control algorithms, and shifting consumer loads when feasible, without interfering with consumer’s comfort. The Origin Project examines three residential communities, in which the consumption is predicated on renewable energy generation, to develop a universal algorithmic method that can be used effectively in demand side management. It incorporates most approaches that have been discussed in the previous sections.

The strategies that the project uses are:

a) Interaction with consumers using information technologies, such as, smart phone applications, and internet web pages, to display system information and login data to enhance system control (fig 8 and 9).

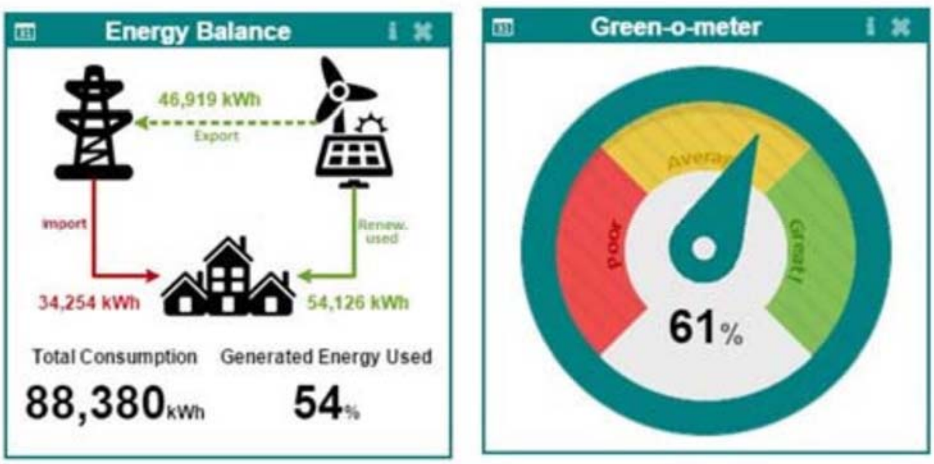


Figure 8 - Origin Project web based interaction widgets (Gerard, P. et al., 2015).

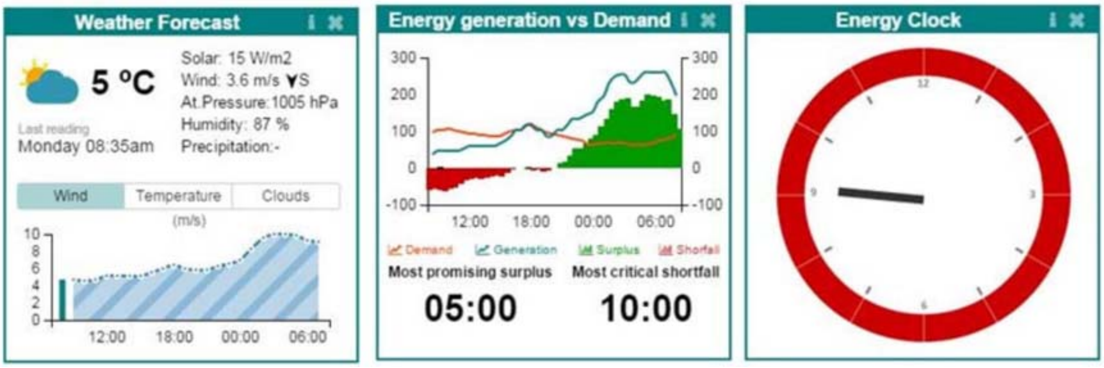


Figure 9 - Origin Project web based interaction widgets (Gerard, P. et al., 2015).

b) Remotely controlling consumer Thermal storage and renewable generation, in coordination with energy supply, using predictive Control algorithms.

The Predictive Control algorithm intends to use the following computations to make the best control decision:

- Weather forecast - hence the expected renewable generation and heating consumption.
- Electricity tariff forecast - to utilize electricity at lowest possible market cost.
- Demand prediction - based on historical performance data
- Gap analysis - to provide consumers with desired behavioural actions that aim to reduce the expected future system Renewable/Demand gap.
- Optimization algorithm - to establish a long-term strategy based on historical accumulation of data.
- Load shifting opportunity algorithm – An algorithm that analyses the expected gap between real and ideal demand, by identifying potential load shifting options, which is then used by the optimization algorithms to select the best action.

5. The role of Control and Automation

5.1.Distributed Control and SCADA systems

Distributed control systems DCS, and Supervisory Control and Data Acquisition SCADA are terms that are used to describe systems that are used to control, monitor and operate any manufacturing, industrial, or energy process.

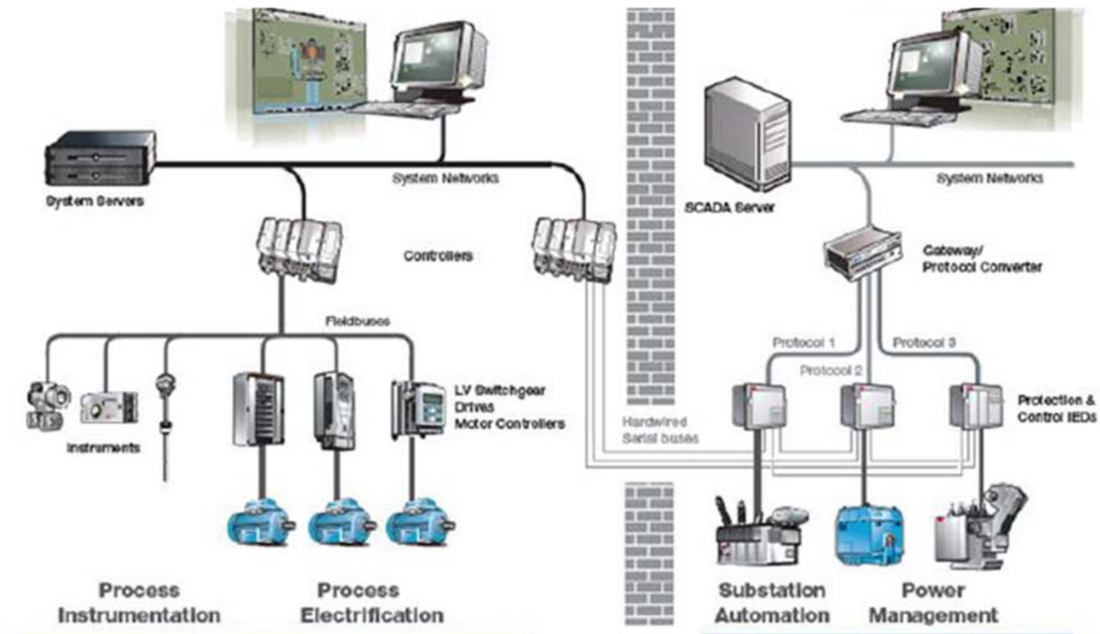


Figure 10 - Standard DCS and SCADA architectures; on the left is a DCS system, and on the right is a SCADA system (Globalspec.com, 2017).

Figure 10, represents the standard Control hierarchises of DCS and SCADA systems. DCS is usually an integrated platform that is manufactured and sold together, and usually, connects all the infrastructure using one ethernet based communication network layer. Fundementally, DCS systems comprise all the control components from the Control Processors and up to the HMI ; while SCADA systems, only comprise the HMI level of operation, including the software gateway that imports the data from the field processors or other systems; the data is then collected through a gateway server (PC) and displayed in the HMI dynamic displays; SCADA systems are usually manufactured and sold separately from the Control processors; usually from different vendors. DCS systems are used when sophisticated or critical real-time control is required in addition to monitoring; while SCADA systems are used when only monitoring and non-critical control actions are required. DCS systems are costlier, as they offer more sophisticated real-time control, and an integrated advanced software package than connects the control processors and the HMI together in one software platform/interface for program and configuring both; to make it clear, DCS systems provide access to field procesors as a part of the system for configuration and monitoring; while SCADA systems only receive data through its gateway, regardless of the source. (fig. 10)

A research was made (Álvarez Álvarez, E. et al., 2010) to design a simple SCADA control system for Microgrids; as shown in fig (11), the field level comprises various sources of microgeneration (Solar Cell, Fuel Cell, Microturbine, Wind turbine, Diesel Engine), and other process instrumentation; such as, sensors and transmitters; these equipment are managed by a group of local control processors (LC), and managed by a Distributed Controller that orchestrate them. The data is collected through communication protocols to the Server, which then display the process control graphics for monitoring and control. Users can input data about their usage and monitor the system performance through a web interface using various devices, to help optimize control. That is very similar to the NINES and Origin projects in concepts and architecture (fig 11).

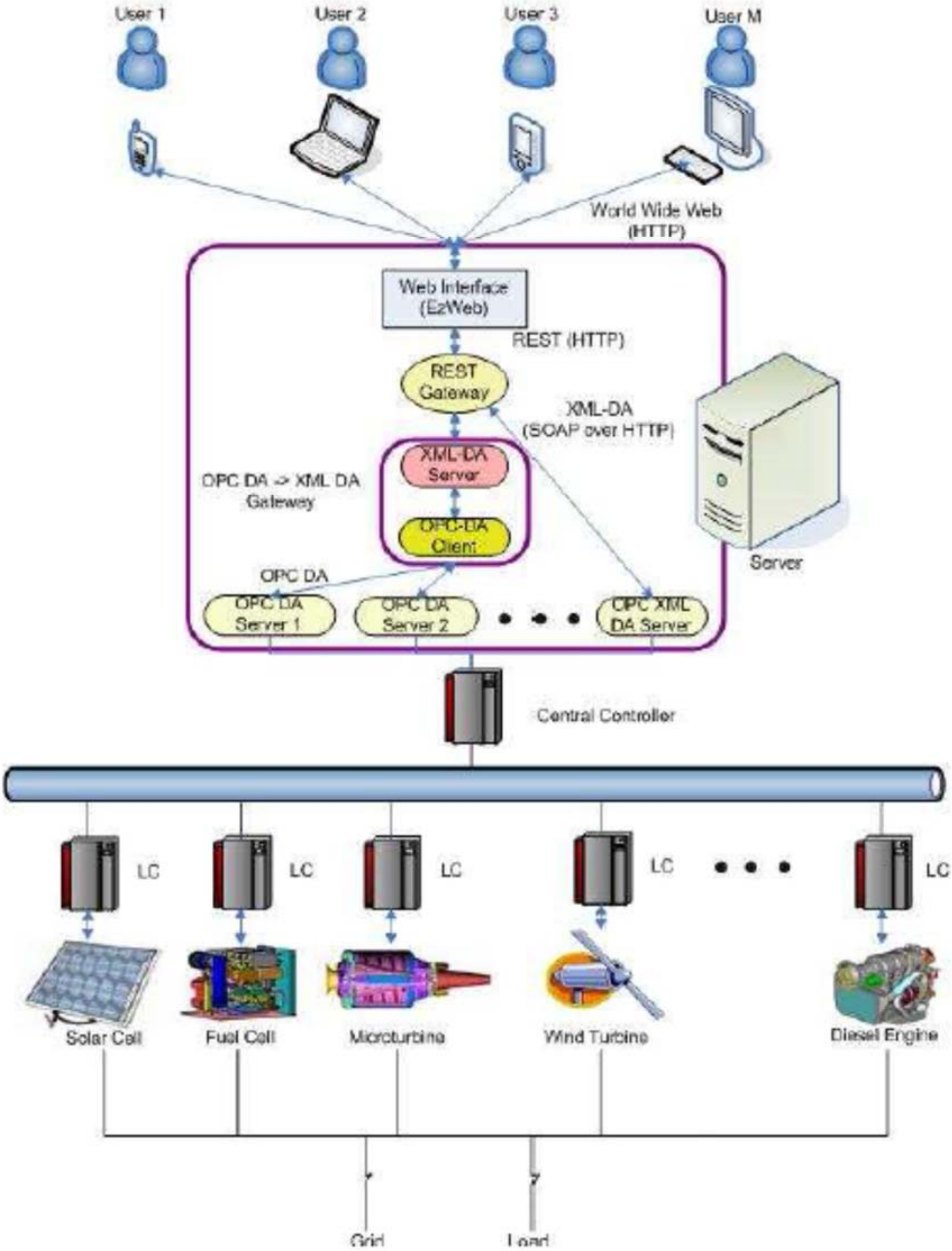


Figure 11 - Micro Grid SCADA Architecture (Álvarez Álvarez, E. et al., 2010)

5.2.Distributed Control Architecture

Distributed Control Systems (DCS) consist of several control layers, aiming at exchanging live process data between the field level, control processors, supervisory level (system operators) and Process analysis level (fig.12).

The field level can be defined as: the instrumentation and devices that function at the end-user level, to gather, measure, and compute the process live values, or act based on control decisions made; either by, controller processors and/or manual system operator inputs. These instruments include sensors, gauges, transmitters, motors, compressors, turbines, engines, generators, valves, dampers, pumps, actuators…etc; the exchanged data is usually referred to as control inputs and outputs.

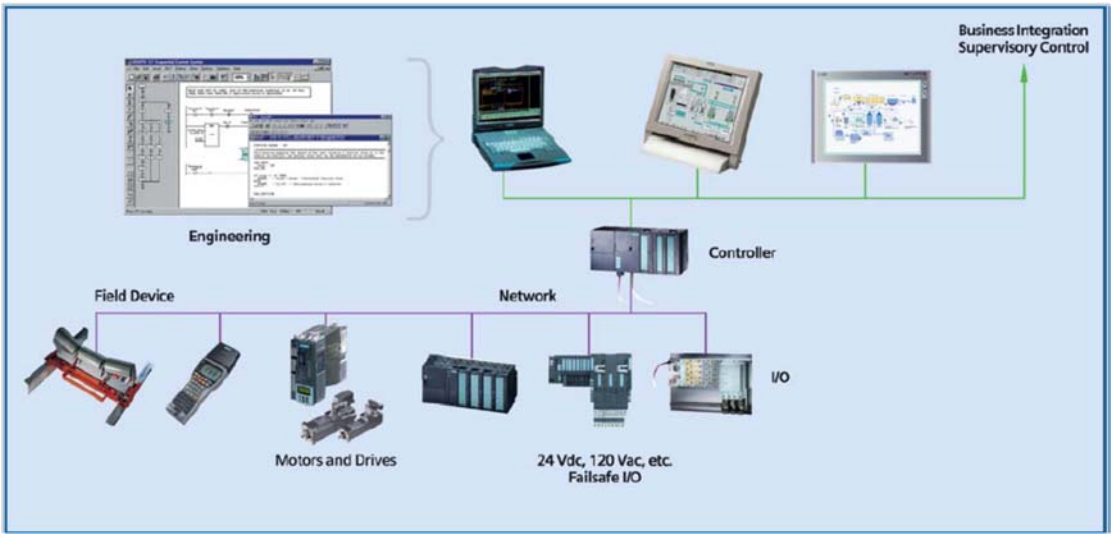


Figure 12 - Typical DCS System Architecture (Siemens, 2007)

The upper layer of control is the Control Network, which consists of Industrial Control Processors that collect field control inputs/outputs using electrical wiring, and marshalling cabinets, through various sophisticated communication protocols. The Control Processors then scan real-time live values of the gathered data, then processes it, using the designated control algorithms to make the most appropriate decisions. Those algorithms can be optimized to make decisions based on long-term anticipation, based on weather and Load forecast, Electricity Market cost forecast, or both (Predictive control).

Load forecasting can be done by analysing existing consumer profiles and patterns of their consumption then mathematically predicting the customer load, few hours in advance, based on expected weather forecast and historical data. Similarly, it can include consumer's input as discussed previously.

The control processors automate the energy generation process, so that it requires minimal manual intervention from the system's operators or end users unless the intervention is for optimization or emergency situations. The control decisions made by the automated control systems may be enhanced by obtaining further data from the field level, by means of end-users manual input. That can be using push-buttons, switches, process touch screen (monitor), and/or using internet websites, smart phone applications, phone text messages (SMS); similar to Origin and NINES projects which have been discussed earlier.

The above layer of control is the Monitoring and Operation level, which consists of Operator screens, usually computers (PCs) or industrial control monitors that are used to visualize the whole process, using dynamic graphical displays, while providing means of manual operator control. That level of operation is often referred to as, "Human Machine Interface" (HMI); however, The term HMIs can also be valid for operator screens that are located at the field level for maintenance or end-user input. HMIs include dynamic process graphic displays that represent the schematics of the process, and the live process values, while providing the system operator the ability to manually intervene and optimize control decisions, or interrupt the process in case of emergency.

A higher level of monitoring may exist, to transfer the process data to business or governmental premises, and allow remote access to the system, for operation or analysing the system's performance. That can aid in asset management, financial planning, and decision making.
Data can be also exchanged at that that level with other interconnected Microgrids or with the main grid, to facilitate electricity trade between them.

5.3. Industrialized Microgrid SCADA systems

5.3.1. Schneider Electric Microgrid SCADA and Microgrid controller

SCADA and DCS manufacturers have recently started to produce Control systems that are customized and specialized in Microgrids (fig.13). A project "Oncor" have been implemented using such systems in 2015 at Lancaster, Texas, utilizing 2 Solar Panels, 1 Micro Turbine,2 Energy Storage Systems, and four diesel generators.

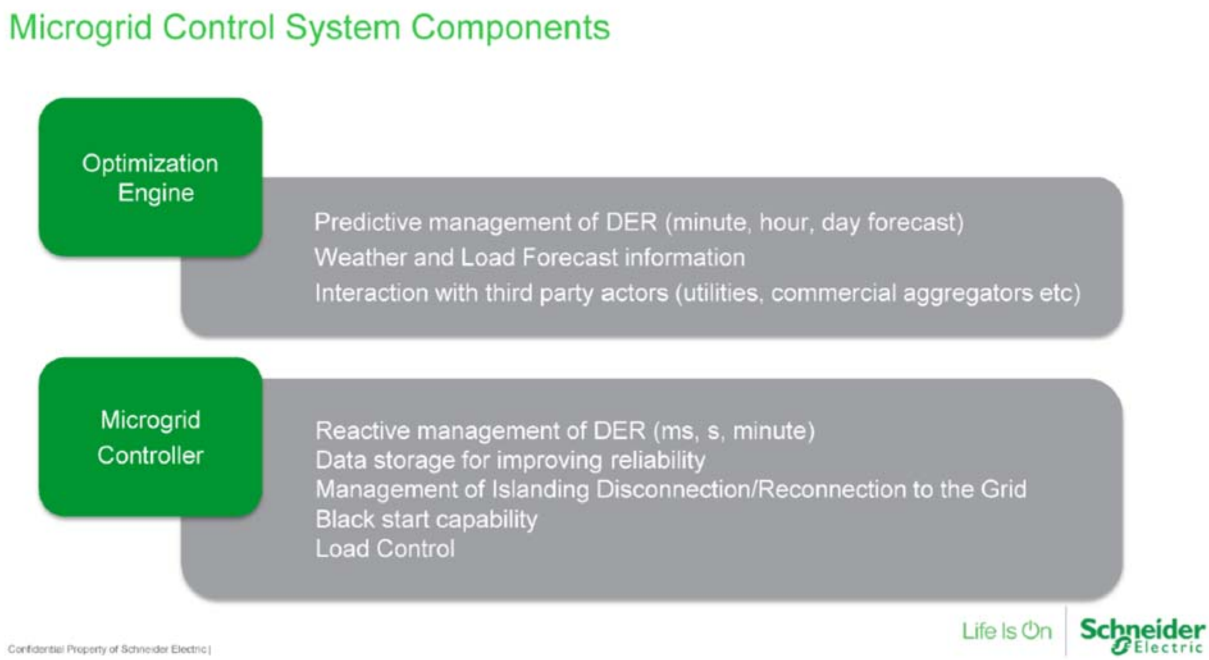


Figure 13 - Schneider Electric Microgrid SCADA system components; Structureware SCADA and Power Logic Controller (S.E., 2016)

Oncor system consists of four interconnected Microgrids that use different distributed generation sources. Schneider Electric has successfully upgraded the installations with a sophisticated SCADA system with enhanced predictive control and detailed monitoring. The project utilized Schneider Electric "PowerLogic" Microgrid Controllers, which is a control processor designed for Microgrid applications.

StruxureWare SCADA and Demand Side operation, is a SCADA cloud based distributed control system that is designed to exchange forecast data across all system parties, which are Users, Control Operators, and Business Units. (fig 14, 15)

Figures 16, 17, 18 show the architecture and main parts of the Oncur project system.

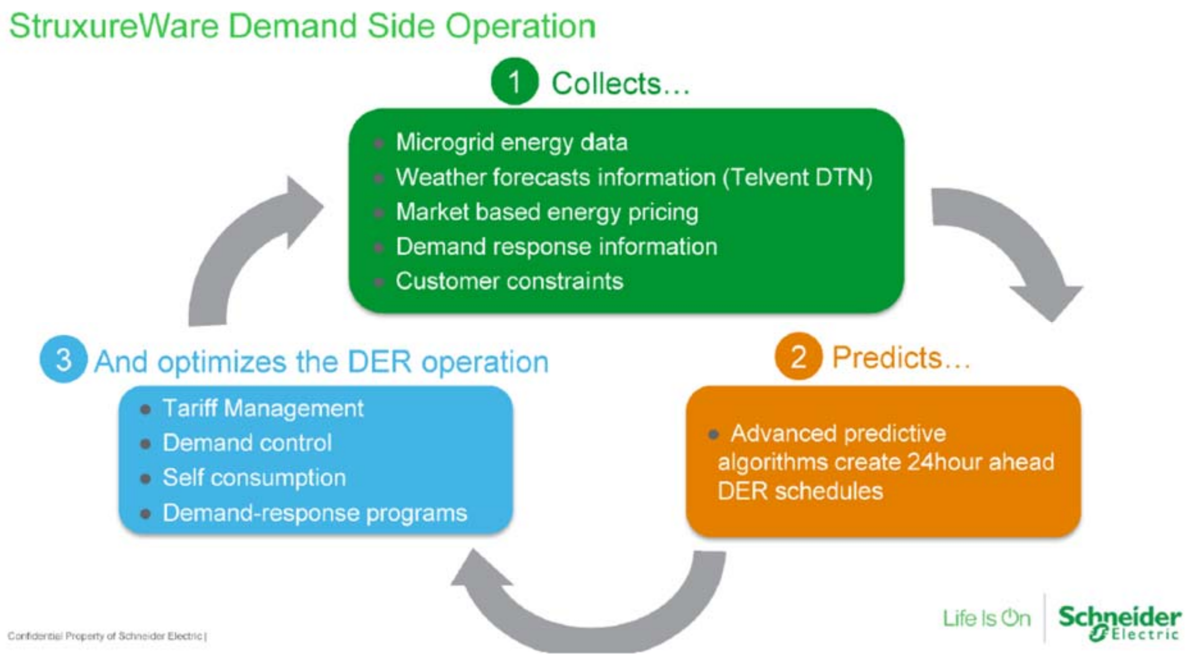


Figure 14 - Structureware Microgrid SCADA system features (S.E., 2016)

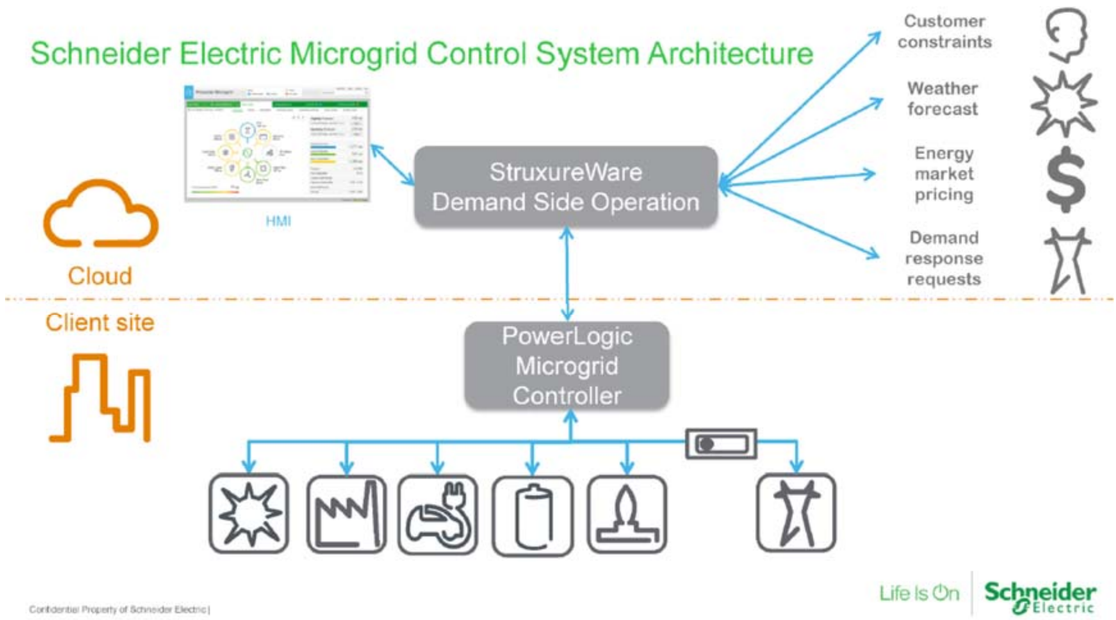


Figure 15 - Schneider Electric Microgrid system architecture; StruxureWare SCADA and Power Logic Controller (S.E., 2016)

