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*DC Microgrid Simulation and Control*

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*July 2017*

## Abstract

Microgrid is a small renewable distribution network that can be connected to the main utility grid and can be operated in islanded mode or disconnected mode. There are two different types of microgrid; ac and dc which depend on the type of renewable source. The variability of renewable energy must operate in conjunction with traditional energy forms.

However, one of the primary challenges in the microgrid is controlling power electronic devices when it is coordinated with the utility grid. The control system in the microgrid has the main objectives, to ensure supply power to the critical loads, to connect and disconnect the load in case of any fault occurring in the microgrid. This thesis investigates different types of strategies used to control and manage a microgrid; also, the report considers inverter control in islanded mode.

This thesis explores the ideas for controlling a microgrid in terms of voltage control in both centralized and decentralized configurations. In more detail, simulations were carried out on two control strategies; inverter control, and frequency control. The inverter control method having the ability to bring the stable and efficient electricity to microgrid system has attracted much consideration in recent years. The droop controller had the capability to autonomously perform equal power sharing and maintain stability in islanded mode of operation.

There are many existing dc microgrid around the world. Kythnos Island microgrid is one of those existing microgrid, which can supply 12 houses within the island by using the inverter controller, as the utility grid is located far away from the microgrid. However, this island is either ac or dc loads, so some inverters and converters will be involved in the network.

The investigation used MATLAB /SIMULINK to simulate the microgrid network. Which done by implementing the controller in the both ac and dc load. The performance measures such as power sharing accuracy between the microgrid and diesel generator will be obtained. The diesel generators used as a backup in the case of any fault occur in the microgrid. The network simulations at different dc and ac loads will be simulating by using Simulink. This then used to calculate the efficiency of the whole network through the Simulink. Then how efficiency is can be used to upgrade the network as future scope.

Active and reactive power in the droop control has been commonly reported on and has been shown to work over a series of the condition of the network. The PQ inverter improves

the performance of microgrid in islanded mode; however, the result demonstrates that the inverter controller performed well in the simulation of the Kythnos microgrid network. The efficiency of the LVDC indicates that inverter controller with the ac load performance higher efficiency compared to the dc loads.

## **Acknowledgements**

I would like to thank first and foremost my supervisor Dr. Ali Arefi, for his support and supervision over the course of this thesis. His broad depth of knowledge was helpful for making this report possible. He has encouraged me to do my best to develop my academic skills. And to my family and friend who kept me sane during this time.

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## Glossary

|      |   |
|------|---|
| AC   | Alternative Current                     |
| BMS  | Battery Management System               |
| DC   | Direct current                          |
| DER  | Distributed Energy Resources            |
| DG   | Distributed Generations                 |
| DILC | Distributed Intelligent Load Controller |
| DPC  | Direct Power Control                    |
| GPRS | General Packet Radio Service            |
| IGBT | Insulated Gate Bipolar Transistor       |
| LC   | Local controllers                       |
| LVDC | Low Voltage Direct Current              |
| MC   | Micro Source Controller                 |
| MG   | Microgrid                               |
| MGCC | Microgrid Central Controller            |
| MMO  | Multi Master Operation                  |
| MS   | Micro Sources                           |
| PLC  | Power Line Communications               |
| PQ   | Active Power and Reactive Power         |
| PV   | Photovoltaic                            |
| PWM  | Pulse Width Modulation                  |
| SG   | Synchronous Generator                   |
| SMO  | Single Master Operation                 |
| SOC  | The State of Charge.                    |
| ST   | Switching Table                         |
| VSI  | Voltage Source Inverter                 |

## 1 Introduction

Over the last decade, the application of the energy over the world is rising on a regular basis. Which is above the boundaries of the traditional grid and development it depends on fossil fuels, and increase the amount of the CO<sub>2</sub> emissions. These things have renewed the activity in finding out ways to decrease power demand on the grid through alternative energy; that is, renewable energy. The main application of the renewable energy is Photovoltaic (PV).

As the common of electronics are operating on direct current and to the renewable energy system, for example, PV power system generating dc power energy usage. With the advance of this, the power inverters technology has tested regarding connecting to the energy resources to the main utility grid. However, it is predictable that the inverters connected in parallel as to supply power to the loads. Therefore, how to control these inverters becomes more challenging. Also how to share the power within those inverters, this occurs when the load demand change. The droop control is used to settle the power sharing between the inverter and conventional technology, this type of controller not required mechanical communication to achieve sharing power automatically.

The microgrids can operate in two ways of islanded mode or grid connected. In the islanded mode the microgrid is disconnected from the main utility grid and can be operated independently, by this mode the network can satisfy the local load requirement. Operating in island mode can protect the components in the case of any fault will occur in the microgrids.

This report will explore the different technology used in the dc microgrids and the performance of inverter control approach. Moreover, based on the research on the existing microgrid network around the world it will be simulated by using the MATLAB/Simulink.

The system simulation will be simulated based on the assumption and approach that consider being implemented as a case study for this project, which due to the availability of network data and MATLAB/SIMULINK block as the limiting of the block is 100 in each workstation. The case study will be about Kythnos Island microgrids to simulate and control the network.



### 1.1 Aim description

The aim of this thesis project is to get familiar with the principle of voltage control method operating in the purely resistive network. Moreover, the project is developed to simulate the case study of existing microgrids with using inverter control to control the network. Comparison between two different ac and dc loads, based on the low voltage DC supply (LVDC).