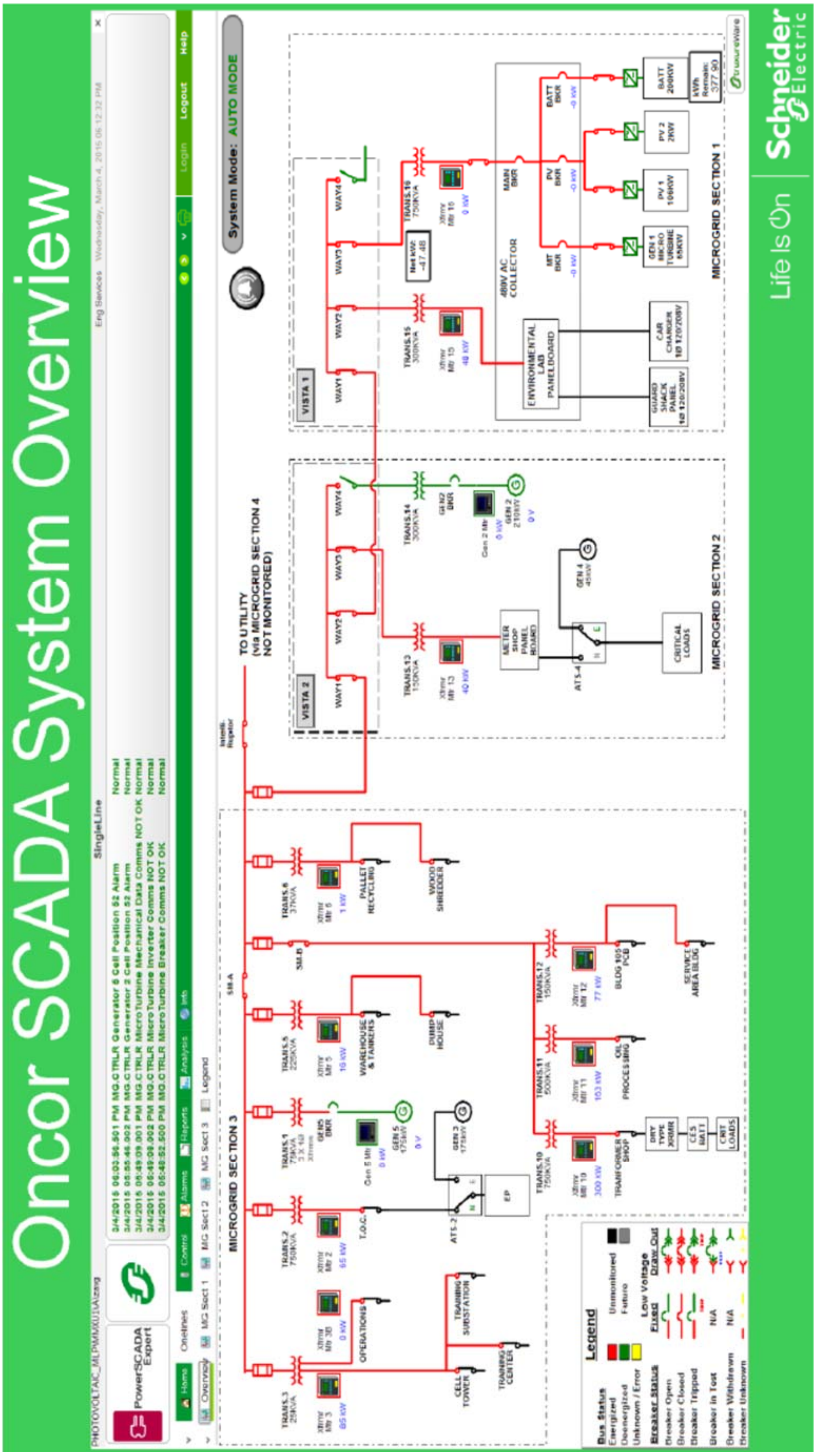


Figure 16 - Oncor Microgrid SCADA system overview graphic display (S.E., 2016)

Figure 17 - Oncur System SCADA Visualization (S.E., 2016)

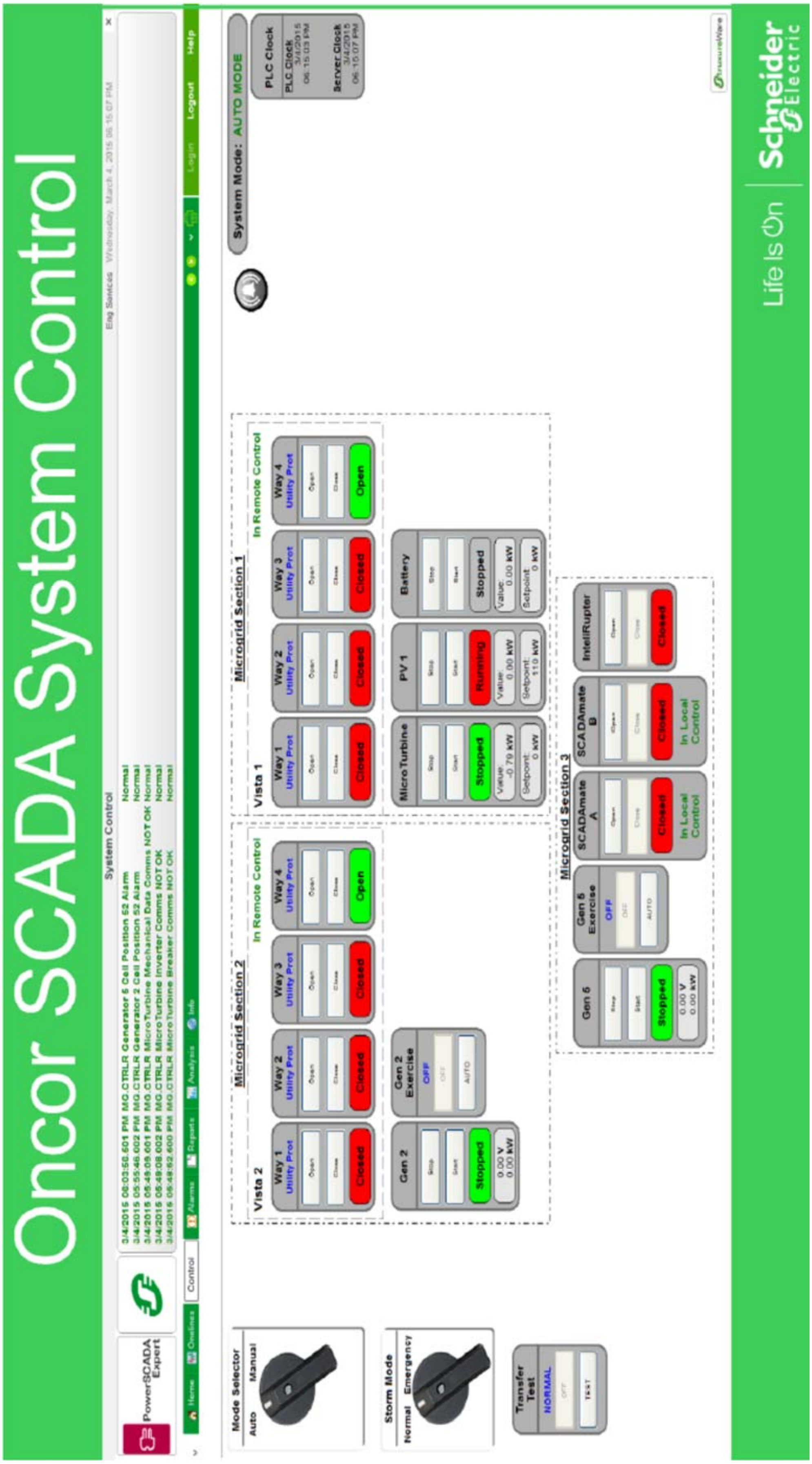


Figure 18 - Oncor Microgrid SCADA system control graphic display (S.E., 2016)

5.3.2. ABB Microgrid control platform

Another product that is designed specifically for Microgrid control is the "Renewable Microgrid Controller MGC600"; a product developed by Asia Brown Boveri ABB. "Renewable Microgrid Controller MGC600" is a Control Hardware Platform that is designed to integrate distributed generation and renewable energy components and devices. These industrial products are very powerful; thus, can be suitable for large scale systems. The system contains various control modules customized for each controllable Microgrid component or distributed generation (fig. 19).

Firmware / Controller	Description
Diesel/Gas generator (MGC600G)	To control, monitor and interface to diesel generators
Distribution Feeder (MGC600F)	To control, monitor and interface to feeders and their protection relays
Photovoltaic Solar (MGC600P)	To control, monitor and interface to solar array inverters
Single/Multiple Load (MGC600L)	To control, monitor and interface to large loads like crushers, boilers, etc.
Hydro generator (MGC600H)	To control, monitor and interface to hydro plants
Energy Storage System (MGC600E)	To control, monitor and interface to the ABB PowerStore™ or other energy storage devices like flywheels and batteries
Network connection of Microgrid (MGC600N)	To control, monitor and interface to other microgrids or larger grids
Wind Turbine (MGC600W)	To control, monitor and interface to wind turbines

Figure 19 - Different software packages to integrate ABB SCADA Microgrid controller MGC600 hardware platform with different Microgrid components (ABB, 2013)

Figure 20 shows various schematics of potential applications for the MGC600 Microgrid control platform.

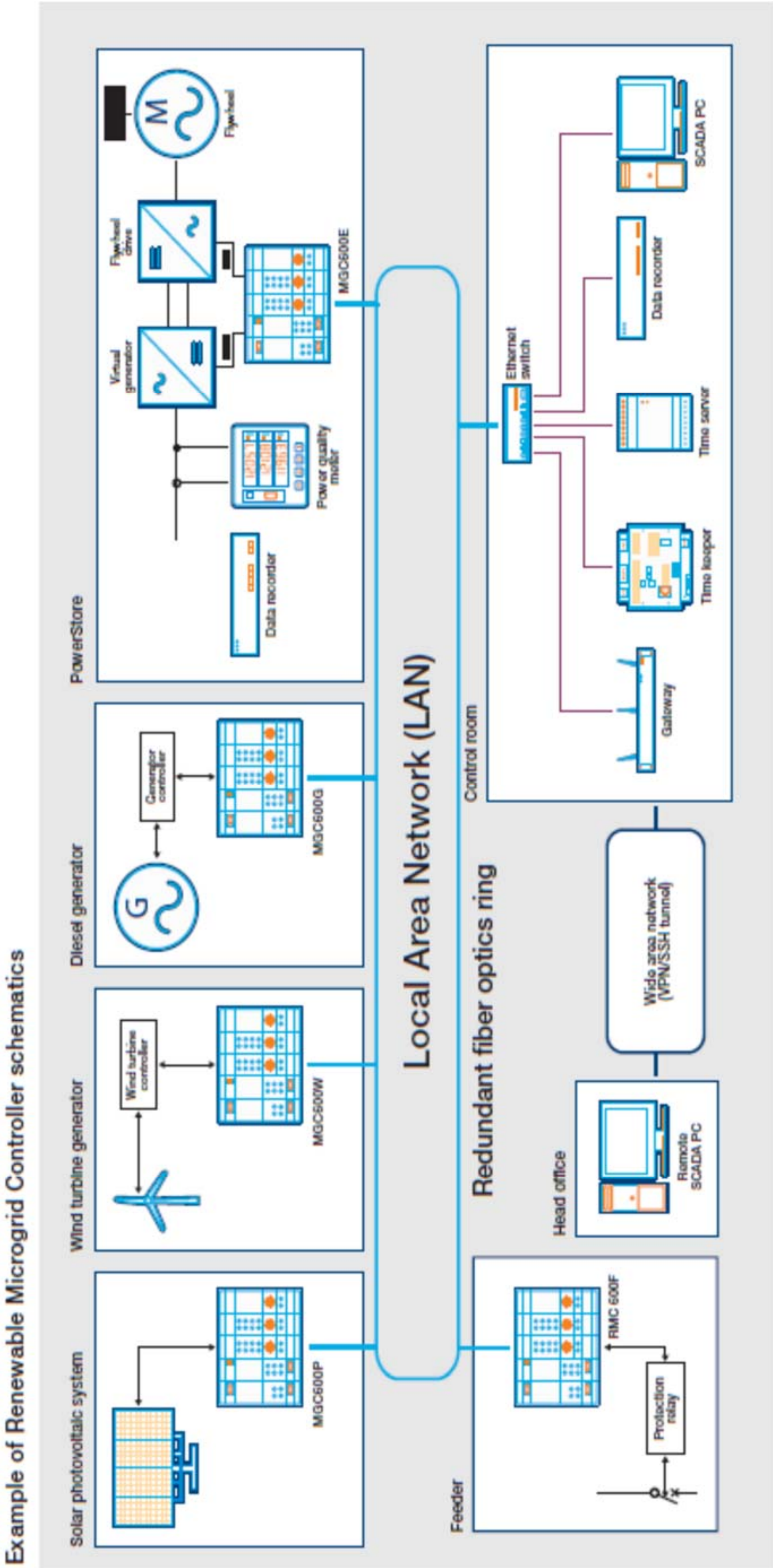


Figure 20 - Examples of MGC600 Controller schematics (ABB, 2013)

6. Modelling Microgrids using LabVIEW and MATLAB + SIMULINK

As discussed earlier, the process of designing a Microgrid project is complex and requires a combination of expertise in a variety of disciplines, to come up with a feasible and attractive solution that would be viable in the market. Modelling and Simulation tools are essential for designing and proposing a mature Engineering solution that is convincing for consumers and investors.

Two of the most popular powerful tools that may be used for offline and real-time modelling and simulation of dynamic systems are MATLB and LabVIEW. The two products have been investigated in this paper for the purpose of modelling and simulating the Microgrid prototype performance, to assess their effectiveness and potential capabilities.

In this Thesis, MATLAB has been chosen for the modelling sample, rather than LAVIEW, for reasons that will be discussed.

6.1.MATLAB+SIMULINK review

First to give an insight of MALAB+SIMULINK and their capabilities, MATLAB is an abbreviation for "Matrix Laboratory" and is a product of an American Company "MATHWORKS". It is intended primarily to act as an offline programming and dynamic simulation environment for mathematical and numerical computations, using a MATLAB exclusive text-based programming language; however, it can be upgraded with a software package "Instrument Control Toolbox", another MATHWORKS product, to interface with physical hardware instruments for real-time control and monitoring. The "Instrument Control Toolbox" software package offers integration with a wide variety of standard communication protocols that include all "National Instruments" hardware products (DAQ, GPIB, Serial, IMAQ, Motion or CAN) (Fig. 21)

Interface / Standard	Manufacturer	Instrument Type
Bluetooth	Agilent	Arbitrary Waveform Generator
GPIB	Anritsu	Digital Multimeter
I2C	Data Translation	Function Generator
IVI	Fluke	Network Analyzer
LXI	JDSU	Oscilloscope
MODBUS	Keithley Instruments	Power Meter
PXI	Keysight	Power Supply
SCPI	Kikusui	Signal Analyzer
Serial	LeCroy	Signal Generator
SPI	National Instruments	Spectrum Analyzer
TCP/IP	Ocean Optics	Switch
UDP	Pico Technology	Other instruments
USB	Rohde & Schwarz	
VISA	Rigol	
VXI	Tabor	
VXIplug&play	Tektronix	
Other interfaces and standards	TTi	
	VTI Instruments	
	Yokogawa	
	ZTEC Instruments	
	Other manufacturers	

Figure 21 - List of Instrument Control Toolbox integrations (N.I., 2017)

MATLAB programming language is text based, but includes a powerful integrated built-in tool a (Graphical User Interface (GUI)), called (SIMULINK), that can be used to construct a block diagram using custom and built in mathematical function blocks, to conduct time based dynamic simulations simultaneously with MATLAB code; MALAB/SIMULINK can be used for offline simulations of mechanical and electrical system models described as mathematical functions..
MATLAB text based programming interface uses an exclusive, proprietary, and user-friendly programming language that, interacts with, and stores mathematical and control variables in the form of arrays or matrices such as [1 2 3] or [1 1 1; 2 2 2; 3 3 3] etc. MATLAB programming language is a fourth-generation language and is object oriented to some degree, which means that It supports Class.Attribute based coding. (Matlab, 2012)

MATLAB+SIMULINK programming environments are interactive and include a graphical plotting feature that can generate and plot either static mathematical functions, or dynamically simulated variables over time. The time variable in SIMULINK is built-in, but can be modified to vary the resolution level of simulations (MathWorks, 2014). MATLAB is advantageous not only for its inclusion of the powerful GUI, SIMULINK, but also for its remarkably rich toolbox library that contains a readily configured and customized mathematical functions for most standard electrical and mechanical engineering components. That can significantly reduce the engineering time and effort consumed to construct a system's model, and was one of the main reasons MATLAB was chosen over LabVIEW for this Thesis work.

6.2. LabVIEW review

Laboratory Virtual Instrument Engineering Workbench (LabVIEW) is a graphical programming environment that is produced by “National Instruments”; an international corporation that produces a wide range of Control and Instrumentation related hardware and software packages. LabVIEW uses a function block based programming language (G) to build function block control diagrams, comprising affiliated interactive graphical objects that can be used as a Human machine interface (HMI) for monitoring and control of a system. It was developed primarily to be used for hardware instruments control and monitoring. LabVIEW acquires process instruments real-time data through Data Acquisition (DAQ) built-in protocols, to compute and control through a function block based graphical representation.

LabVIEW programming structures the code into subroutines called VI (Virtual Instrument). Each VI consists of three components (windows): a graphical control interface, a function block diagram, and a connector panel, to display the linkages with other VIs. VIs are intended to be used for structuring and managing the control application; each VI can contain the controls for one instrument or more, an area of the process, or a full system model, depending on programming strategy of the user. VIs can also be assigned different execution rates and order, which can be useful in structuring large applications, where a variety of types, criticality and priority of instruments is operated. In large real-time applications, configuring all instrument blocks with the same execution rate can consume the CPU memory; hence, cause run-time errors, instability, or inefficient performance. LabVIEW code execution order is based on the block diagram dataflow order, unlike the text-based code that is executed in based on the code instructions, such as in MATLAB. Function block based control applications are easier to visualize and interact with which makes it easier to use to monitor and control a live system.

LabVIEW inclusion of combined control diagrams, and operation interface objects, make it ideal for resembling SCADA and DCS systems similar to the ones that were discussed previously. To illustrate, LabVIEW software would act as the Human Machine Interface (HMI) and control platform, while the computer processor would simulate the industrial control processor (The Programmable Logic Controller PLC).

LabVIEW can install the “Math Script RT” module to import, build, customize and integrate text-based MATLAB codes (code.m) with the Graphical G code; in more precise words, this add-on module also enables developing LabVIEW Subroutines in MATLAB code. The “Control Design and Simulation” module is required for dynamic simulations regardless of which code is used (MATLAB, 2012). To embed a MATLAB script inside LabVEIW, a MATLAB license is required on the computer used.

LabVIEW code is graphically oriented, which means that the code must be embedded within the graphical objects (function blocks and Vis); that is unlike SIMULINK GUI where the text code runs in the MATLAB and the variables need to be declared in MATLAB “workspace”, then interfaced with the SIMULINK functions in order to function simultaneously. Another advantage of LabVIEWis that its subroutines (VIs) can be converted using an add-on “Math Interface Toolkit” into a MATLAB MEX-function and imported into MATLAB in a DLL format.

LabVIEW can be used to communicate with SIMULINK graphical interface to operate the SIMULINK model. (FIG. 22)

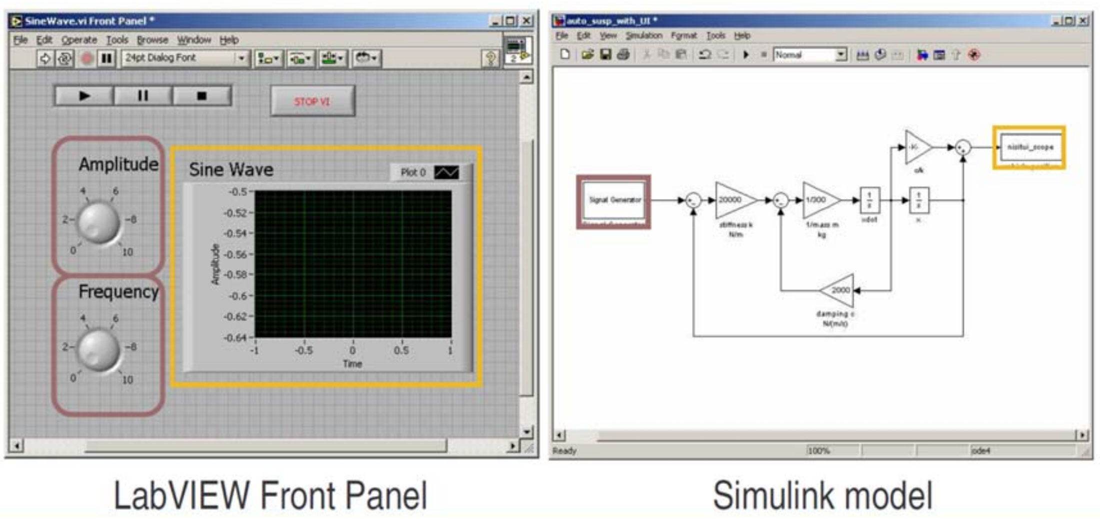


Figure 22 - Using Labview to monitor and control a SIMULINK model (Tillet, R., 2011)

LabVIEW can also be used to import the SIMLINK built model and migrate (convert) it into LabVIEW Graphical code "G" using the add-on module "Control Design and Simulation Module", which can convert .mdl files into LabVIEW VIs (FIG. 23, 24)

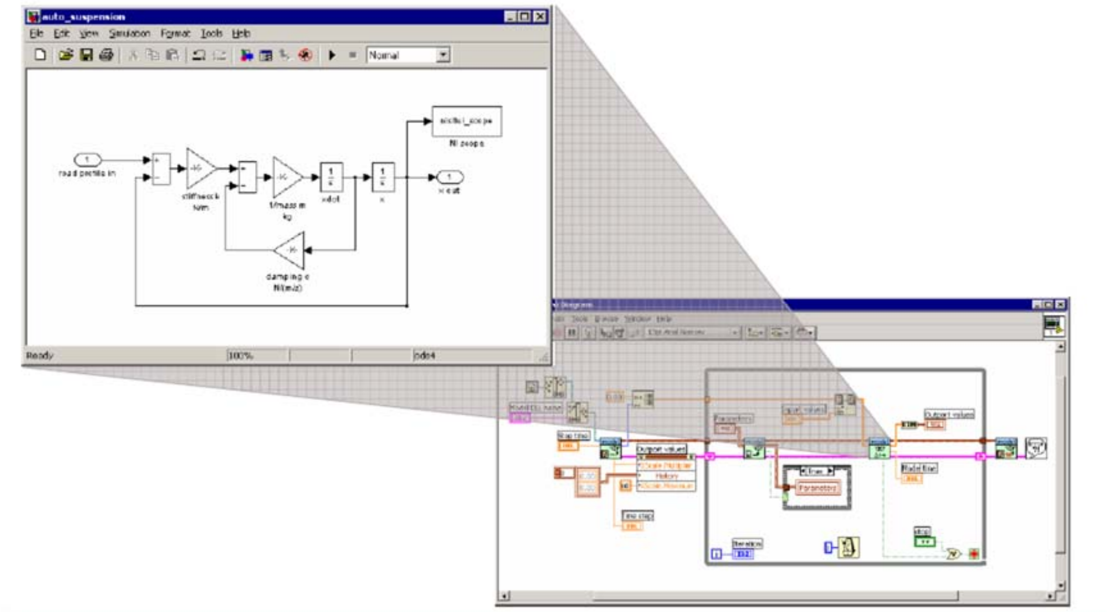


Figure 23 - Migrating a SIMULINK model to Labview (Tillet, R., 2011)

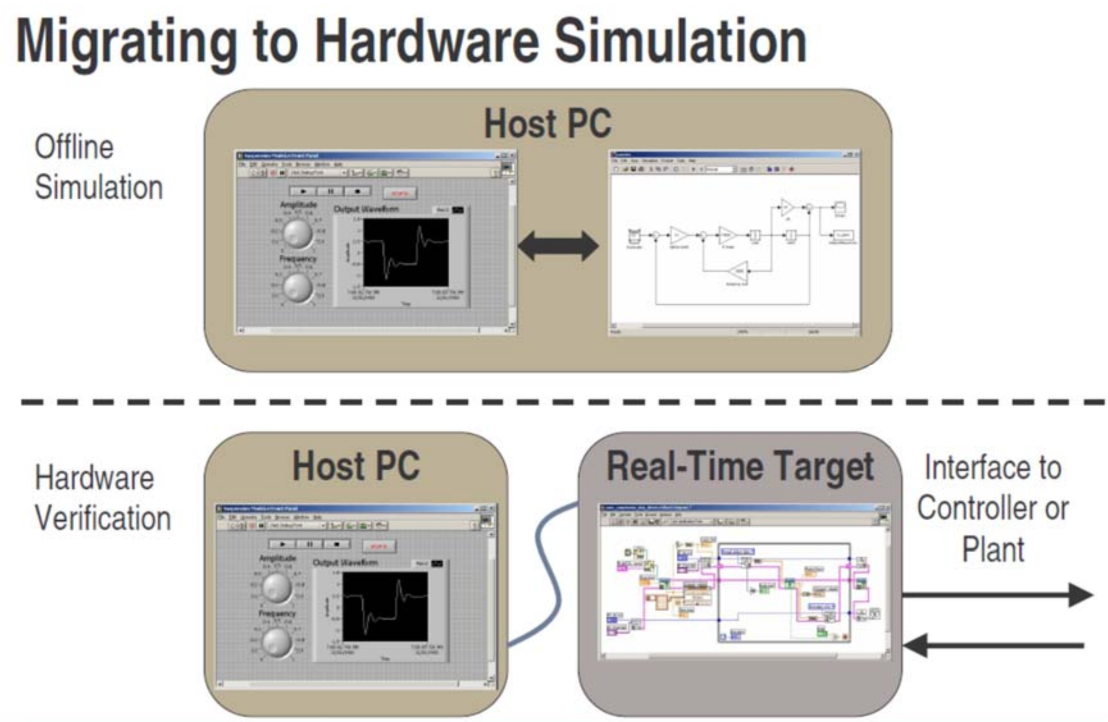


Figure 24 - Migrating a SIMULINK model to Labview for hardware simulation (Tillet, R., 2011)

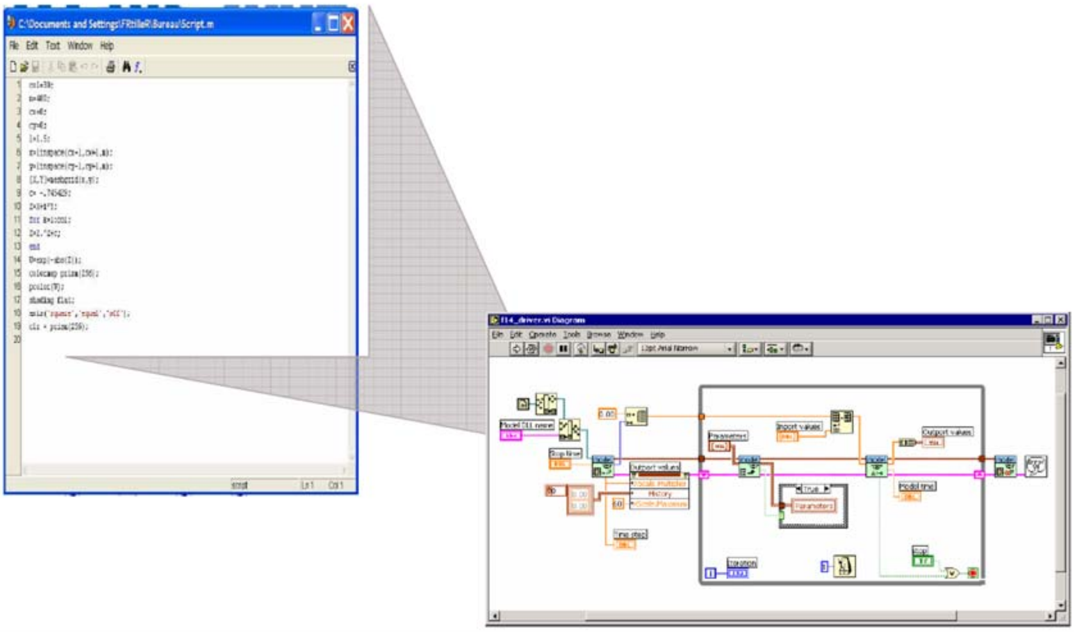


Figure 25 - Using Labview code in Labview function blocks (Tillet, R., 2011)

These integrations make it convenient to migrate projects from MATLAB or carry on combined engineering using both software platforms.

6.3.LabVIEW applications

Several methods were identified to simulate a Microgrid prototype in LabVIEW

- Using Multisim standalone software

Multisim is a product by National Instruments for Electronic circuits design and dynamic simulation; offline and real-time using hardware. The software package includes a sophisticated toolbox library of standard electronic components that are used in power electronics and renewable energy systems. That is a specialized software that is expected to be superior to SIMULINK; it is not available for free use; however, the student edition is available for a cheap price.

6.3.1. Using LabVIEW combined with the "Control Design and Simulation toolkit" add-on.

The toolkit is designed for dynamic simulations for systems that are built in LabVIEW; However, the Microgrid system/model would need more effort to be built in mathematical equations using the LabVIEW graphical programming language, as there is no power electronics specific library associated with the package.
The paper by Lucia - Andreea MITULEŢ1 was identified that has used this method to build and simulate a model of a small scale Microgrid for a case study proposal. The mathematical equations implemented in the control diagram are published in the paper.

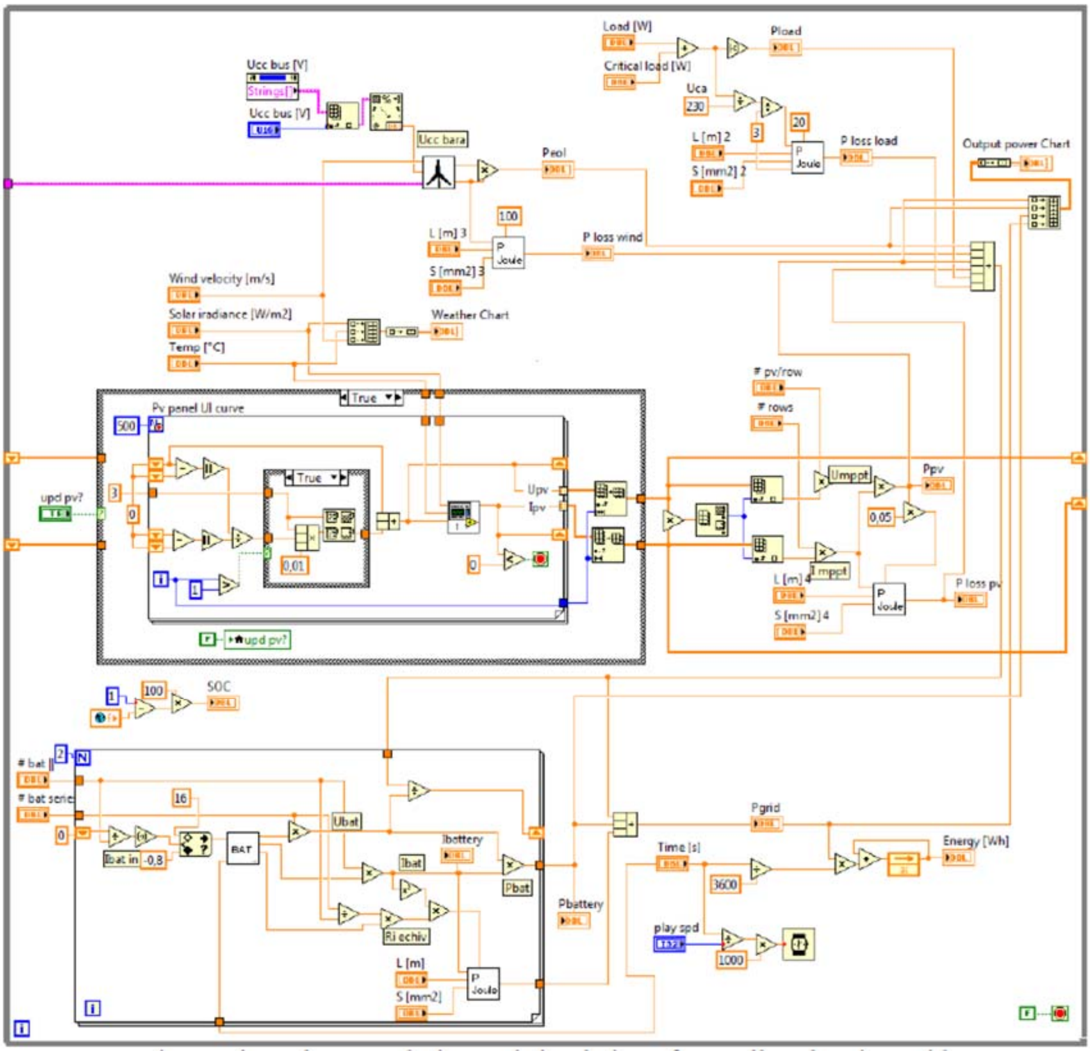


Figure 26 - LabVIEW design and simulation of a small scale microgrid (Nicolaie, S. et.al., 2016)

6.3.2. Using LabVIEW combined with Single-Board RIO embedded controller

National Instruments is specialized in Instrumentation and Control; the company offers a plethora of hardware and software that cover almost all applications in the mentioned discipline. One of the products that has been used in Microgrid applications is the Single board controller "Single-Board RIO", which is an embedded controller board that can be programmed using LabVIEW to function as a control processor interfacing with various field instruments. (fig. 27)

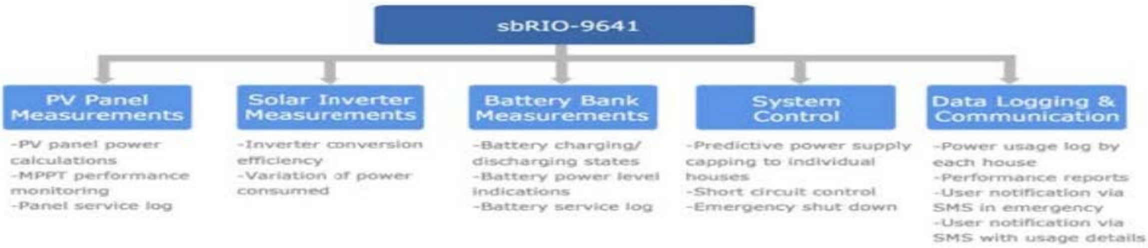


Figure 27 - National Instruments sbRIO-9641 embedded control board features (Shankar, G., 2017)

In this research, two projects have been identified that have used the Single-Board RIO; The first is an actual project that was implemented in India; an Island Microgrid has been designed by a company named FluxGen Engineering technologies, an Engineering company in India that develops Renewable Energy solutions. Using the National Instruments Single Board RIO sbRIO-9641 embedded controller and LabVIEW the company developed a control application to monitor and control a Microgrid system that has been installed and commissioned successfully in Mendel village, Belgaum, Karnataka, India. Pvt. Ltd. (fig. 28).

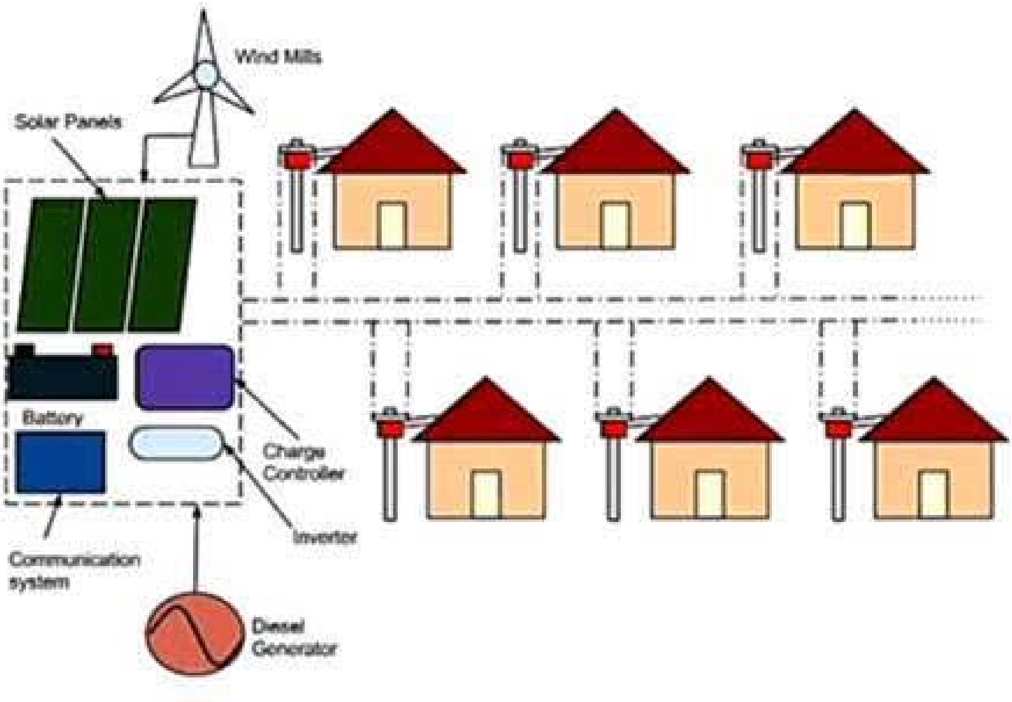


Figure 28 - Flux Engineering Microgrid case study using LabVIEW and National Instruments SBRIO Board (Shankar, G., 2017)

As seen in the figure, the Microgrid designed consisted of a Solar farm, an emergency diesel generator, battery storage, inverters; the windmill is just for demonstration but was not installed. According to FluxGen, combining battery storage and solar power generation in a centralized form significantly reduced the cost of electricity than installing individual solar panels and batteries for each of the houses (decentralization). The communication system allows remotely controlling the Microgrid through the internet. Similarly, for testing and simulation, the RIO board can be programmed and monitored using LabVIEW software while using simulation hardware to Mimic the Microgrid instruments in real time, while monitoring and recording the data. A project has been implemented in that manner by (Petrochenkov, Anton, et al., 2014); a National Research Polytechnic University, where the students have simulated a Microgrid that is monitored and controlled by a SCADA system. The project was implemented using National Instruments control and instrumentation hardware; in addition to LabVIEW acting as Human Machine Interface HMI, and hosting the master control application. An RIO board was programmed to perform the live real-time control and monitoring. (fig. 29, 30, 31, 32)

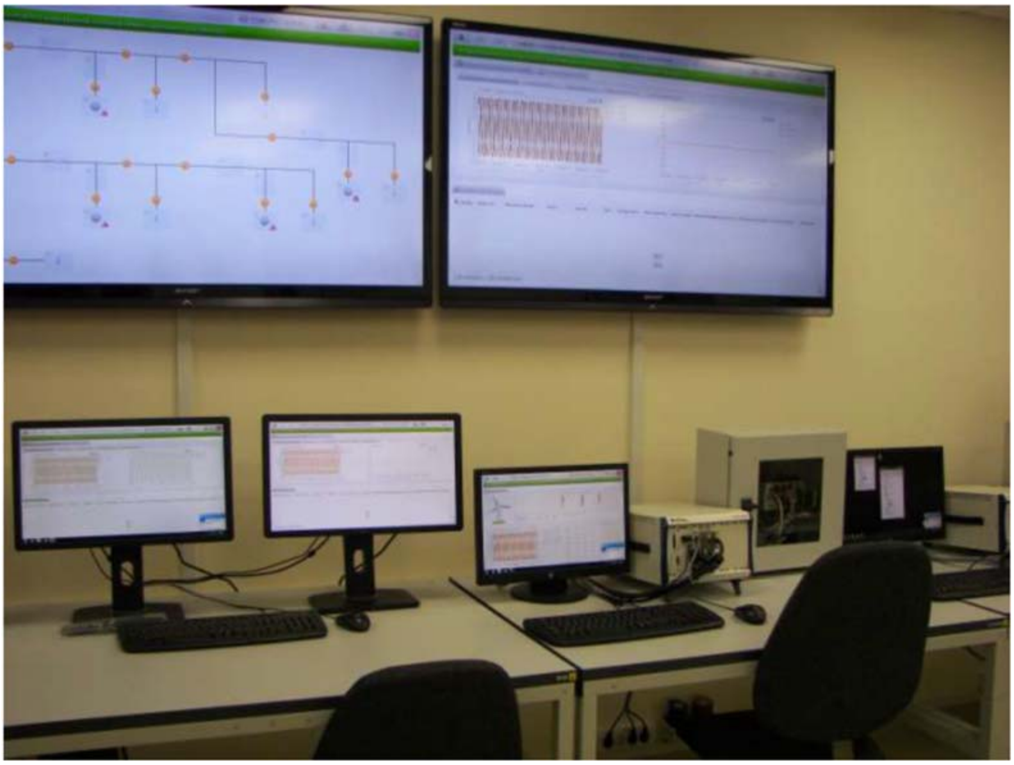


Figure 29 - SCADA System using Labview at Perm National Research University in Russia (Petrochenkov, Anton, et al., 2014)

Figure 30 - Microgrid Simulation hardware at Perm National Research University; simulating micro sources and loads using National Instruments Hardware (Petrochenkov, Anton, et al., 2014)

Figure 31 - National Instruments RIO embedded controller with National Instruments IO cards

(Petrochenkov, Anton, et al., 2014)

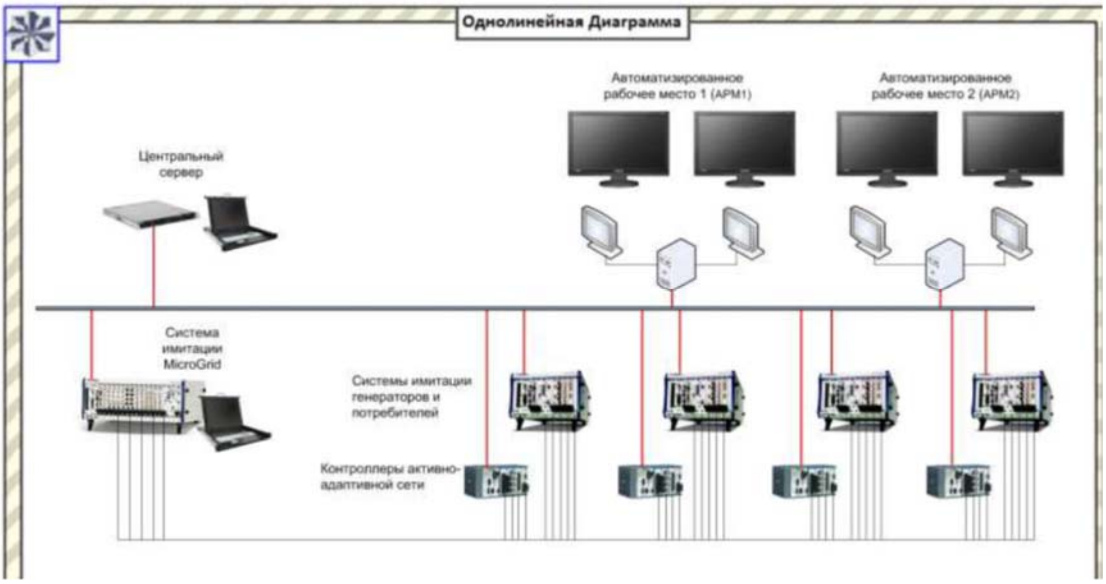


Figure 32 - Microgrid SCADA test environment established by Perm National University in Russia

(Petrochenkov, Anton, et al., 2014)

6.3.3. Combining LabVIEW with MATLAB+SIMULINK

A research was conducted using LabVIEW and SIMULINK to simulate a hybrid power generation system. The research used MATLAB+SIMULINK to establish the Wind power mathematical computations; the research (Lu, N. & Yi, L., 2015) concluded that: “MATLAB interface is poor and not intuitive and is complex in data input”; hence, interfaced the MATLAB+SIMULINK with the LabVIEW as an operation and control interface. LabVIEW usage was not included in this Thesis as the operation interface was not required, and the Microgrid model was developed only for demonstration.
To establish the communication between LabVIEW and SIMULINK, the LabVIEW add-on Simulation Interface Toolkit (SIT) was installed, which is developed particularly to interface LabVIEW with Math Works products via TCP/IP; by investigation, it has been found that this add-on is now obsolete and its functionality has been migrated to LabVIEW Model Interface Toolkit (N.I., 2017).

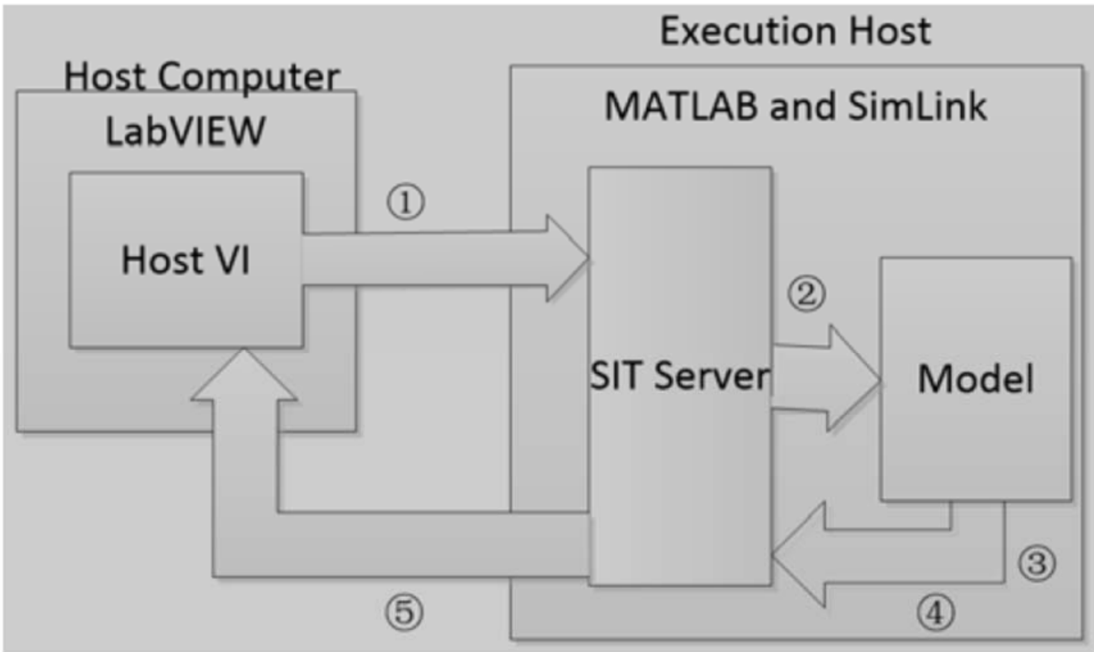


Fig. 1. Interface between LabVIEW and Simulink.

Figure 33 - Communication between LabVIEW and Simulink using Simulation Interface Toolkit (SIT). (Lu, N. & Yi, L., 2015)

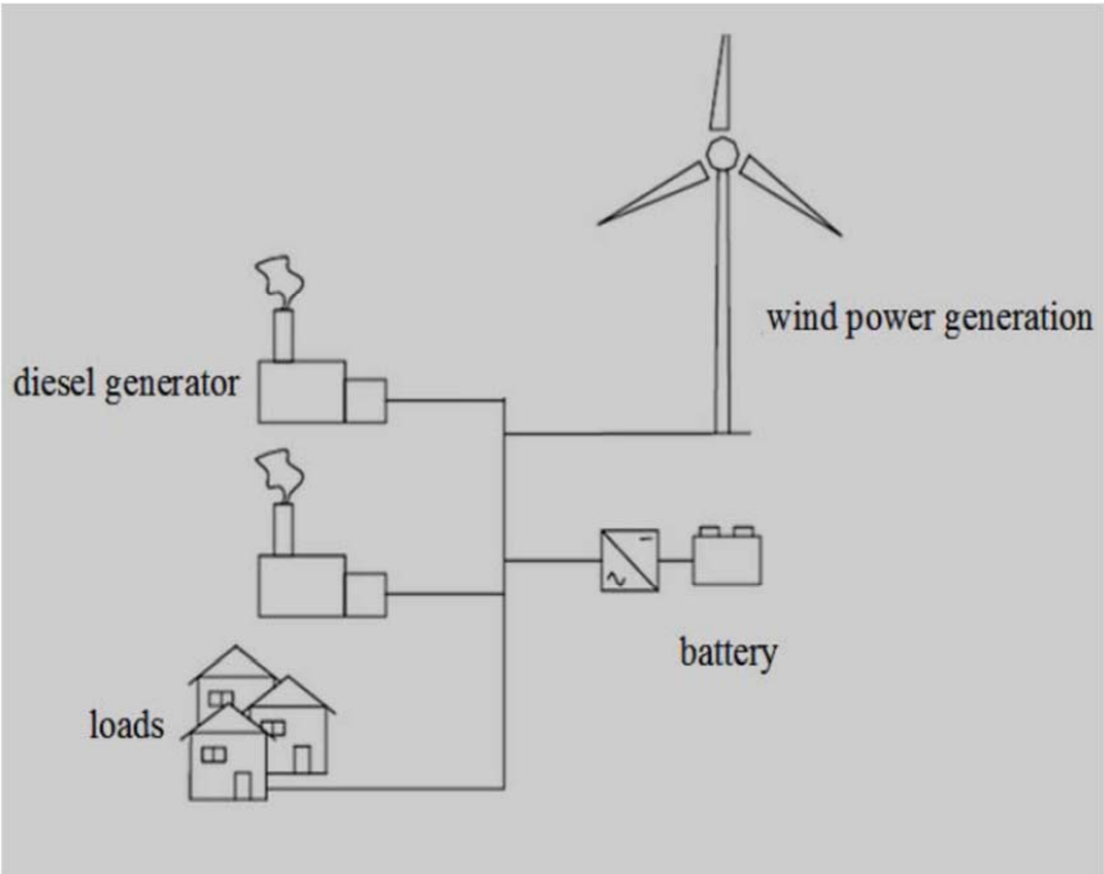


Figure 34 - Hybrid Energy structure simulated using Labveiw and SIMULINK (Lu, N. & Yi, L., 2015)

As shown in figure 34, the system consists of hybrid supply source of Wind and diesel generators, battery storage and a variable load. That is similar to the MATLAB model create in this Thesis; however, in this thesis, Solar PV was also used and connection to the main grid.

Figure 35 shows the LabVIEW graphical interface that was developed for operating the system; as shown, the interface consists of analog and digital values, indicators, setpoint inputs, and push buttons for analog and digital inputs to the system; that is a good demonstration for the previous SCADA section.

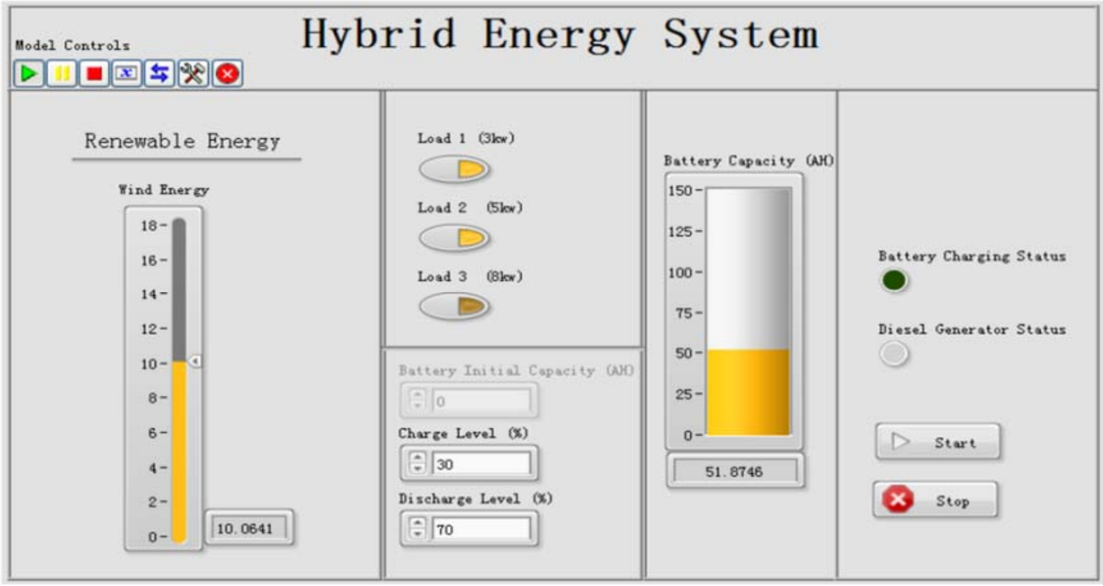


Figure 35 Simulation Operation Interface of the Hybrid Energy System using Labview. (Lu, N. & Yi, L., 2015)

6.3.4. Using LabVIEW to Simulate a SCADA system using a Programmable Logic Controller.

A PLC is an industrial controller (control processor) that is optimized for industrial usage, it can be considered as an embedded control board (similar to the RIO board) that has been enhanced with casing, connection ports, communication cards, memory cards, and power supply. PLCs are usually programmed with higher level programming language and integrated dedicated software.

A project has been implemented, at Nanyang Technological University, that used LabVIEW to develop a control application and HMI to control a group of instruments simulating a Microgrid (fig. 36). Figures 37, 38, and 39, show some highlights of the project.

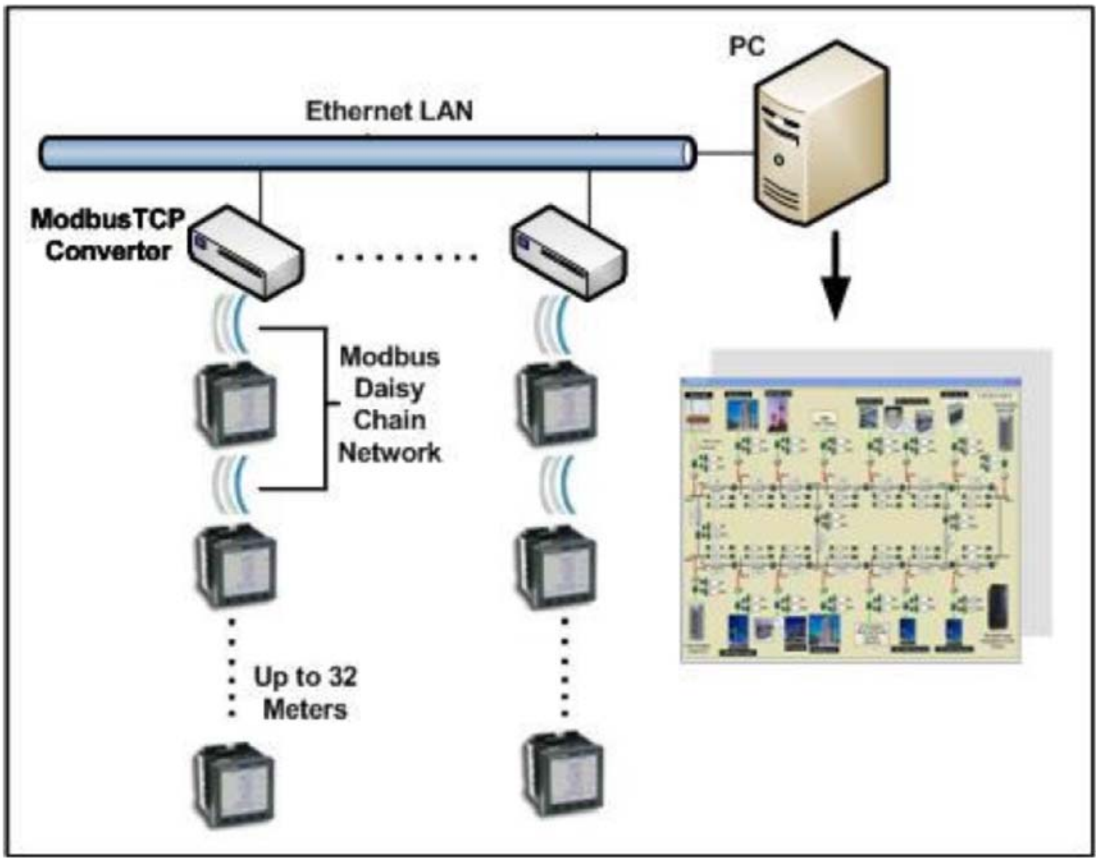


Figure 36 - LabVIEW instrumentation control using Modbus communication protocol (Nanyang uni., 2011)

Figure 37 - Sample of equipment used for Microgrid simulation (Nanyang uni., 2011)

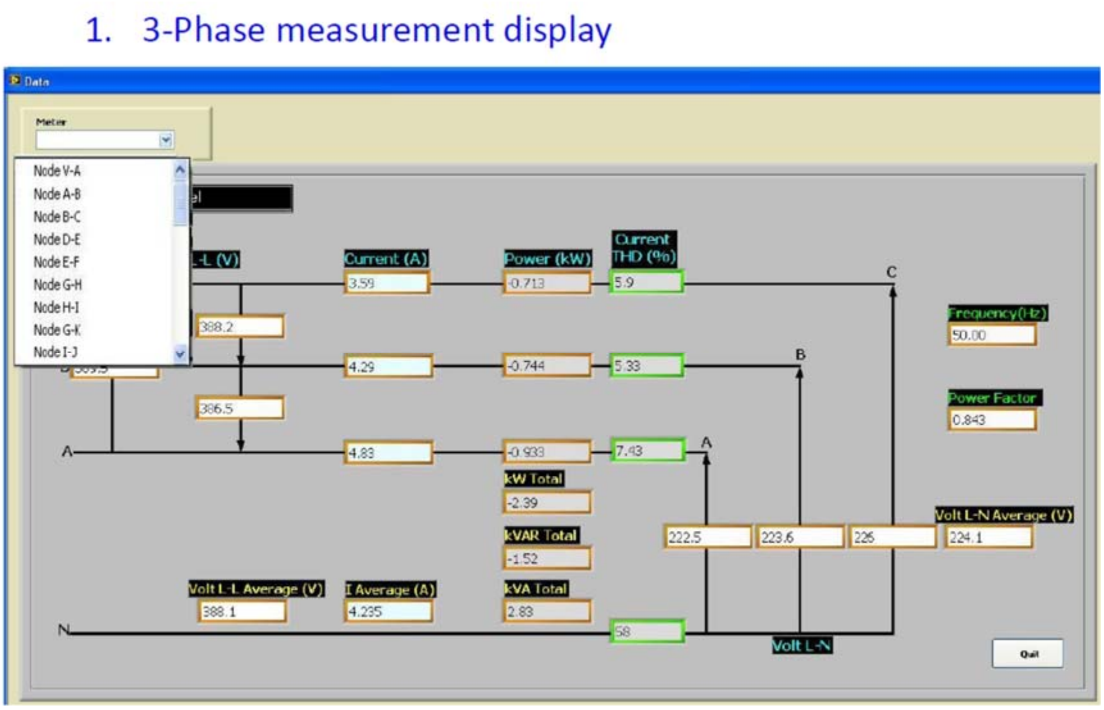


Figure 38 – Microgrid SCADA monitoring graphic display using LabVIEW (Nanyang uni., 2011)

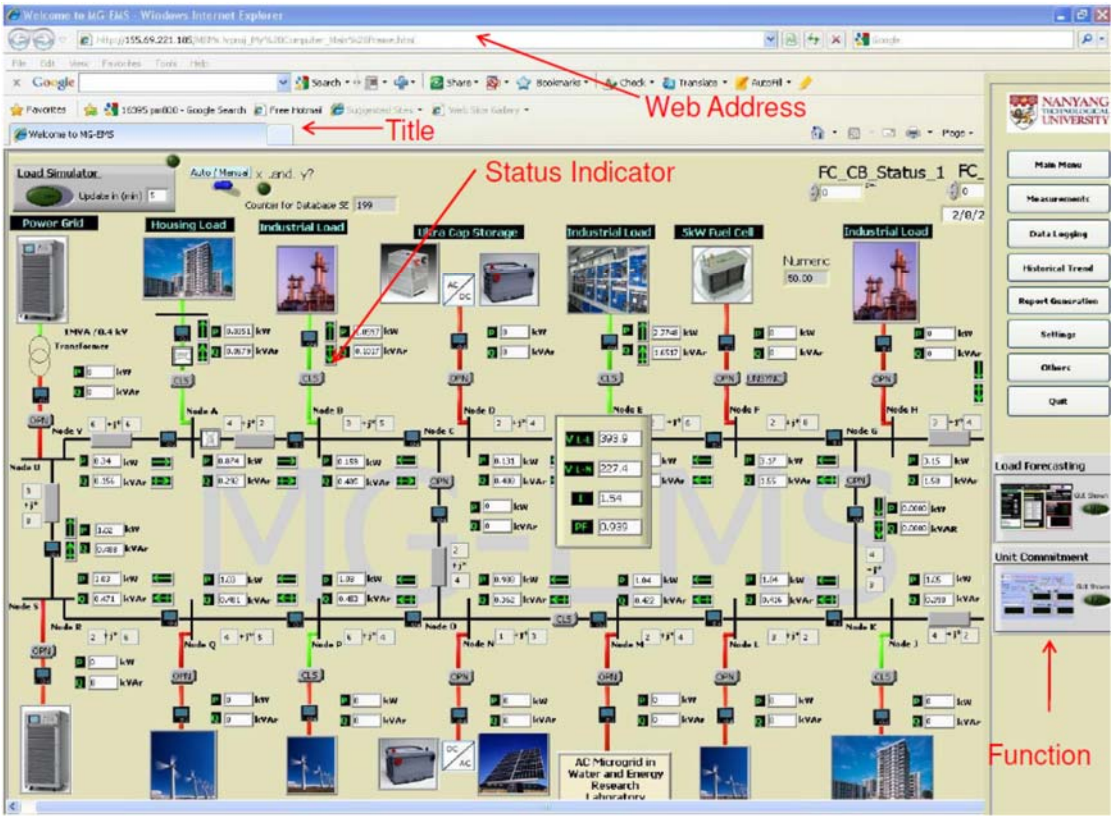


Figure 39 - Microgrid SCADA monitoring graphic display, web browser integration using Labview, for remote access (Nanyang uni., 2011)

7. Modelling using MATLAB+SIMULINK

Modelling Microgrids and renewable energy systems is essential during their design phase, to predict the behaviour of the systems under different circumstances and estimate the cost, challenges, risks and expected outcomes. Modelling is also crucial to develop efficient and reliable control algorithms and strategies, which aids in optimizing performance. Modelling and simulation can also help reducing the initial capital cost by selecting the most ideal system specifications.

A series of online trainings provided by MATWORKS have been undertaken to aid in this research; following that, a MATLAB+SIMULINK model has been designed in coordination with a specialized MATLAB+SIMULINK code developer "MATLAB SOLUTIONS" (Matlabsolutions.com, 2017) that has provided remarkable technical support, which was very effective in the learning process. The model has been developed to resemble a residential community, and to demonstrate how Modelling and simulation software applications can be used to analyse Microgrid performance, while hoping that this work contributes and inspire further research and development in the Strathclyde University. The simulation was run offline, without any hardware components to simulate the loads and generation.

The model created consists of a locally centralized Solar Farm, wind turbine, Battery storage, diesel generator; in addition to a connection to the main grid, and a variable load to resemble the small community energy consumption; the diesel generator works in case of the unavailability of renewable sources. The model is fully flexible, editable, and can be upgraded with a control algorithm, to test its outcome on the Microgrid model performance over time; control optimization was discussed in a previous section. The model control for the Load, generation, and storage, is linear; and is based on the availability of the generation sources; however, in the future, a control code can be written in MATLAB to orchestrate generation sources. The work was done using SIMULINK standard library blocks based on several research papers. Each part of the model is discussed in the following sections and described using MATLAB+SIMULINK Documentation. As mentioned earlier, this model is built for linear simulation, using phasor equations, at a specified frequency, to assess the power, energy and load consumption in a time variable. The model doesn't compute the differential equations for power quality and wave form; nevertheless, that can be customized in future work. The simulation can be used to estimate the energy cost, the ideal specifications for microgeneration sources and battery storage; and most importantly, to test and simulate the overall performance of control algorithms that can be used to for generation and storage interaction.

Simscape Power Systems™ is the standard SIMULINK library that was used mainly in this project. It consists of a comprehensive database of electric components, and modelling and analysis tools for electric power systems. The Library is also designated to develop and test control systems in integration the electric power ones; that makes it very suitable for Microgrids modelling.

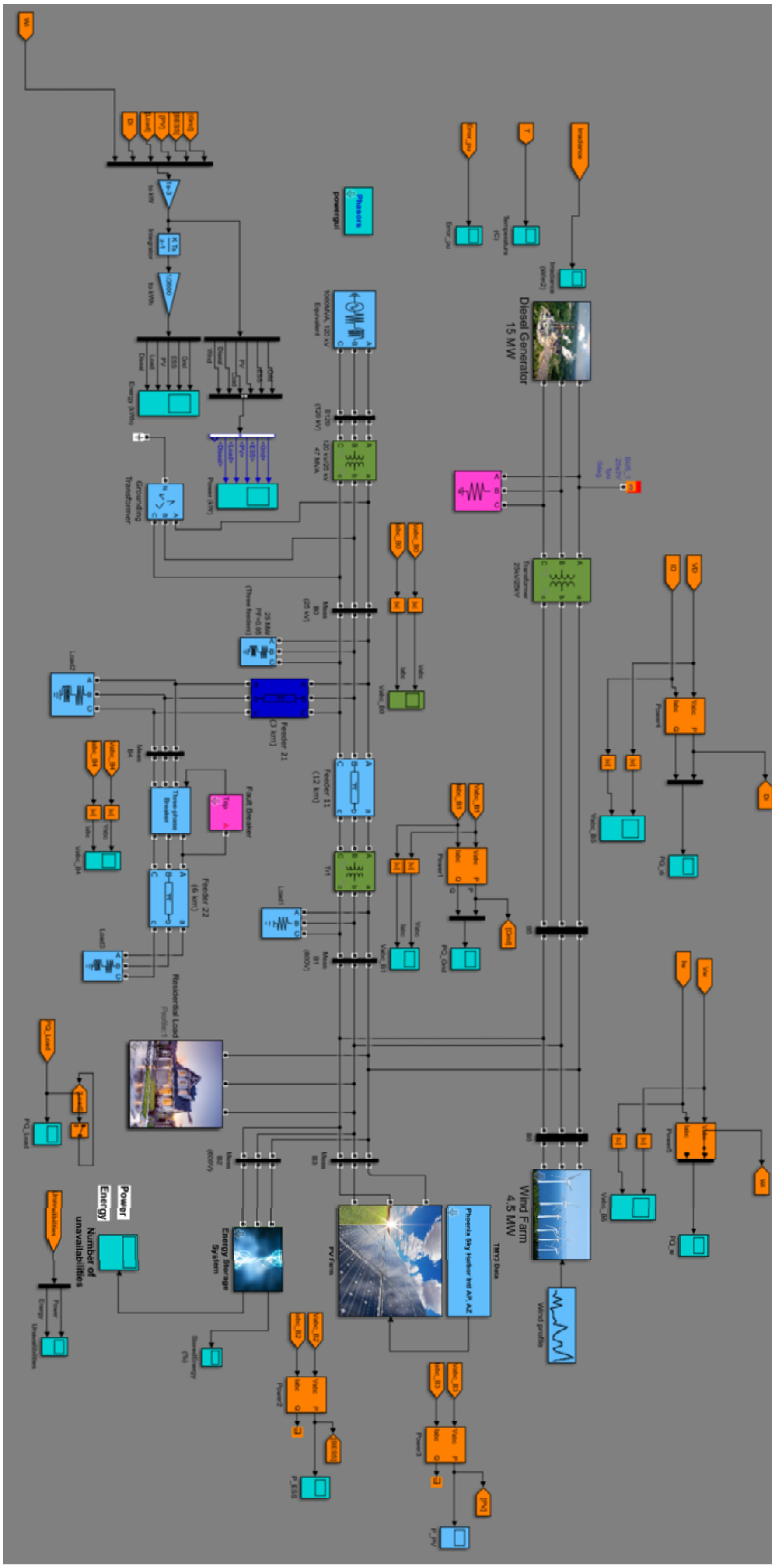


Figure 40 – Full project Microgrid Model using SIMULINK (Snapshot)

7.1.Model parts

7.1.1. Solar PV farm

Solar energy is the most abundant source of energy, and is the fundamental source of every form of energy that exists on earth. Solar energy is delivered to earth in the form of electromagnetic radiation of a range of wavelengths, and intensities that are relative to their inclination and travel distance. Solar radiation strikes earth directly in the form of direct radiation; however, some radiation scatters while travelling through the clouds and atmosphere producing diffuse radiation. Solar Photovoltaics (PV) are capable of harnessing both types of radiation; which makes it very useful in the UK and Europe, as a majority of their available solar energy is in the form of diffuse radiation (Boyle, G., 2012). Solar PV is the most convenient and flexible renewable energy source, as its size can be customized to suit the size of application, regardless of how small it is, which is relatively not the case for wind power, where capacity is limited to larger applications; often, PVs are installed at individual buildings for individual use, but also can be aggregated to a single centralized solar farm, which was the choice for this project model and similar to the project discussed at section 6.3.2 (fig.28).

PV Solar panels have prospered noticeably in the recent years as their cost feasibility has become much higher. In the current market, Solar PV defeats any other renewable technology in terms of feasibility and potential. Figute 41, shows a zoom at the part of the PV model.

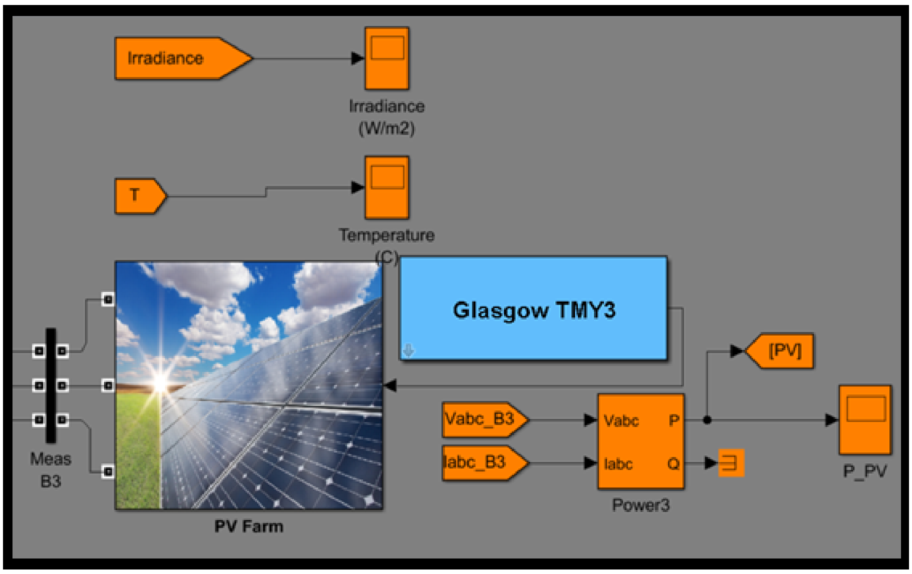


Figure 41 - Solar PV farm model overview

The PV farm is meant to represent a group of solar photovoltaic panels of a given total surface area and efficiency. The system was designed to feed electric power to the grid based on prescribed weather and Solar data. The system consists of two function blocks PV Farm and TMY3 (Typical Meteorological Year), both together calculate the estimated power fed to the grid per unit time. The Orange indicator blocks: Irradiance (W/m^2), Temperature (C), and P_PV, are “Scope” blocks that are used to display the simulation results per unit time.

Solar irradiance is the electromagnetic radiation per unit area (W/m^2) measured perpendicular to the sun rays. Each part of the model will be discussed in details.

7.1.1.1. TMY3 Data

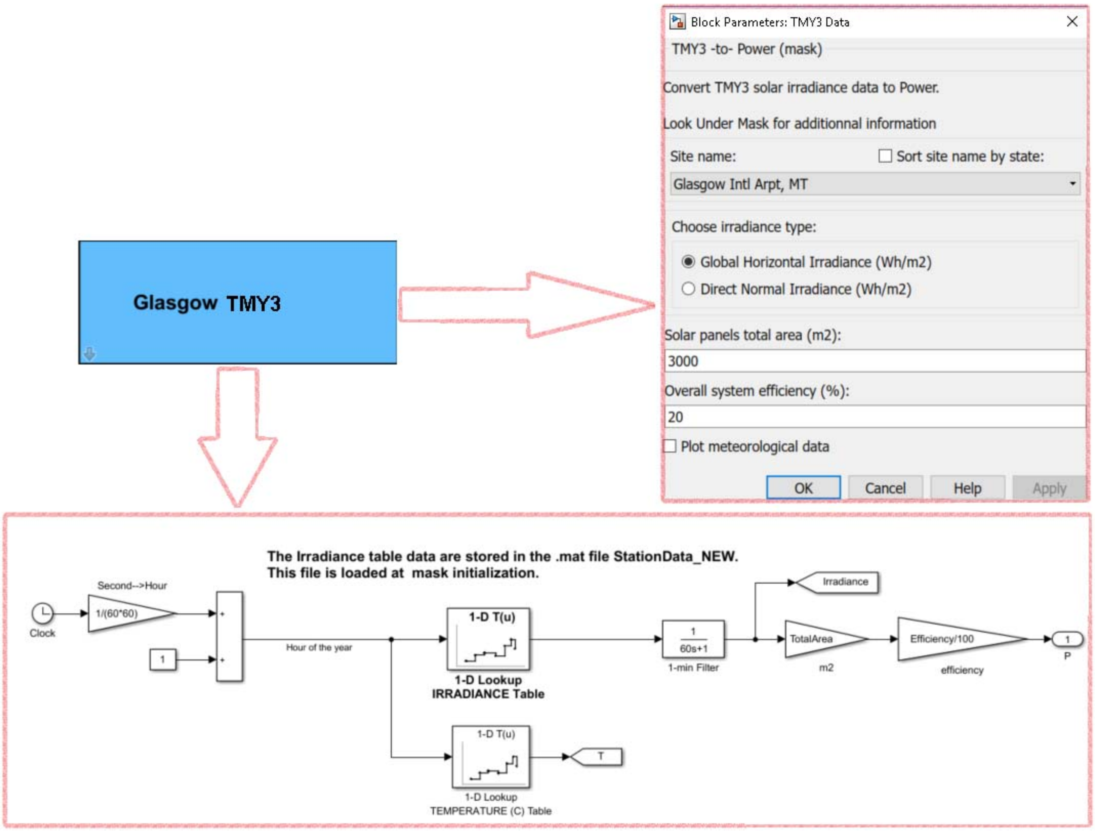


Figure 42 - TMY3 for solar irradiance data Block details

Typical Meteorological Year is the average one-year period weather data for a certain geographical location based on broad range of data. Typical Meteorological Year is used to predict the energy performance during building design (Wilcox, S. et al., 2008).

The figure 42 shows a breakdown of the TMY3; at the top right of the figure is block entry parameters; it is possible to specify the total surface area of the solar panels and the power generation efficiency before starting the simulation. In the bottom the figure shows the functions used to calculate the expected power output (watts). The clock block generates the time/year in seconds as an integer, the gain block is used to convert the time into hour/year, were 1 year has 8760 hours.

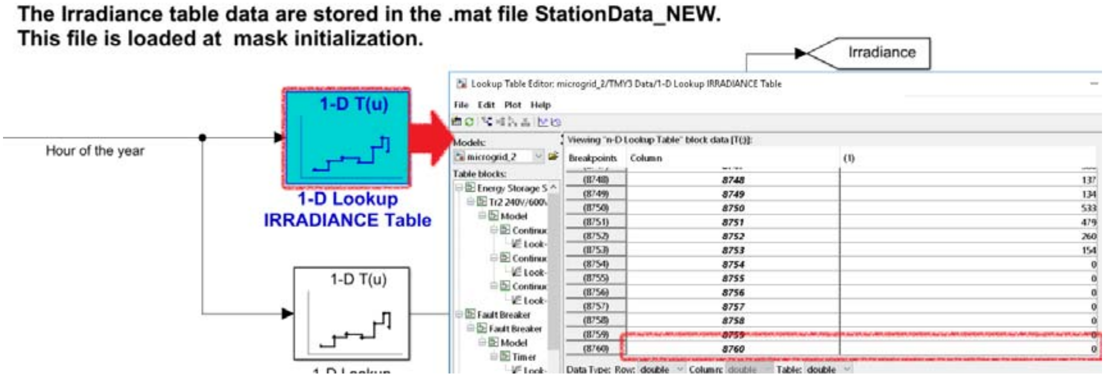


Figure 43 - Solar irradiance profile lookup table block

Within the TMY3 block, the look up table blocks are used to determine the solar irradiance and weather at the given input hour; 8760 hours in total (fig. 43). Solar irradiance is defined in the lookup table as Watt hour / m^2; that is then multiplied by the total surface area of the solar panels and the efficiency to calculate the power output (P) in Watts.

7.1.1.2. PV Farm

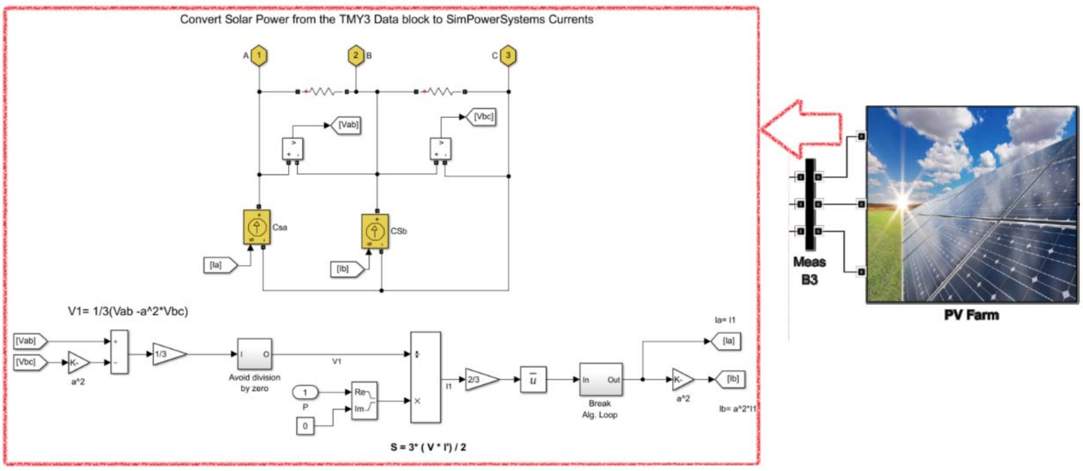


Figure 44 - PV farm generation block details

As shown in figure (44) The Power (P) is then used to calculate the Real Power S = 3* (V * I) / 2. This standard loop in the bottom og the figure computes the line to line voltages Vab and Vbc, and line voltages and currents Va, Vb, Vc. Ia, Ib, Ic from the power output of the solar farm to be supplied to the three-phase grid. The same circuit is used at every microgeneration model for the same purpose. Using the equation: V= $1/3(V_{ab} - a^{\wedge 2} * V_{bc})$

7.1.2. Dynamic Residential Load

The Residential Load is a variable three phase dynamic load designed to change according to prescribed Load Profile per unit time. The load profile is defined for per hour, for one day, for simple simulation; however, higher resolution can be made. The Load Profile block does an interpolation between the three columns to estimate the load at the given hour (fig. 46).

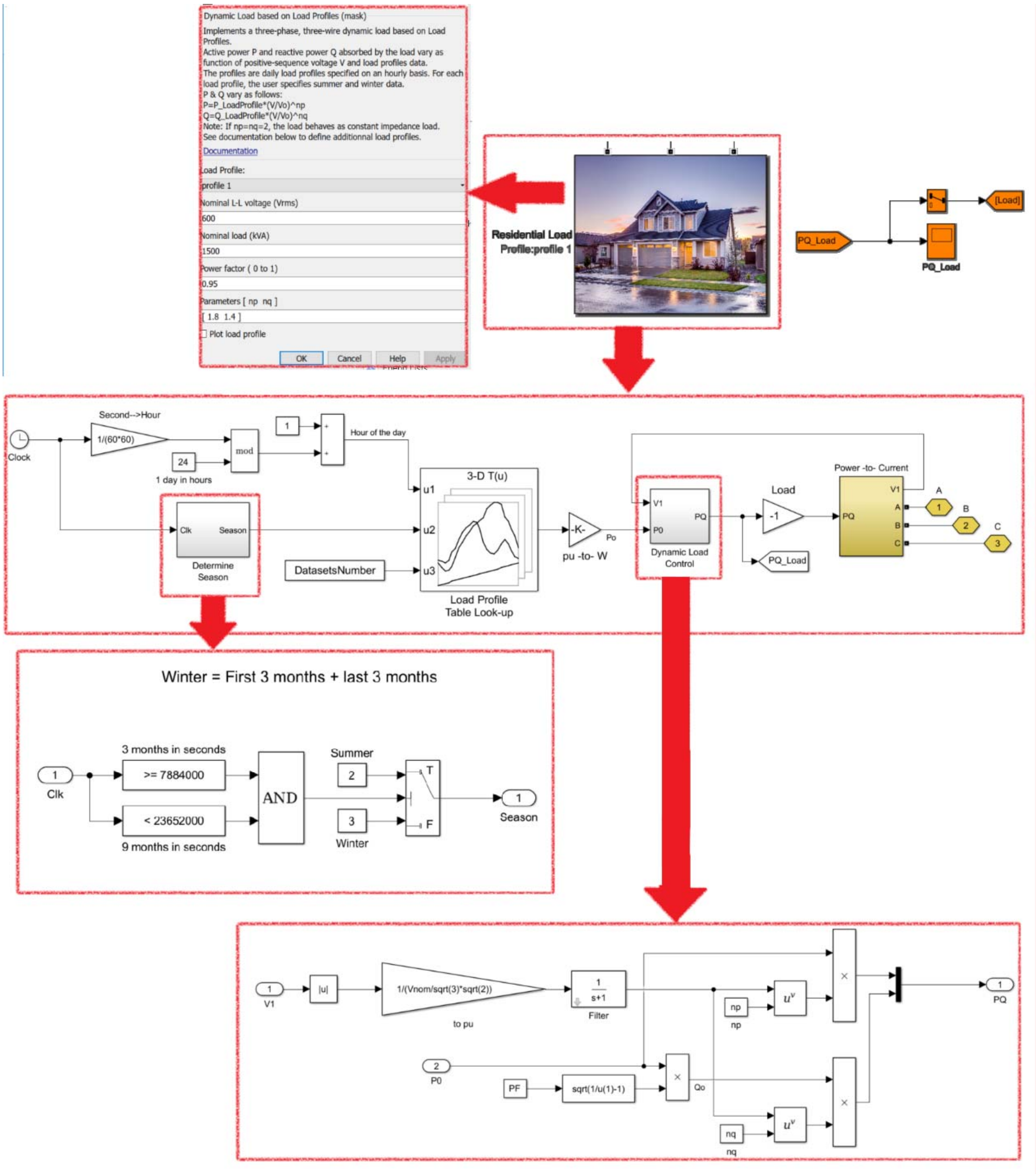
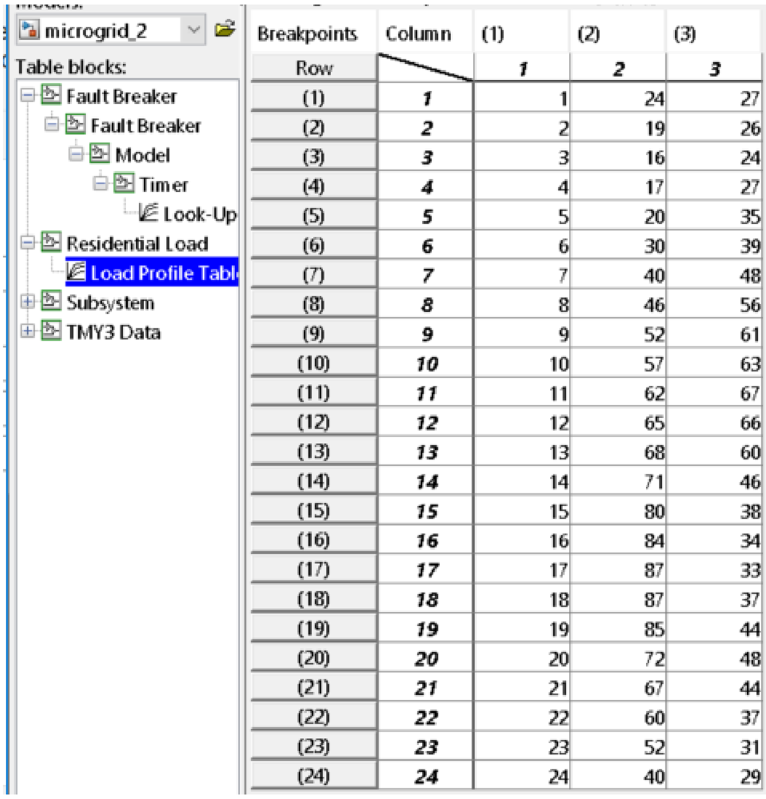


Figure 45 - Residential Variable Load block details



Breakpoints	Column	(1)	(2)	(3)
Row		1	2	3
(1)	1	1	24	27
(2)	2	2	19	26
(3)	3	3	16	24
(4)	4	4	17	27
(5)	5	5	20	35
(6)	6	6	30	39
(7)	7	7	40	48
(8)	8	8	46	56
(9)	9	9	52	61
(10)	10	10	57	63
(11)	11	11	62	67
(12)	12	12	65	66
(13)	13	13	68	60
(14)	14	14	71	46
(15)	15	15	80	38
(16)	16	16	84	34
(17)	17	17	87	33
(18)	18	18	87	37
(19)	19	19	85	44
(20)	20	20	72	48
(21)	21	21	67	44
(22)	22	22	60	37
(23)	23	23	52	31
(24)	24	24	40	29

Figure 46 - Load profile table, interpolation is made between the three columns.

7.1.3. Distribution Power System

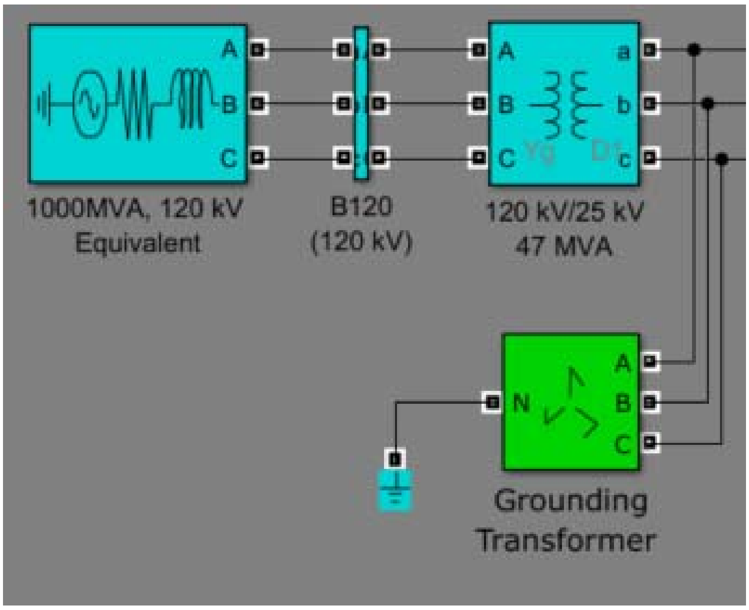


Figure 47- Main grid distribution

A 120-kV transmission is configured to supply Transformers of 25 kV. The grounding transformer provides a neutral point and limits overvoltage of healthy phases during a single-phase fault (fig. 47). The Scope block (fig. 48), Power (Kw) is used to display the Power output after simulation, for all sources of generation (Grid, Battery Storage BESS, PV Farm), in addition to the Load consumption. Similar scope blocks exist for other variables and will be discussed in the results section.

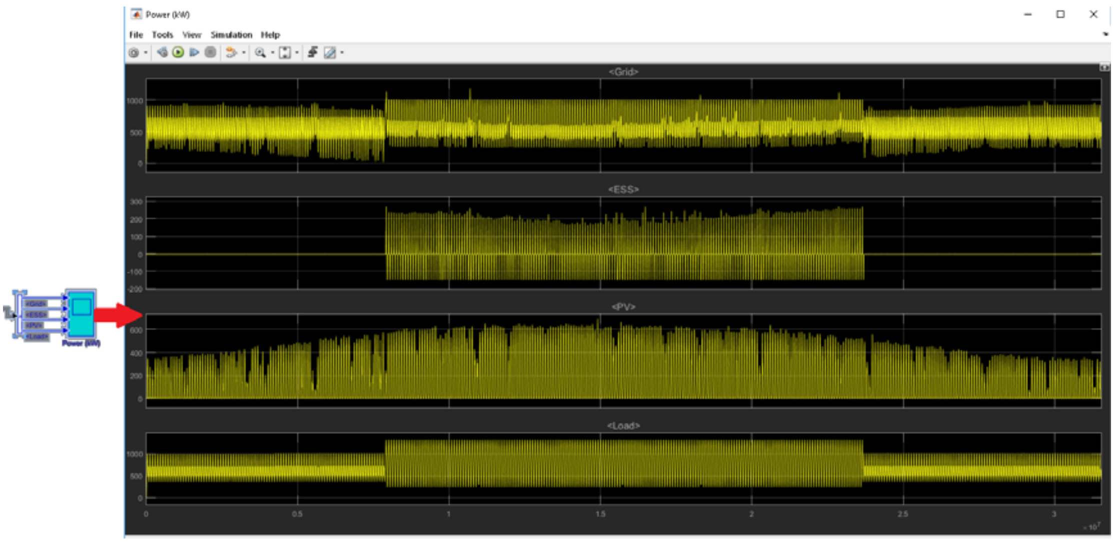


Figure 48 - Scope block displays results after simulation

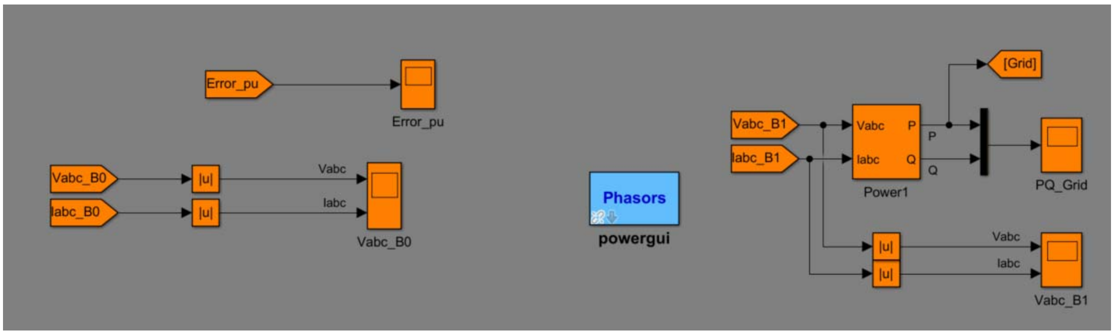


Figure 49 - Powergui block

The powergui block is a standard block for Simscape Power Systems models; it is required for any SIMULINK model containing Simscape Power Systems blocks, as it stores the equivalent SIMULINK circuit that represents the state-space equations of the model (MathWorks, 2014). Multiple powergui blocks can be used in case of simulating two independent circuits that require different solvers (different modes of simulation); however, in this project, only one block was needed for the whole model (fig. 49).

The powergui block allows simulating the circuit in different modes; continuous, discrete, or phasor; for this project, the Phasor mode was used.

Phasor simulation is intended for simple linear circuits and it is suitable for Three-Phase Systems and Machines. Phasor simulation is suitable when the analysis is just concerned with changes of magnitude of voltages and currents rather than solving all differential equations (state-space model) resulting from the interaction of R, L, and C elements. The phasor simulation solves the model using simple algebraic equations to compute the voltages and currents phasors at a fixed frequency specified in the phasor block (fig. 50) to simulate and test the power quality (frequency, wave form. Etc) other type of simulation would be needed; in addition to more details and components.

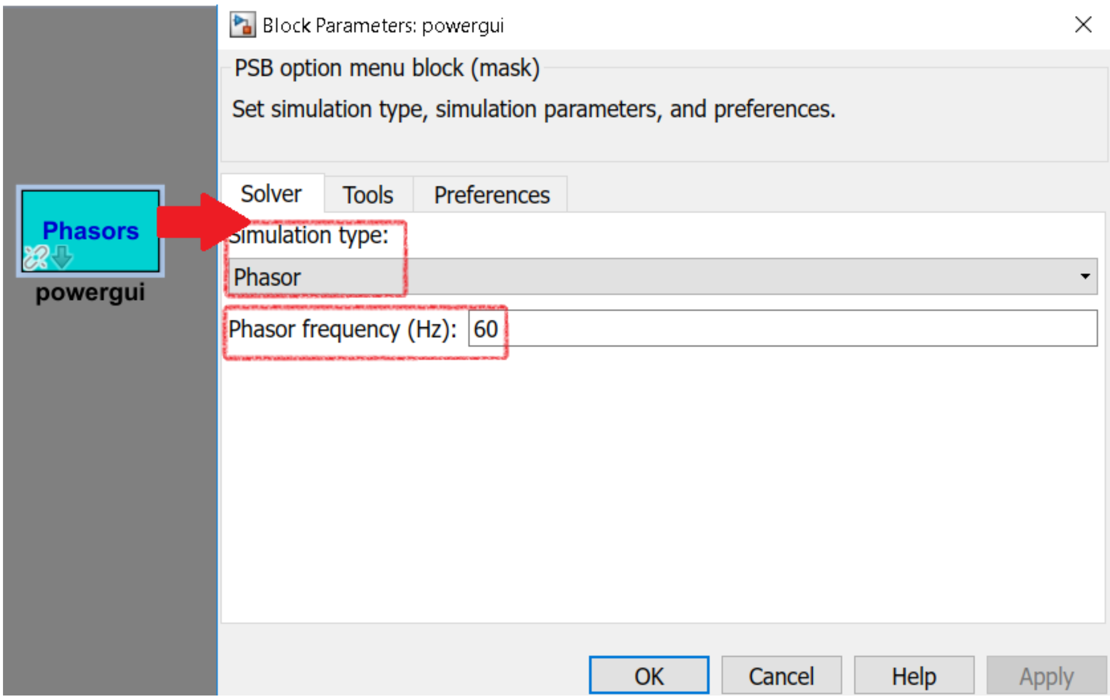


Figure 50 - Powergui block details - frequency specified for all circuit at 60 HZ and phasor type simulation

As shown in figure 51, feeders are connected to the 25-kV bus. Feeder 11 supplies power to the community attached the PV farm and energy storage, while Feeder 21 supplies two static loads that can be used to represent utilities, or critical loads that needs to be kept powered up, in case of absence of renewable generation, and stored energy, or in case of failures. Those loads can also be used to represent the non-critical loads that can be disconnected in case of absence of renewables generation and storage, or in case of failures; moreover, it could represent certain critical loads that need to be powered up within certain times during the day. In this model, those loads are disregarded.

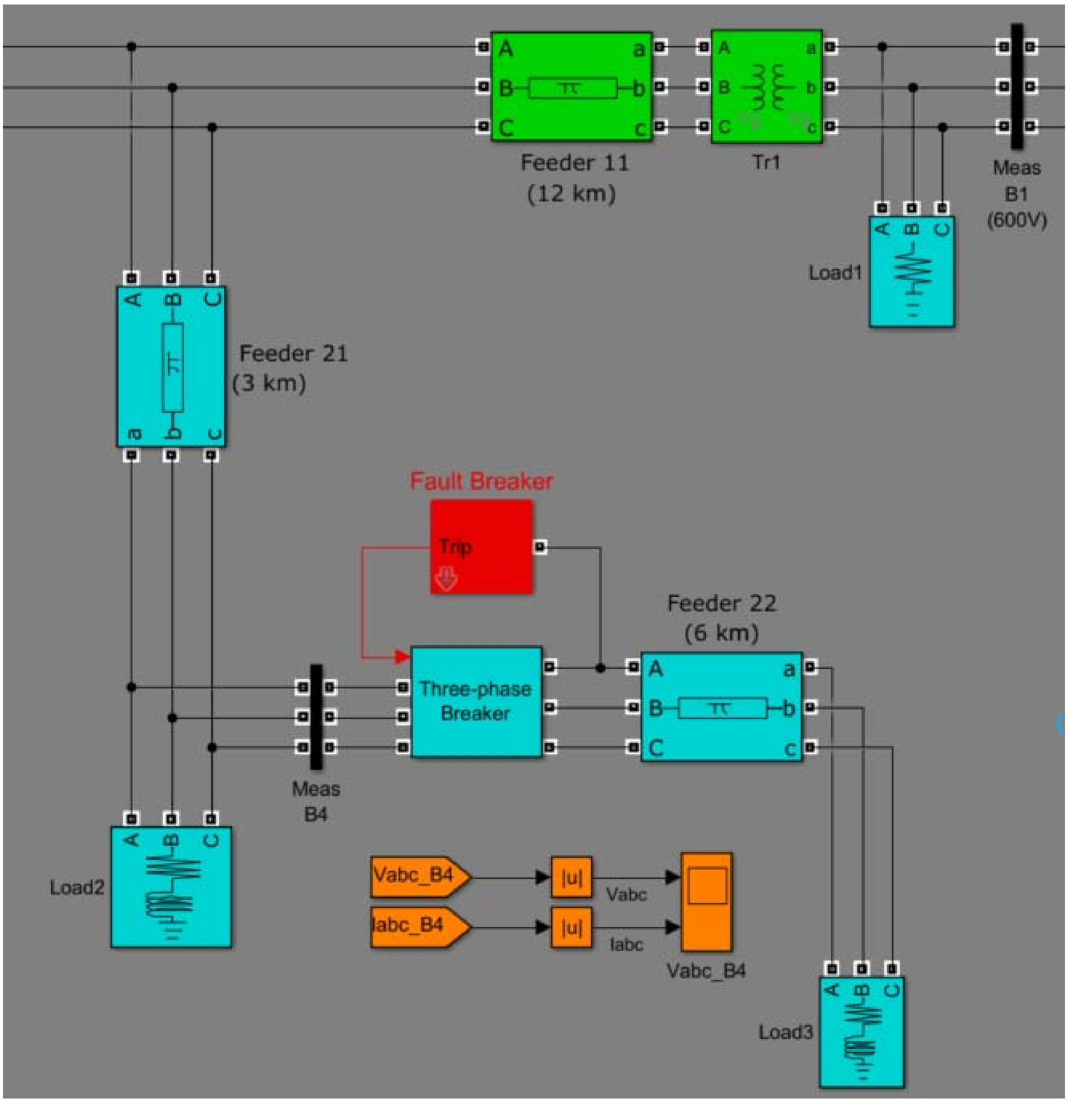


Figure 51 - Feeders and Static loads

Connecting and disconnecting the loads can be done using fault breakers (fig. 51), which could then be controlled using control algorithms that are written in MATLAB text-based code. Breakers would then be placed at all Main grid connections, microgeneration sources, storage, and loads and opened/closed by the control commands at the appropriate conditions as will be discussed in the discussion section.

7.1.4. Wind Turbine

The biggest advantage of the wind energy is its abundance, and the biggest challenge is converting this abundant energy into electrical power in a feasible manner. Wind Energy exists in the form of kinetic energy; to convert it to electrical power a wind turbine and a generator are used, to capture the kinetic energy in the form of mechanical energy, then convert it to electrical energy, using the generator; during that process, significant losses are incurred which reduces its efficiency to Betz limit (David, C. & Mackay, J.C., 2009). To harness a rewarding amount of energy in a reasonable efficiency, higher capacity wind turbines are a better option; However, large capacity turbines need to withstand tremendous physical pressure and mechanical stresses, which requires solid structural design and construction; hence, a significantly higher cost. The UK was able recently to drastically increase its Wind power capacity to 37678221 MWh/p.a (Boyle, 2012) through extensive research and governmental subsidies; subsidies such as capital cost loans and extended payments are available in the UK, which makes Wind Turbines a very promising solution to utilize in Microgrids.

The Wind Turbine is a very promising technology particularly in the UK due to the abundance of wind energy all over the year; Scotland particularly, has the highest wind energy availability in Europe (Boyle, 2012); however, there are some technical and environmental challenges that face this technology. Environmental challenges comprise hazards to bird's wildlife including some rare species; especially during bird's immigration seasons, as they may get killed by the turbine blades; for which some incidents have been recorded. Wind Turbines can be installed either onshore or offshore; the ones that are installed at depth less of than 25 meters are called Shallow Offshore Turbines; Deep offshore Turbines that need to be installed at larger depth don't have much economic feasibility. Although it might sound convenient and environment-friendly to significantly increase the amount of UK wind power capacity; areas that can contain onshore and Shallow wind turbines are limited. Another challenges when designing the turbine specs is the annual variability of wind speed, which needs to be considered carefully; Wind turbines can't harness energy from wind above its "rated speed" and is shut down below its "cut-out speed"; that means that only the wind speed within this range is harnessed and the rest is wasted. The Velocity exceedance curve (Association, R, 2016) is used to evaluate the expected annual energy capture while designing the turbine. Wind Turbines intend to convert the kinetic energy induced from the wind flow on a rotating mechanical turbine into electricity using a generator. The graph in figure 5 shows a sample of the hourly output of wind generation; the figure reveals the intermittent nature of wind energy. Given the Wind speed fluctuations and unpredictability; modelling and simulation of the systems performance during design can certainly help in optimizing control and setting up the optimal system parameters and specifications.

The Wind farm model for this project was taken from the research (Manyonge, A.W. et al., 2012) which used MATLAB+SIMULINK for modelling and analysis of wind energy systems.

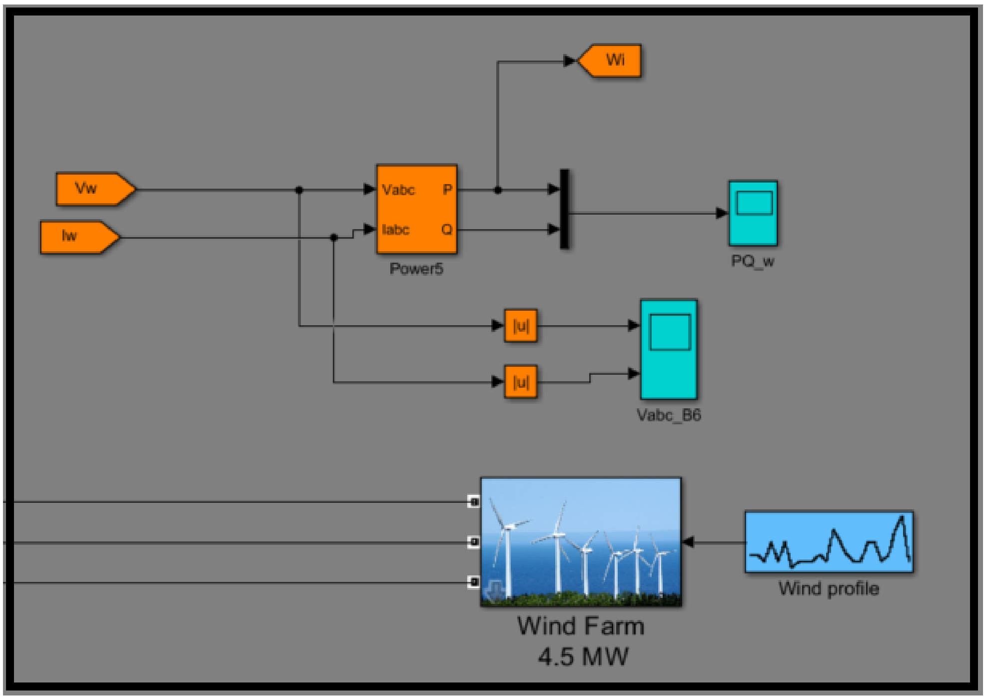


Figure 52 - Wind farm model overview

7.1.4.1. Wind profile

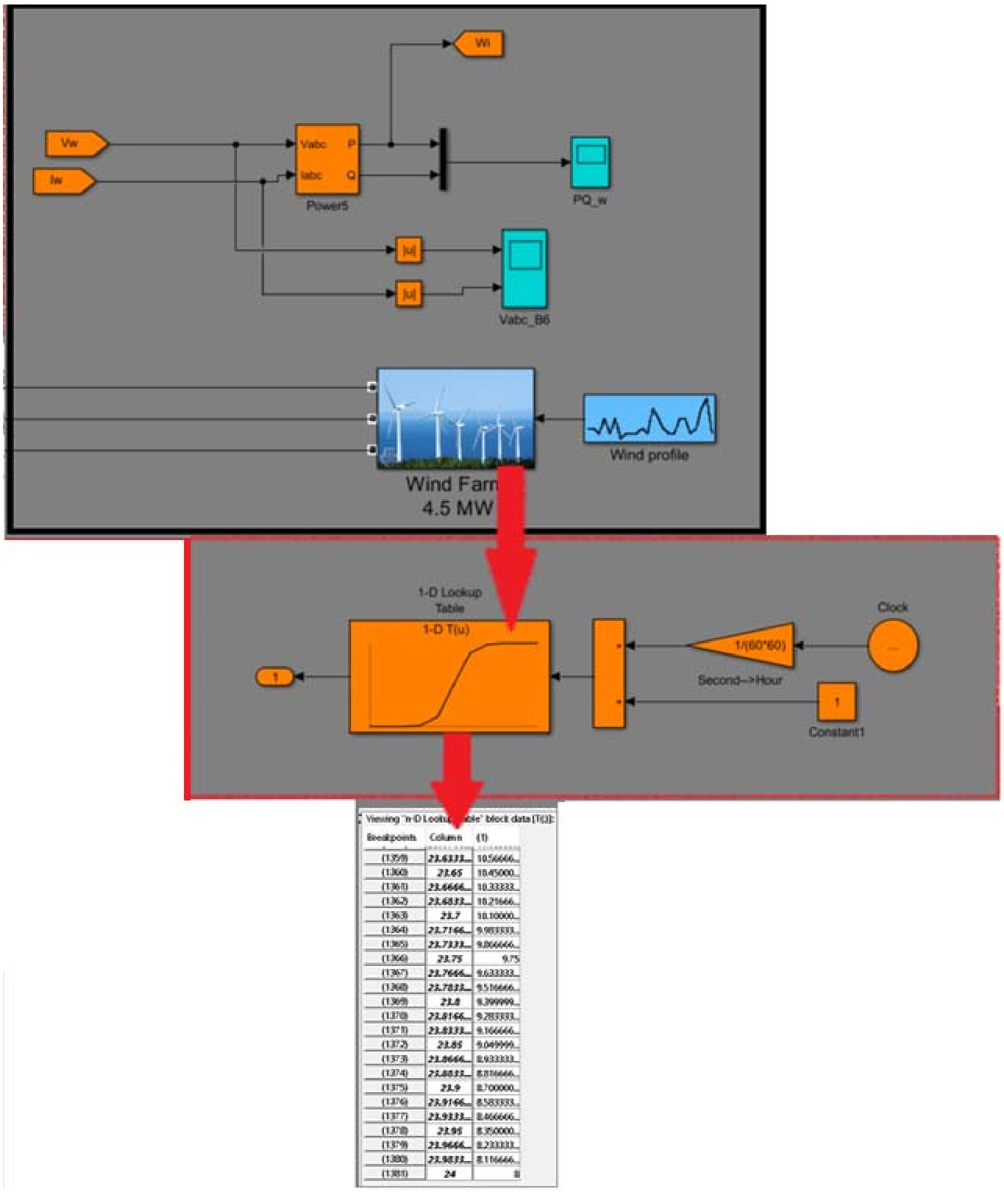


Figure 53 - Wind profile lookup table

As shown in figure 53, Wind profile block details, the wind profile block imports the Wind availability from the specified data table and transfer it to the Wind Farm block at port number 1 (irradiance). The Lookup table does a linear interpolation between the two columns at the given input hour by the clock; sampling is made per hour; however, the resolution can be increased for more detailed simulation.

For this simulation, they have been set to the following:

Nominal Power 4.5Mw, Nominal wind speed – 13.5 m/s, Maximum wind speed -15 m/s.

7.1.4.2. Wind Farm block

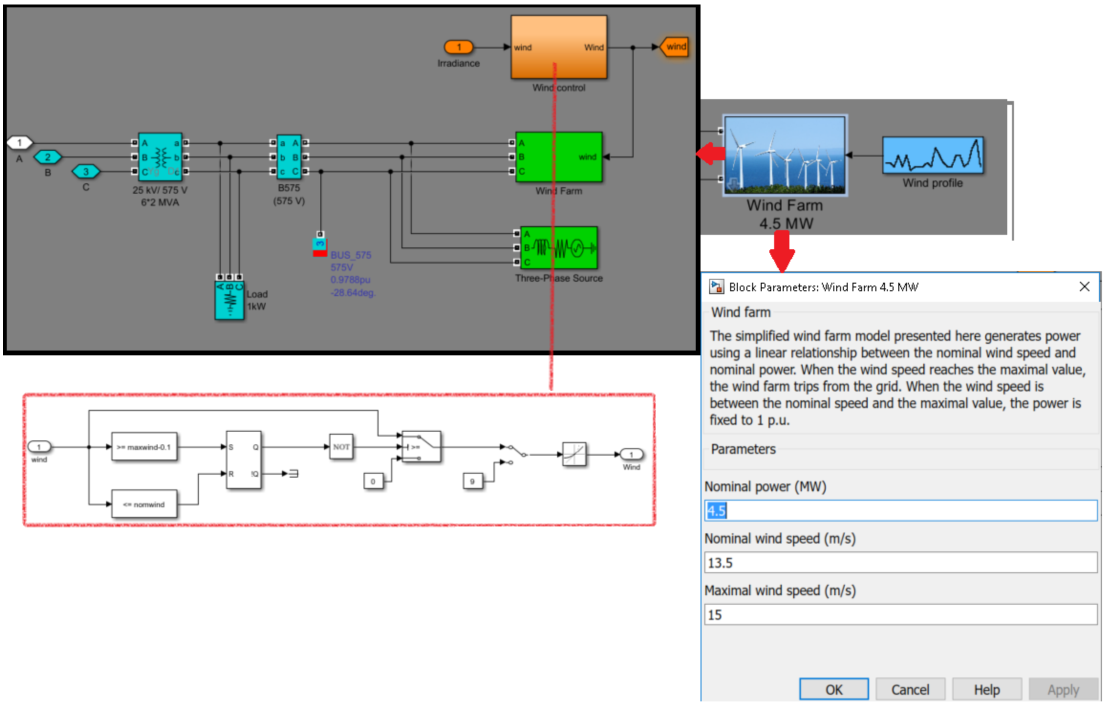


Figure 54 - Wind control block details

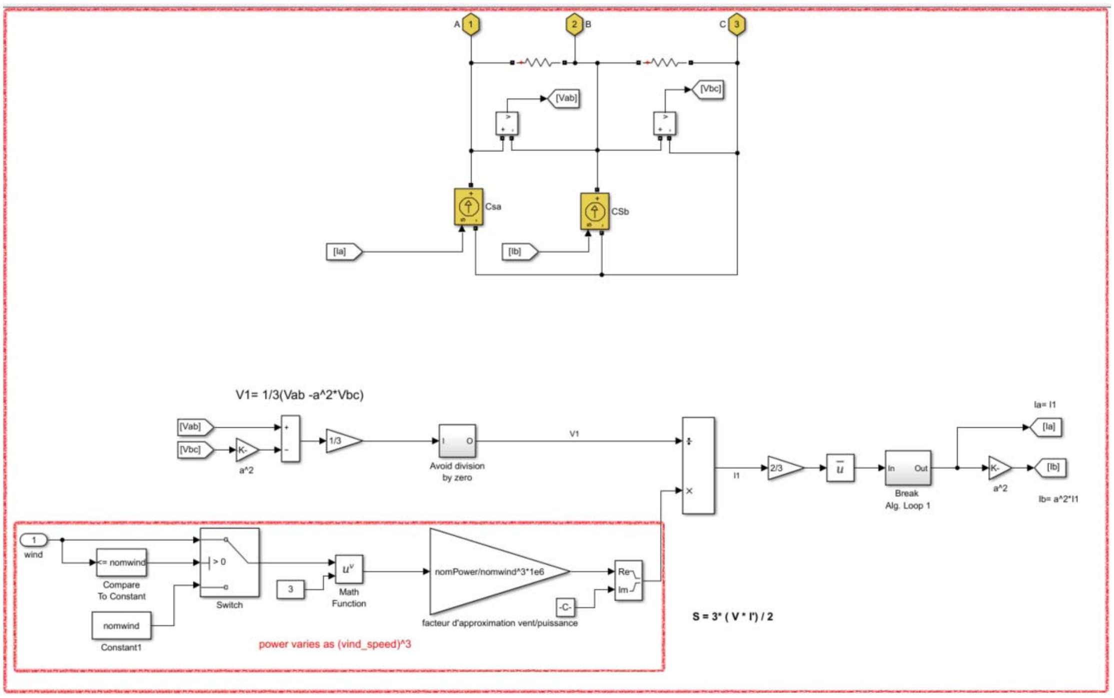


Figure 55 - Wind farm generation block details

As shown in the figure 54, the wind control block receives the wind speed/irradiance at port 1, the Set/Reset block is responsible to connect the output only if within a certain limit (minimum limit set to 0 just for the sake of this demonstration). The wind farm block faceplate enables entering values manually for Nominal power, Nominal wind speed and maximum wind speed. A calculation is made to obtain the generated power using the standard basic equations $P=1/2\rho Av^3$ (Manyonge, A.W. et al., 2012).
Voltage and current are then calculated using the equation S (Real Power) = (3/2) * Voltage (V) * Current (I). The standard loop at the top of fig(55) computes the line to line voltages Vab and Vbc, and line voltages and currents Va, Vb, Vc. Ia, Ib, Ic

7.1.5. Diesel Generator

The Diesel Generator is set to run in absence of both of Wind and Solar Energy. It can keep running on an overload for a short time. A prime mover is required to initiate the movement of the alternator rotor; a diesel combustion engine is used for this process. This system is intended to be used only in case of emergency due to the high cost of diesel compared to other means of generation.

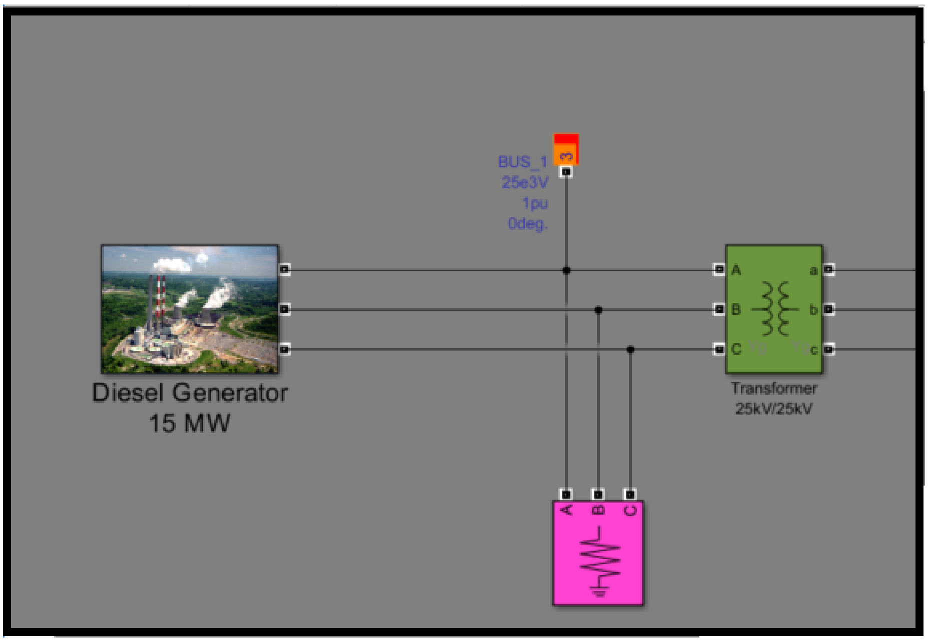


Figure 56 - Diesel Generator block overview

The model was used from the research (Prenc, R., 2015) research "Marine Diesel-generator Model for Voltage and Frequency Variation Analysis During Fault Scenarios".

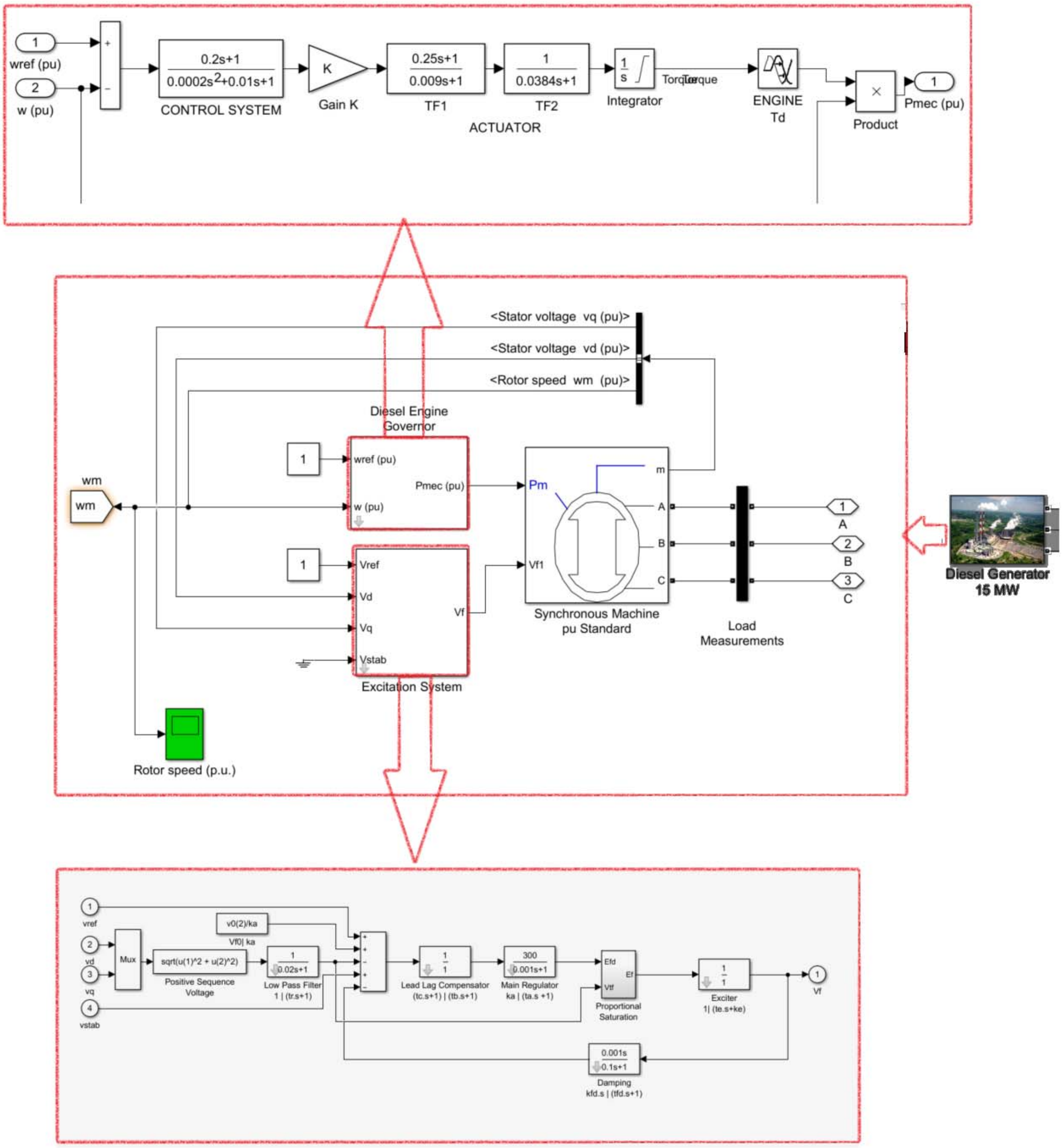


Figure 57 - Diesel generator block details

The synchronous generator was built from several system parts using standard SIMULINK library blocks; the parts are as follows:

7.1.5.1. Excitation System

Standard SIMULINK Block; consists of a voltage regulator and a DC exciter described in (MathWorks, 2014). The exciter represents the following transfer function between the exciter voltage V_{fd} and the regulator's output e_f: $V_{fd}/e_f = 1/(K_e+sT_e)$
The outputs of the Exciter block are field voltage V_{fd}, in pu, and is designed to be applied for the V_f of the standard Synchronous Machine block. Both, the excitation system block, and the Synchronous Machine pu standard block, are standard SIMULINK library blocks. The V_d and V_q measurements signals are to be connected to the outputs of the SIMULINK standard Synchronous Machine block.

<u>Inputs and Outputs:</u>

V_{ref} - The setpoint value of the stator terminal voltage (pu).
V_d - V_d component of the terminal voltage (pu).
V_q - V_q component of the terminal voltage (pu).
V_{stab} - Power system stabilizer; provides additional stabilization of power oscillations.
V_f - Field voltage for the Synchronous Machine block. (pu).

7.1.5.2. Synchronous Machine pu Standard

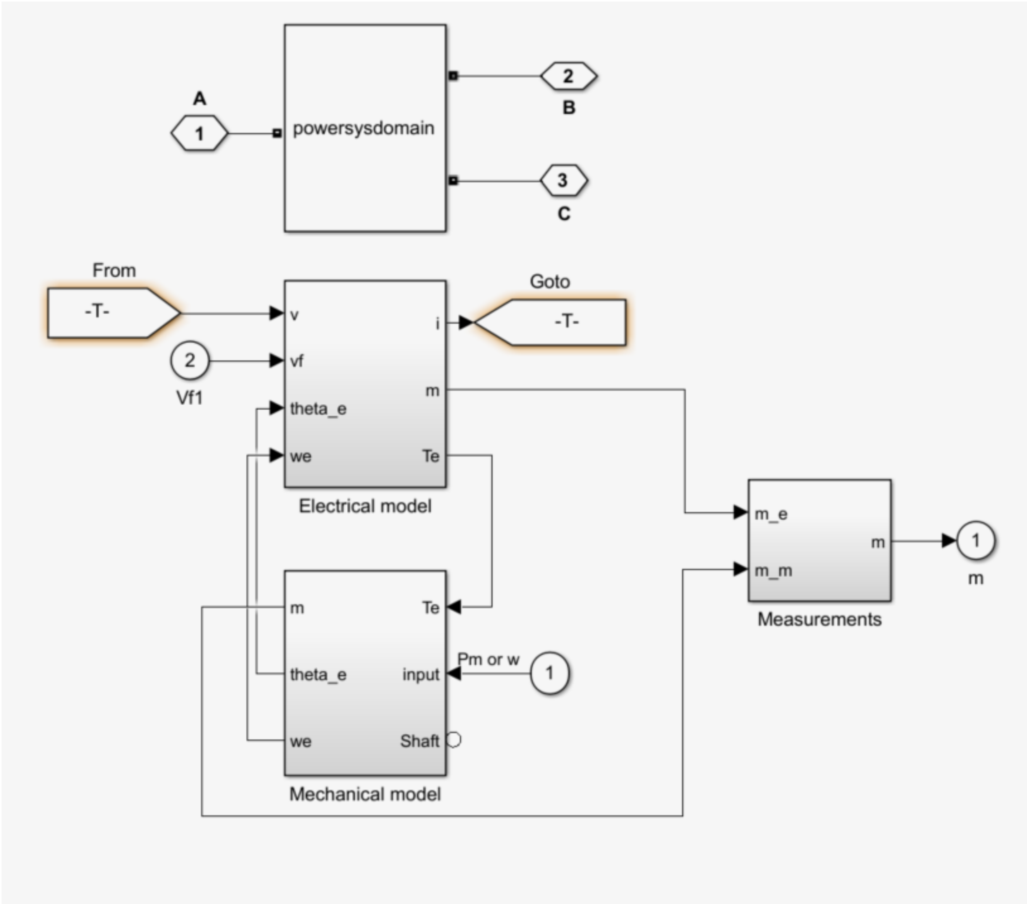


Figure 58 - standard library block "Synchronous Machine pu Standard"

The Synchronous Machine pu Standard is a Standard SIMULINK block; the block operates in either generator or motor mode, based on the sign of mechanical power (+ve or -ve). It represents a three-phase custom synchronous machine.

<u>Inputs and Outputs:</u>

P_m- The mechanical power at the machine's shaft. In generating mode, this input can be a positive constant or function or the output of a prime mover block (see the Hydraulic Turbine and Governor or Steam Turbine and Governor blocks). In motoring mode, this input is usually a negative constant or function.

V_f - Field voltage; supplied by the excitation system.

m - Output of the block; a vector containing measurement signals. Demultiplex by the Bus selector into Stator Voltage Vq, Stator Voltage Vd, Rotator speed Vm

7.1.5.3. Diesel Energy Governor

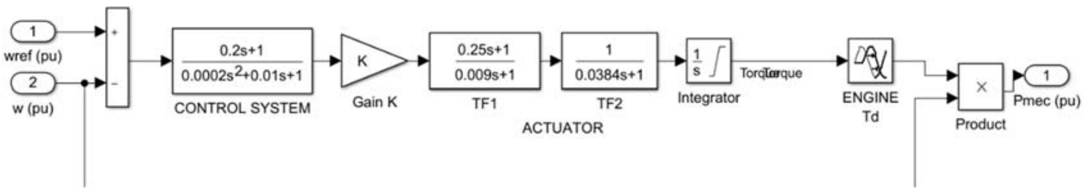


Figure 59 - Diesel Generator governer block details in MATLAB model

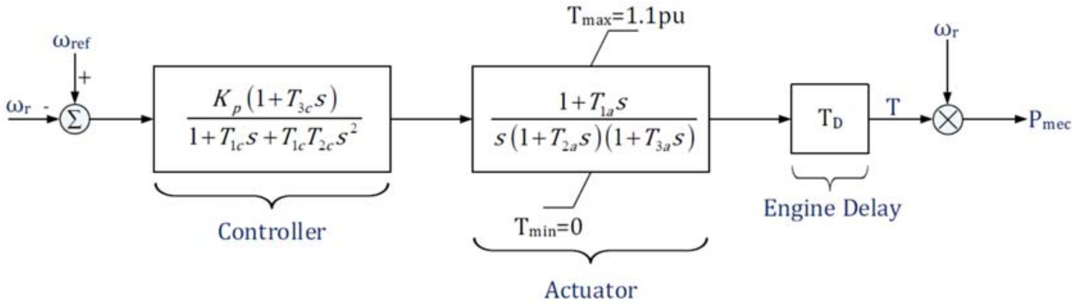


Figure 3. Block diagram of the diesel-engine governor model

Figure 60 - Block Diagram of diesel generator governor model mathematical function. figure from (Prenc, R., 2015) research on Diesel-generator Model for Voltage and Frequency Variation Analysis

The Governor block was built using SIMULINK blocks based on the equation in figure 60. Figure 59 shows the model build in SIMULINK. The generator actual speed W_r is compared with the reference speed W_f, and the Error is directed to the input of controller. The K_p is the gain and T_{1a}, T_{2a},T_{3a} are the actuator time constants and T_{1c}, T_{2c}, T_{3c} are the controller time constants. The output of the actuator is the prime mover torque command; it is sent the engine delay block (Engine Td) then multiplied with W_r; the output is connected to P_m in the Synchronous Machine block (See previous section) to be directed as the input for the mechanical model part of the Synchronous machine block (see fig. 58).

7.1.6. Battery Storage

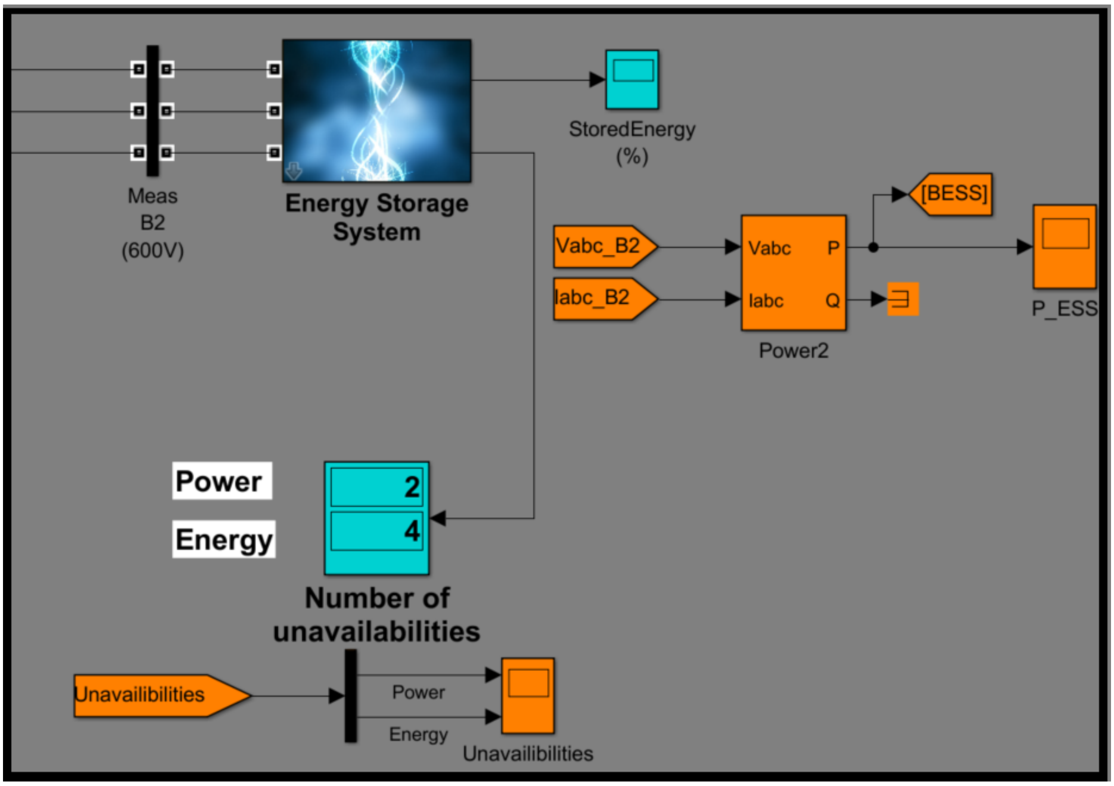


Figure 61 - Battery storage system overview

The Battery storage system in fig. 61 is designed to feed to the grid with a sufficient amount of power to maintain the minimum power required by the loads. The model describes a generic storage system that is connected to the grid through an Inverter.

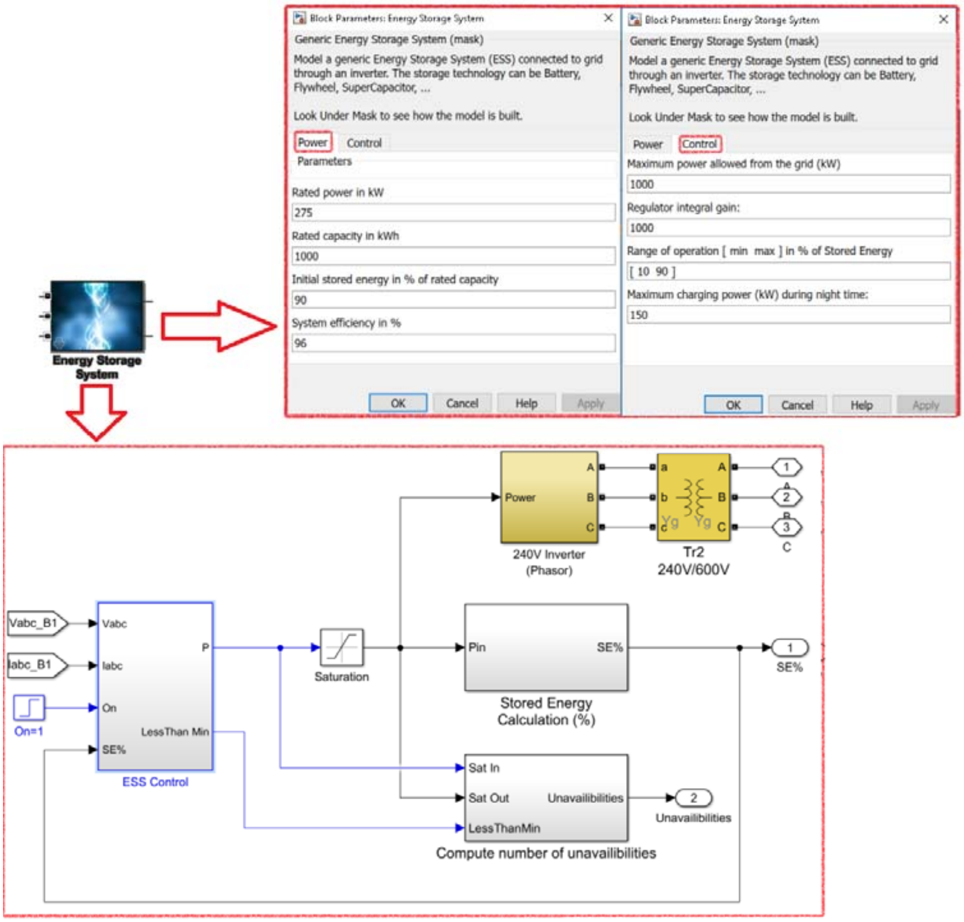


Figure 62 - Energy Storage System block details

As shown in figure 62, power is fed to the grid through a Power to Current calculation (Block 240V inverter) through a step-up transformer Tr2. The Energy Storage System displayed is flexible and can represent any type of storage, such as hydro or hydrogen, and not essentially a Battery Storage; however, in this simulation we assume it is a battery storage. Configuration parameters can be entered before simulation (see top fig. 62).

As shown in the fig. 62, The Battery Storage system consists of the following blocks:

7.1.6.1. Stored energy calculation

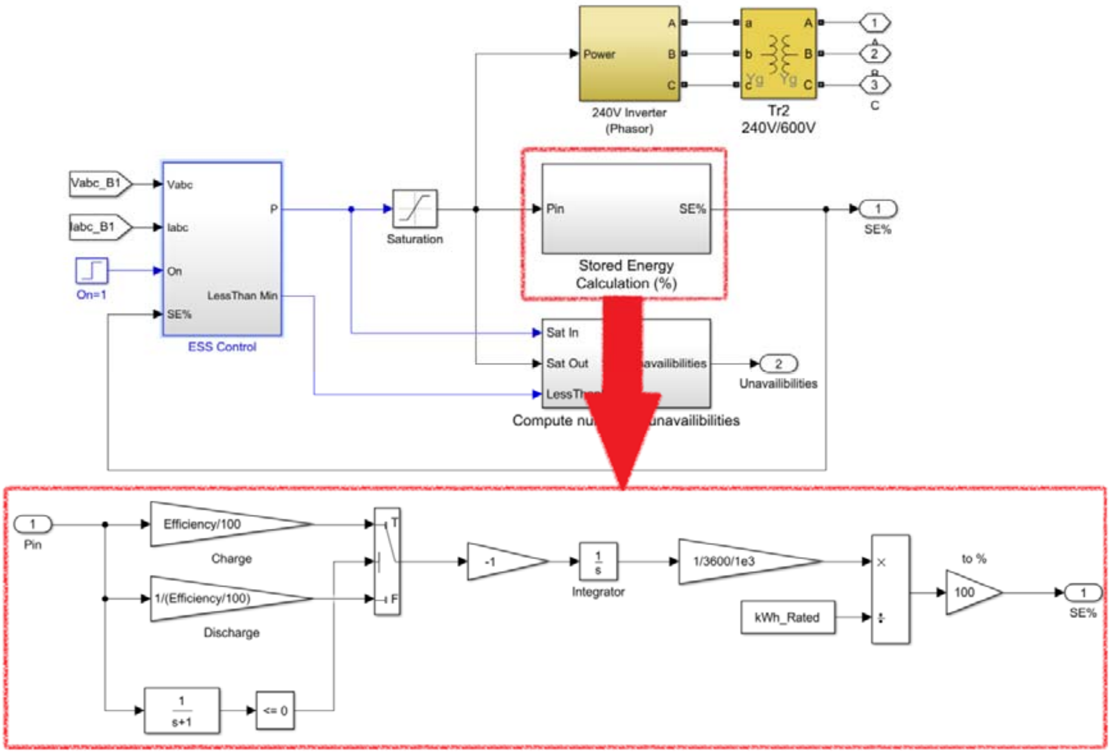


Figure 63 - Stored energy calculation block details

The energy storage calculation has two modes, charge and discharge (fig. 63). When it is in charge mode, it accumulates (increments) the power suppled at port 1, which is linked to the grid connection, over time, to compute the amount of expected saved energy in the battery after factoring the efficiency and rated power of the battery. In the discharge mode, it does exactly the opposite by deducting the amount of power withdrawn. The integrator block acts as a store register for the battery charge value; when in charge mode, the value increases and when in discharge mode vice versa.

7.1.6.2. – ESS Control

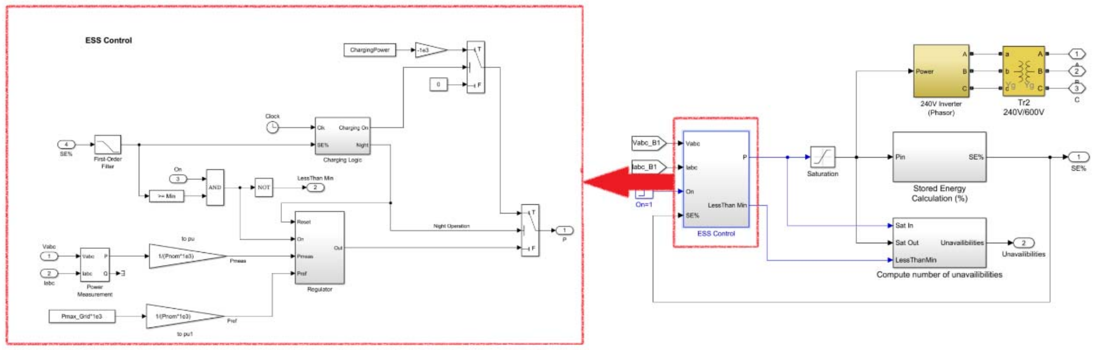


Figure 64 - ESS Control block details

The ESS Control block consists of a Charging Block, Regulator, and two switches; these will be described individually in the next pages.

7.1.6.2.1. Charging Logic block

In this project for demonstration, the battery charges within 12-6 am, if the charge is less than max stored energy which is specified as 90% for this simulation in the battery Energy Storage System faceplate (fig. 62); see the AND gate in Charging Logic block details) showing both conditions that activate output port 1 (Charging On) (fig. 65). Port 4 (SE%) is the value of the battery charge increment that is calculated in the Stored energy calculation block (fig. 64) from previous section.

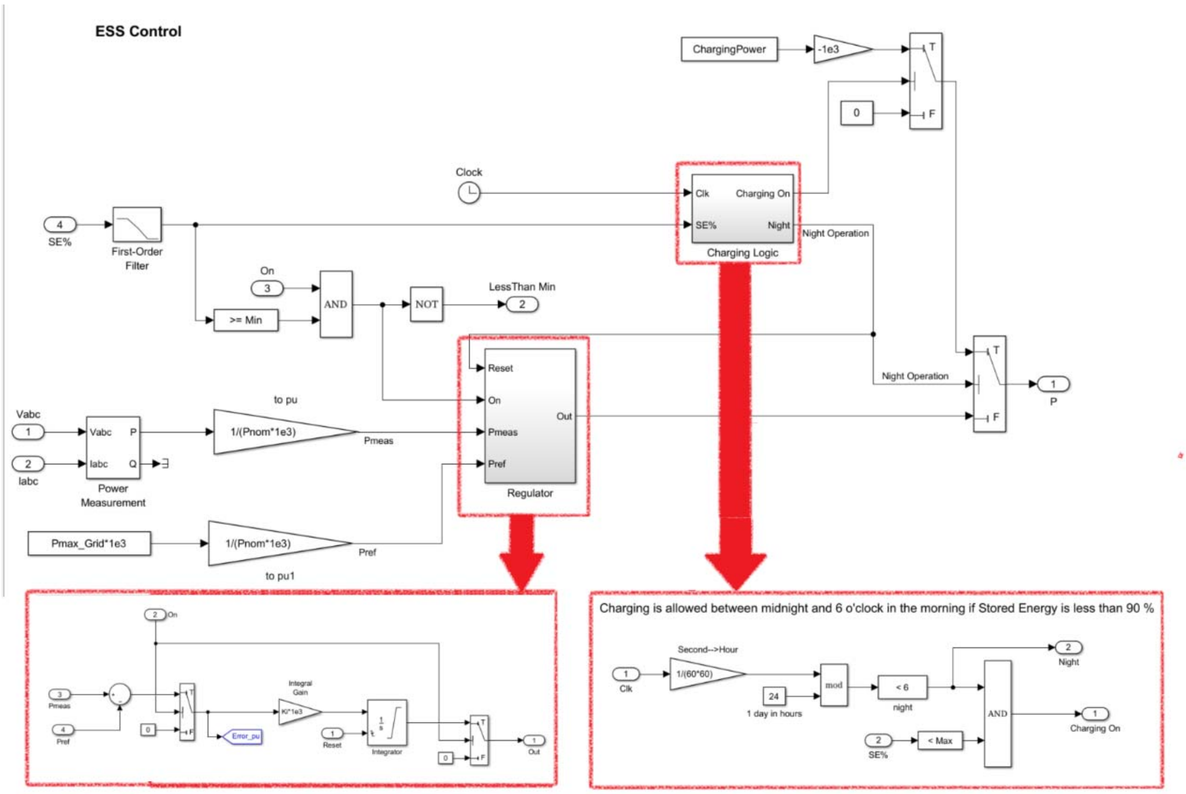


Figure 65 – Inside ESS Control block details; Charging block and Regulator block details

7.1.6.2.2. Regulator

The regulator stops the battery from supplying power if the charge (Port 4 SE%) drops below the specified minimum % of operation which is set to 10% in this simulation (see fig 62). It also controls the output of the battery during supplying the grid within the grid limit based on the measured grid line voltages and currents Vabc and Iabc (to prevent over supply of power); the equation is given Pout = Pmeas – Pref (fig. 65)
In a real battery, the regulator is meant to act as a protection from over voltage, over charging, and depletion of charge.

7.1.6.2.3. Switches

During the night charging period and below the minimum SE% 10% charge, the Charging logic sends a signal to the output switch to direct the output to the constant Charging Power block (fig. 65); at the same time, the stored energy calculation block that was discussed in the previous section directs the Output Port 1 (P) to the charge mode and the battery gets charged. The bottom switch directs the output to the regulator when not in charging mode.

7.1.6.3. – Compute number of unavailability

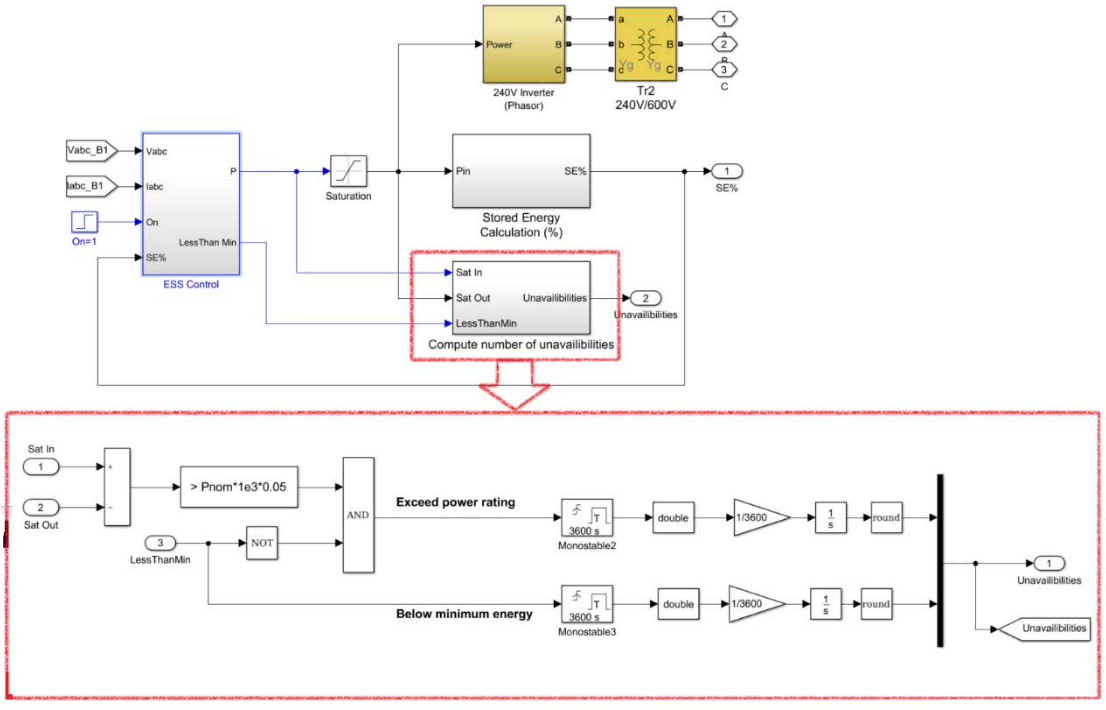


Figure 66 - Energy Storage system details; Compute number of availabilities block details

The unavailability block detects the periods when the power output exceeds the power rating or the battery charge drops below the minimum charge (10%) (Fig. 66).

7.2.Simulation results

The simulation was run in accelerator mode for a period of one year (60*60*24*365 seconds). Due to computer processor limitations, the simulation was run without the wind turbine and diesel generator. To include the model with the wind turbine and diesel generator the simulation time can be up to several days; unless it is run on a very powerful processor using the "Rapid Accelerator Mode".

After running the simulation, the following results were obtained using scope blocks and Powergui block

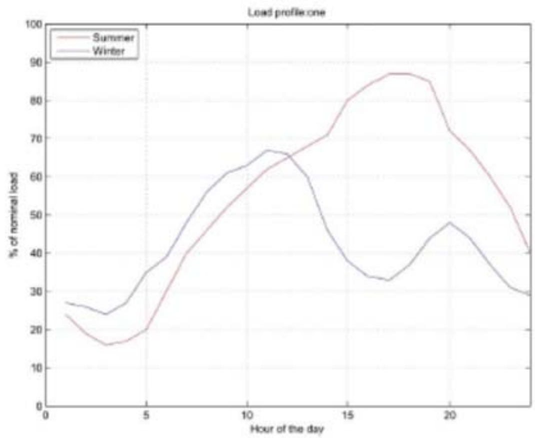


Figure 67 - Variable Load profile based on defined lookup table

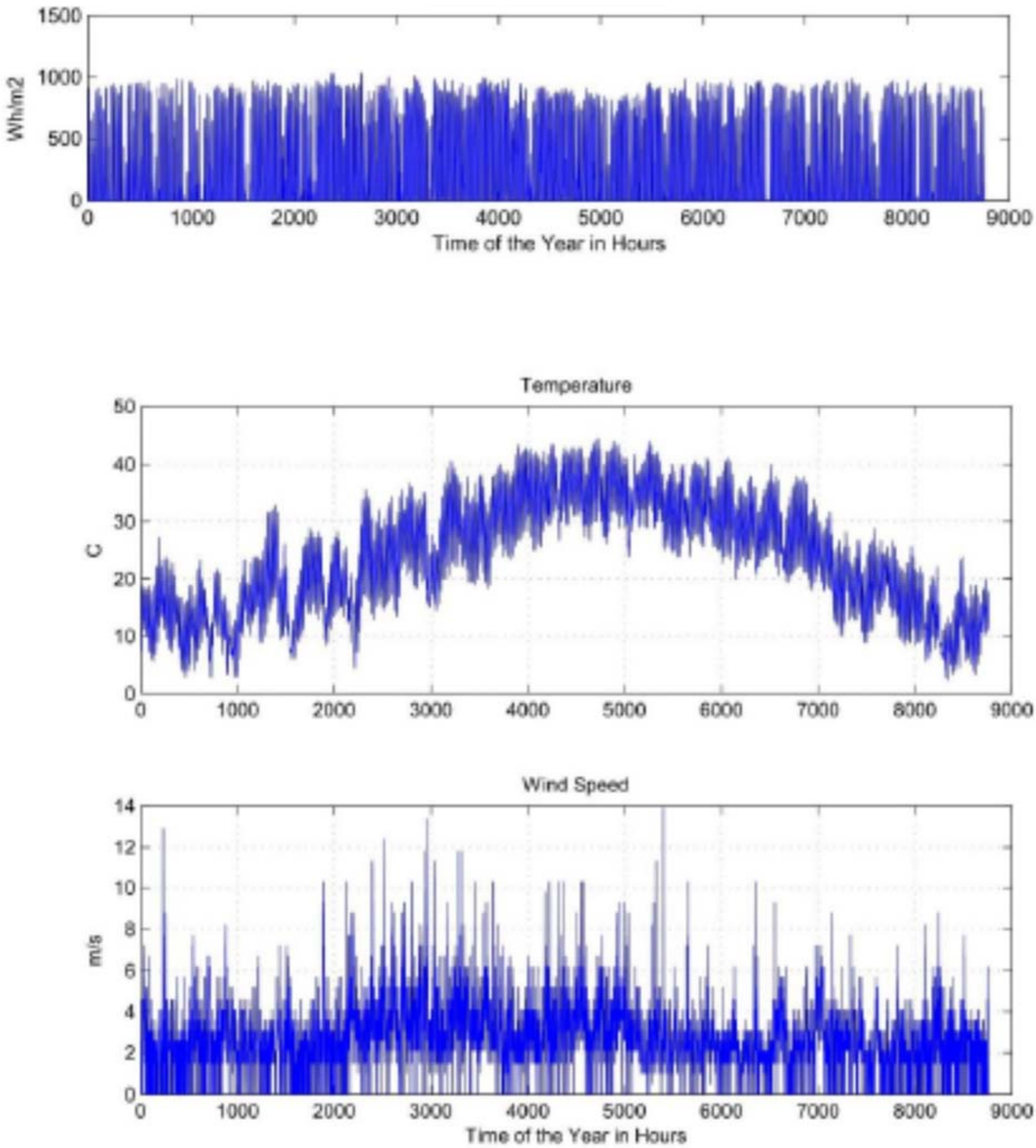


Figure 68 - Solar irradiance, Weather, and Wind speed profile over one year simulation; all generated based on data imported by lookup table blocks as discussed previously.

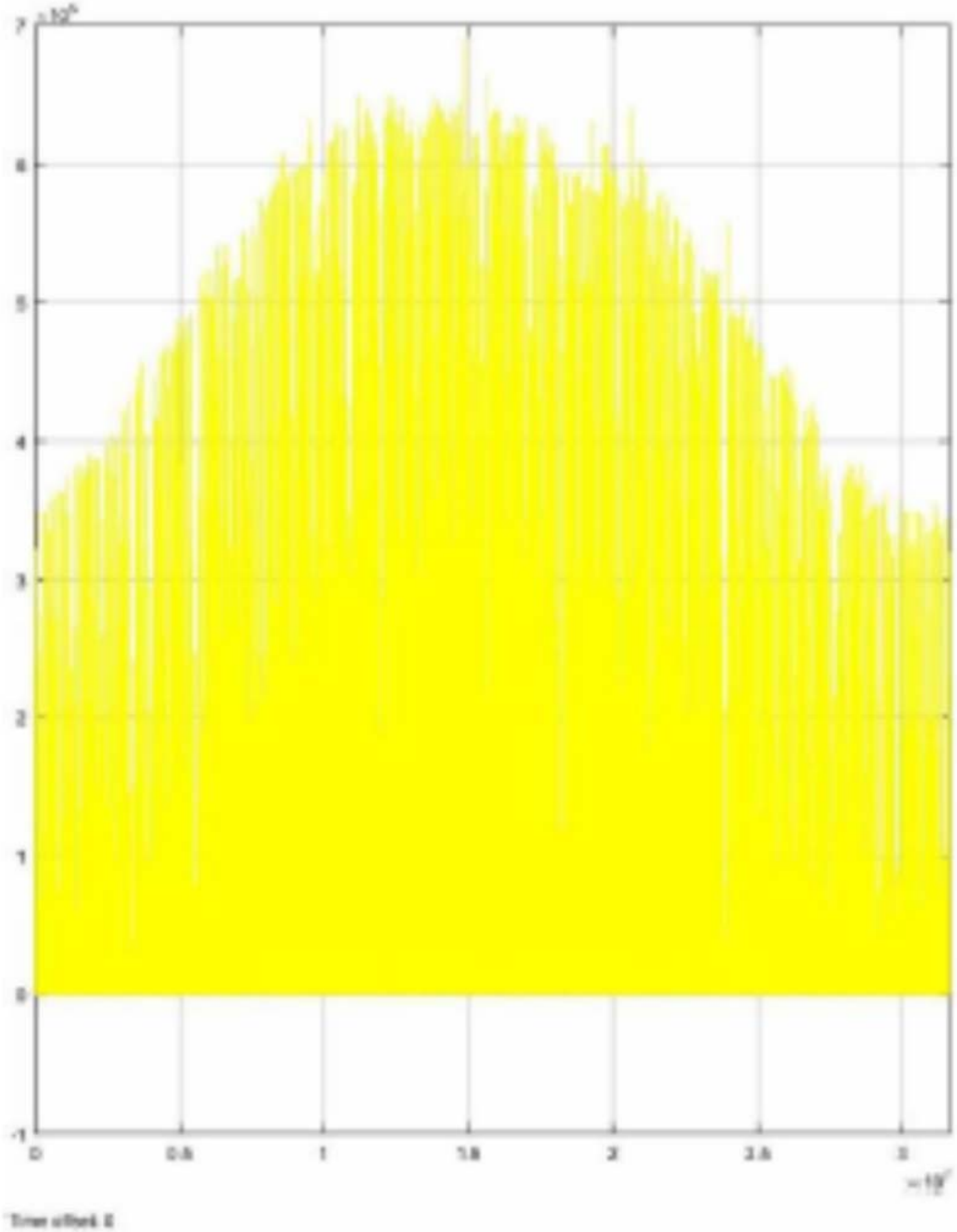


Figure 69 - Annual PV Farm Power Output

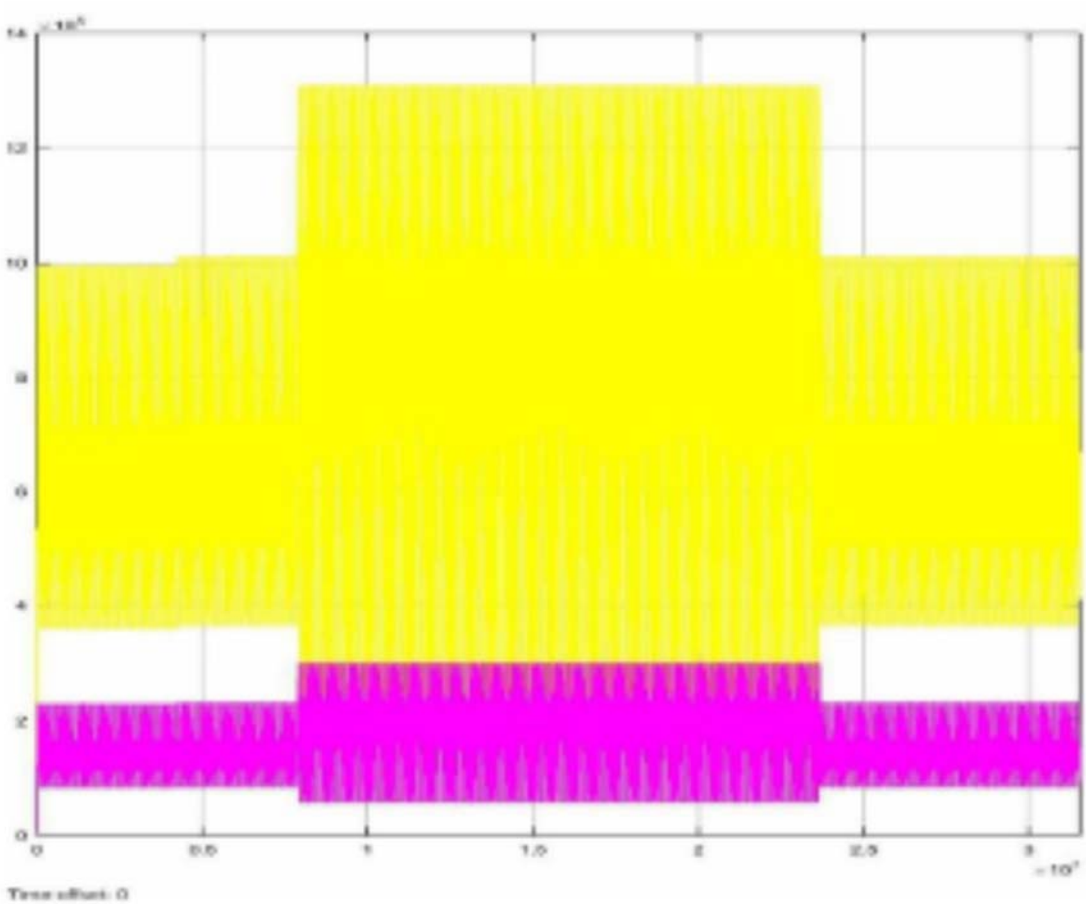


Figure 70 - Load active and reactive power (PQ_Load)

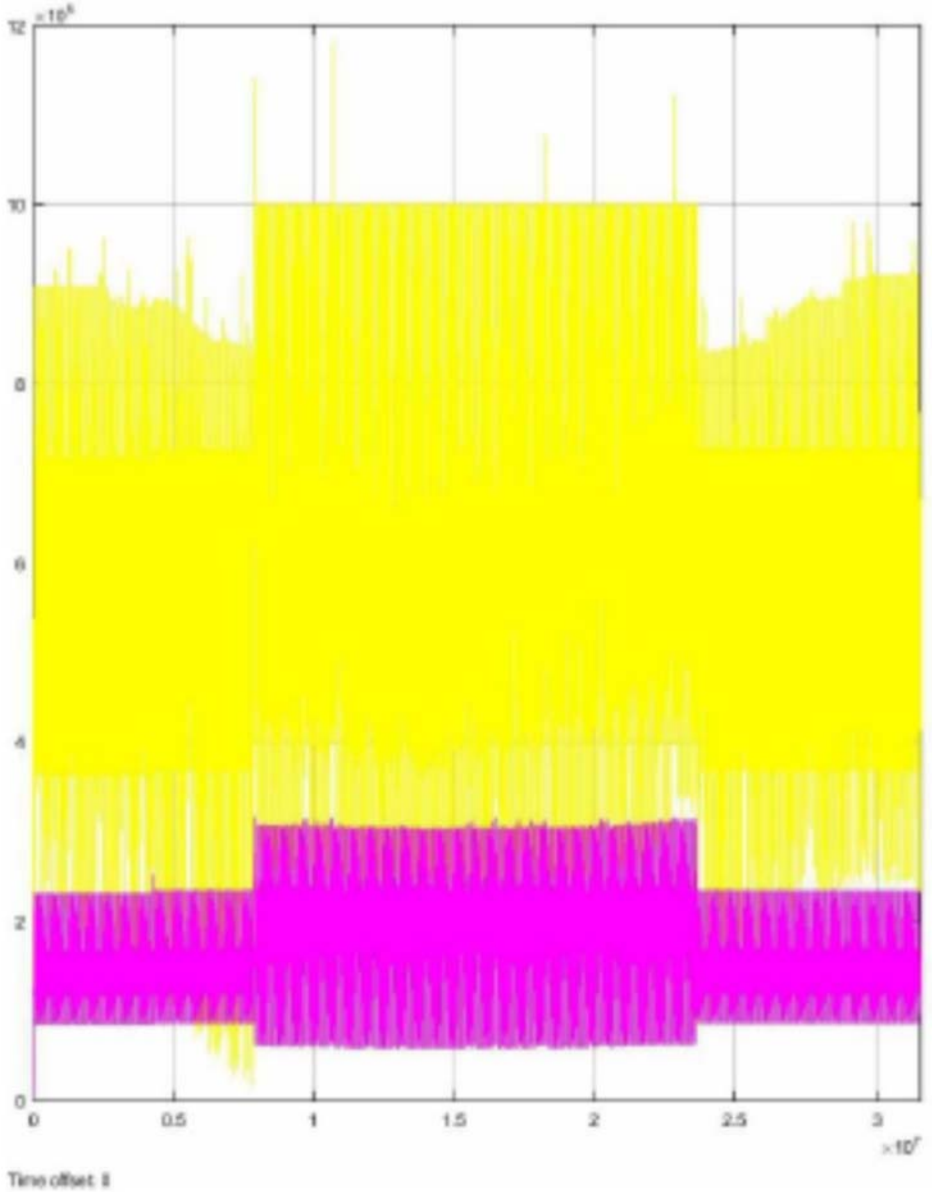


Figure 71 - Grid active and reactive power (PQ_Grid)

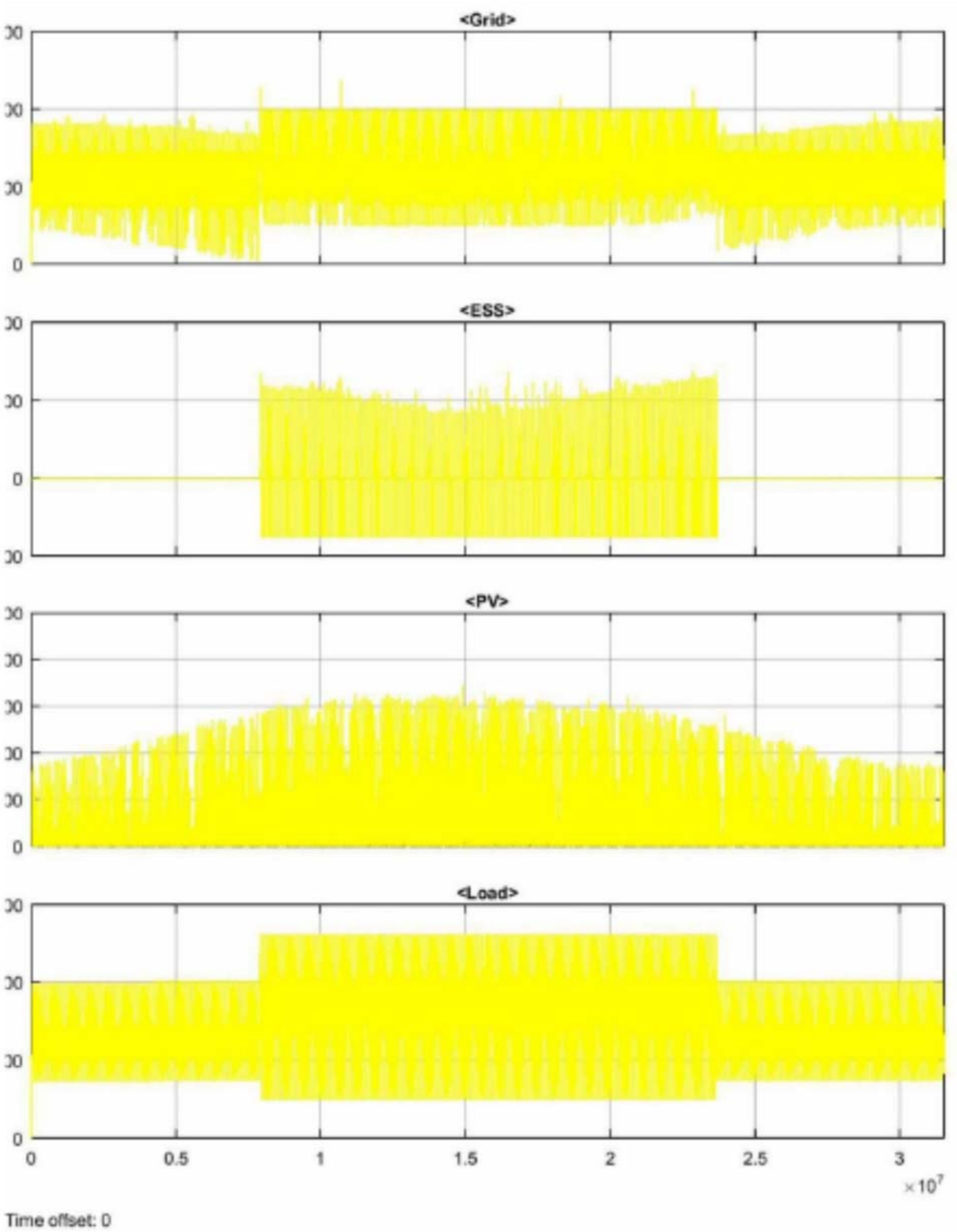


Figure 72 - Overall system Power output (Simulation run without wind and diesel due to system limitations)

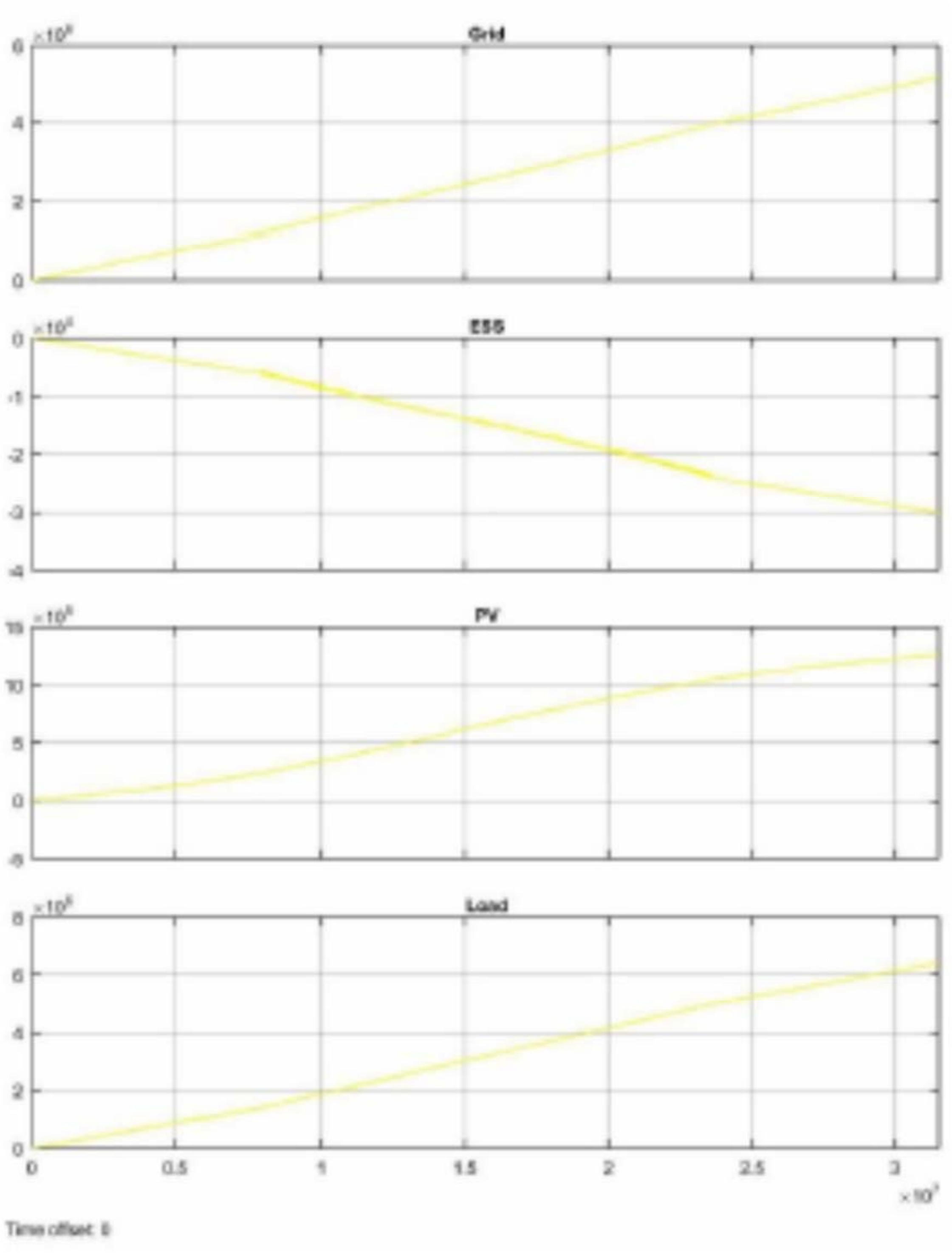


Figure 73 - Overall system Energy output (Simulation run without wind and diesel due to system limitations)

7.3. Discussion

As represented in the previous section, some basic results have been obtained from the simulation, which are sufficient to demonstrate the capabilities and the methods that can be used for modelling and simulating a Microgrid, using MATLAB+SIMULINK. It may be worth emphasizing that it has been noticed during this project the detailed structure of SIMULINK platform, and its outstanding flexibility, and high resolution of details; however, LABVIEW seems to be more practical, and seamless in developing larger applications; especially, if it involves iterations, or requires more structuring. As discussed earlier, the purpose of building this model was to establish a good foundation for modelling Microgrids, and simulating their controls.

To add further demonstration on how a the microgrid model can be operated using a MATLAB code; a perceived scenario has been expressed in If-else Statement in this section. The following scenario is an example of what a linear control strategy could look like. The code is supposed to perform as following:
Renewable energy will supply the main load whenever available; if the renewable energy supply is not sufficient for load demand, the Battery supply will kick in. If the battery storage drops below 30% the system will start withdrawing power from the main grid; if the grid doesn't kick in and the battery storage drops more below 20%, the system will power down the main variable load and power up the emergency UPS that supposedly powers up only the critical loads; in other words, if the battery storage drops below 20%, the system will get rid of the non-critical loads. If the battery drops more below 10%, which means that the main grid failed to kick in, the diesel generator will start running.

Assume renewable energy generation permanently supplies the main variable load and battery charge and that battery charge is automatically run whenever any source is available.

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a) **If** renewable energy is sufficient to power up the main variable load **OR** Main grid is available **OR** Battery storage is >10%; **THEN** TRIP Diesel Generator; **Else,** run Diesel Generator.

   Endif;

b) **If** renewable energy is sufficient to power up the main variable load **OR** Main grid is running **OR** Battery supply is running and >20% **THEN** Power up main variable load, AND TRIP static loads (Assume static loads as emergency UPS); **Else** Trip main variable load, **AND** Power Up static loads (UPS).

   Endif;

c) **If** the battery storage was >30 **AND** the renewable energy is sufficient to power up the variable load; **THEN** Trip main grid supply; **Else** run main grid supply.

   Endif;

d) **If** renewable energy generation is **NOT** sufficient to power up the main variable load; **THEN** run Battery Supply;
   Elseif (Battery storage < 25% full **AND** Main grid supply is running) OR (Battery storage < 20% full **AND** Diesel generator is running) then Trip Battery Supply.

As discussed, predictive control can be also implemented, by factoring in weather and load profile forecasts, based on Meteorological data and user interaction with the users; such as in the Origin project that has been discussed in section 4.

8. Analysis and Conclusions

MATLAB VS LABVIEW review

Both MATLAB and LabVIEW are produced by reputable American International companies. Both vendors provide exceptional online based technical support, basic online trainings, self-learning documentation and manuals; however, due to the greater popularity of MATLAB+SIMULINK , more free of charge, working examples and libraries, are available for the latter; furthermore, MATLAB offers access to a noticeable larger open-source of toolboxes and libraries that are free for use, whilst only few demonstration examples are available in LabVIEW that are free of charge. Both manufacturers websites include knowledge exchange community forums to discuss technical issues and accumulate a knowledge base for their entire products. Users are highly likely to get helpful responses, through other experienced users, and devoted technical team within few days of raising a query; which is adequate for self-learning and educational use; for commercial and corporate users. Both MathWorks and National Instruments offer numerous training packages for purchase, for either academic or commercial use.

The higher popularity of MATLAB seems to be since it is suited for a wider variety of applications; mainly because LabVIEW is mostly designated and specialized in control and instrumentation applications, which is advantageous if that was the core focus of the application. However, National Instruments offers a software product “Multisim” which is used to build and simulate electronic circuits in a very similar manner to SIMULINK, and with even richer libraries that are equipped with power electronics, renewable energy, and complete analog and digital components, for offline or hardware simulation. Numerous add-on tool kits can be purchased to extend the functionalities and integration of LabVIEW, some of which have discussed in section 5. In LabVIEW, “Control Design and Simulation Module” needs to be installed for dynamic simulations, whilst this is a fundamental function of SIMULINK (offline dynamic simulations of systems based on their mathematical functions).

As discussed, LabVIEW can install the “Math Script RT” module to integrate MATLAB codes (code.m) with the Graphical G code; also, SIMULINK models can be imported and migrated smoothly to LabVIEW VIs, without additional engineering. On the other hand, MATLAB can be upgraded with the MathWorks “Instrument Control Toolbox” to monitor and control process instrumentation including LabVIEW hardware products; however, LabVIEW is still advantageous for instrument control and monitoring, due to its Graphical programming language, which is easier for monitoring real-time applications than the text-based language, and is more accurate and efficient in real-time signal processing and simulations; LabVIEW is also advantageous for its ability to build high level operator interfaces using its VIs graphical interface component (window), which is a built-in feature; similar applications have been discussed in section 5. While MATLAB is limited in graphical modelling and simulation tools.; LABVIEW’s graphical interface is far more sophisticated and suitable for process control operation and monitoring. According to (Aribor, U.N.O.F.M. et al), a paper aiming and comparing between both software packages, mathematical text-based codes were easier to implement, and three times faster in execution with MATLAB than LabVIEW, while the latter was more accurate and efficient for instrument control and signal processing, the paper concludes that MATLAB is preferable in mathematical and numerical computations than LabVIEW, due to the faster execution of the text based code than the function block execution. The paper also concludes that LabVIEW is noticeably easier and quicker in constructing system models, and block diagrams, than SIMULINK; however, it also mentions that the programming languages for both software platforms are easy to learn and use, which was confirmed by this project.

MATLAB+SIMULINK have been chosen in this Thesis over LabVIEW; Although LabVIEW has tremendous features and advantages; it would cost more and consume more time and effort to construct a “simple” model, due to the limited availability of (free to use) templates, and open-source libraries for Microgrids and their components. LabVIEW is more sophisticated and specialized when it comes to monitoring, control and graphical representation, but that comes with the extra cost that is required for purchasing additional tool-kits and template libraries; It can be concluded that its powerful features make it more suitable for larger and commercial use. LabVIEW is far more advantageous that MATLAB+SIMULINK when programming larger applications or higher resolution models, and is far more suited for the purpose of creating a test-bed or a simulation environment for academic or commercial long-term use as demonstrated in several case studies in section 5.

The reasons for these advantages are:

- The code can be structured using VIs, in a modular way, which makes it much more convenient to build a large application that may require replication of certain control loops, or an application that consists of different joint systems. That also helps incorporating text-based subroutines with the graphical block diagram based control loops. In a Microgrid model VIs can be used to break-down loads and micro generation sources into several VIs (Acting as subroutines) to provide more resolution for the analysis.

- In the occasion of using Hardware to resemble the system's components, National Instruments provides a full range of necessary equipment that are designed to Integrate with LABVIEW.

- The opportunity to construct graphical HMI for monitoring and interactive control is only available in LabVIEW; SIMULINK only includes blocks with embedded mathematical functions, to represent and dynamically simulate the system over a time duration; the only means to operate and control the SIMULINK model during simulation would be through the MATLAB text-based code while in LABVIEW interacting with the model through graphical interface is possible during simulation.

- LabVIEW can combine both the text-based code with its graphical code (G), in the same platform, without the need to interface, which provides much higher flexibility when large applications, as some subroutines might be easier to build using text-based code, such as mathematical functions, while others would be easier to implement using blocks. Both type of programming differs in their execution order which can be a decisive element for choosing with different applications.

- As mentioned, National Instruments offers a product “Multism”, which is not free of charge, that is specialised in offline dynamic and real-time hardware modelling of power electronics and renewable energy systems, and includes full ready to use libraries for these mentioned applications; the product is very like SIMULINK. If the aim is just offline simulation of a simple mathematical functions based model; Multisim would be the best alternative for SIMULINK.
- LABVIEW is capable of importing both MATLAB codes and SIMULINK functions with minimal requirement of Engineering time.

In Microgrid design, technical challenges seem to be case dependent, and vary in relation to design type, desired functionalities, and objectives. Microgrids running in Island mode are likely to encompass higher complexity and challenges due to their prescribed ability of self-reliance and running independently, which requires high flexibility and efficacy of Supply-Demand matching, to maintain an adequate level of system stability. To promote the replication of Microgrids projects, they need to be appealing for consumers and business investors; for that to happen, the technical and economic challenges need to be all addressed, considered and alleviated, when attainable; thus a deep feasibility analysis should be undertaken carefully while considering long-term, planned and unexpected, maintenance activities; in addition to potential future changes in arrangements, structure or scale.
The main goal of this project was to demonstrate the potential benefits of Microgrid simulation, while investigating the potential and possible arrangements for creating a Microgrid simulation environment. A MATLAB+SIMULINK model was used to conduct basic offline analysis for a Microgrid model, for demonstration, aiming to inspire further work of establishing a Microgrid test environment.

This project has successfully accomplished all its goals and would hopefully contribute towards a Microgrid testbed at the Strathclyde University.

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