### 1.2 Thesis Construction

This project will evaluate the network of simple dc microgrid controller at two different types of loads dc and ac load with the inverter control. Then the power sharing between three parallel Inverters. The report is divided into five chapters. Chapter 1 will explore the entire thesis work. Chapter 2 will review the background about microgrid, advantage and disadvantage of using microgrids. Chapter 3, illustrate the comparison between alternating current and direct current microgrid. This chapter will also explore the main difference between two microgrids, following be calculating the efficiency when the LVDC supply to the ac and dc loads.

In Chapter 4, different types of control will be explored, in terms of the control schematic, mathematics block diagram and the development based on the research paper. In Chapter 5, the case study of the existing microgrid will be simulated by using the MATLAB/SIMULINK at different loads.

Also, it provides all the result of the projects. Chapter 6 will conclude the project and recommend improvements to the conventional inverter control.

## 2 Background about Microgrids.

A microgrid is fundamentally a low or medium voltage distribution network which consists of a grouping of an electricity source and loads. There are different types of micro-sources, for example; fuel cell, wind turbine, and photovoltaic array, which are called distributed generators (DG). Moreover, the microgrid can be locally controlled from that, they can disconnect from the grid when there is any fault that could occur in the main grid [1]. Microgrid could categorize into different groups based on the type, size, application, and connectivity.

- a) Type of microgrid, for example, campus, residential, commercial, industrial and military.

- b) The size of the microgrid classified into three sizes small, medium and large scale.
- c) Application of the microgrid such as premium power, resilience-oriented, and loss reduction. The connectivity of microgrids either remote or grid connected.

Moreover, microgrid types can be identified based on the voltage and current modified which are; alternating current (ac) microgrid, direct current (dc) and hybrid microgrid.

In the ac microgrid, all the distributed energy resources (DER) and loads are attached to a common ac bus as shown in Figure 1. Then dc generating units, as well as energy storage, will be connected through ac bus via dc to ac inverters, and further ac to dc rectifiers used for supplying dc loads [2] .

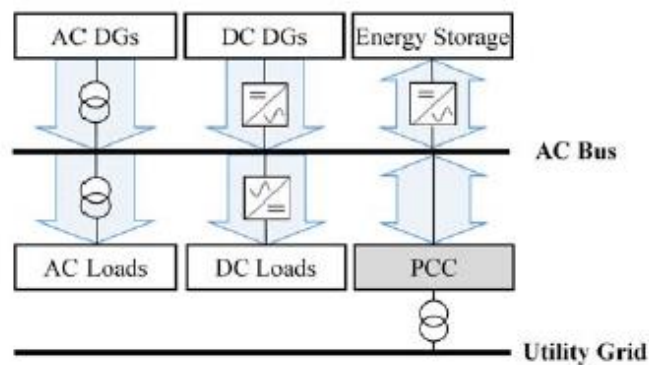


Figure 1 General Structure of AC Microgrid [2].

In dc microgrids, the common bus is dc, where ac to dc rectifiers used for connecting AC generating units. Also, a dc to ac inverter is used for supplying ac loads, as shown in Figure 2. Hybrid microgrids can be considered as a combination of both ac and dc microgrid, where both types of buses exist, and the kind of connection to each bus depends on the proximity of distributed energy resources (DER) and load to the bus. In depth explanation, the difference between ac and dc microgrid will be explained in comparison section [2].

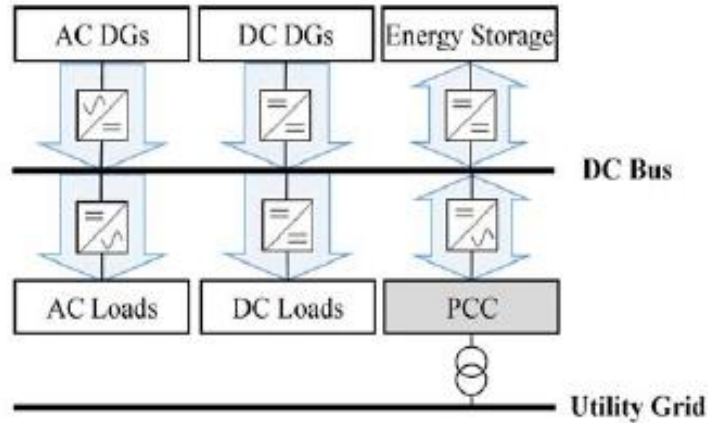


Figure 2 General Structure of DC Microgrid [2].

## 2.1 Advantage and Disadvantage of Using Microgrids.

An increased demand for using microgrids is very promising for the electrical energy industry as the following benefits: environmental, operation, power quality, cost saving and market. In the environmental, it reduces carbon footprint, then in operation and investment, by a decrease of the physical and electrical distance between the micro source and loads. Could be contributing to main benefits, that is an advance of reactive support of the whole system, which in turn will enhance the voltage profile. Power quality, as microgrid increase reliability locally through the establishment of a specific reliability improvement plan.

This combines redundant distribution, automation, smart switch, power generation and energy storage [3]. Then, cost saving affecting by two ways: Firstly, by utilization of waste heat in combined heat and a power mode of operation, as the source located nearby the customer loads, no essential infrastructure is required for heat transmission. Secondly, cost saving also made through the integration of several micro sources.

Even though there are potential benefits to the development of microgrids, it could face potential difficulties. Most of these could be overcome by time and encouragement of the government and customer. Disadvantages of the microgrid are:

- a) High charges of distributed energy resource: the most affecting difficulty for the microgrids is the high installation cost.
- b) Lack of standards: as microgrids quite new area, and the standards are not yet available for addressing operation and protection issues [4].

### 2.1.1 Microgrid Architecture and Classification.

The simple architecture of a microgrid system is shown in Figure 3. A microgrid system consists of four parts: Distribution System, DG sources, Energy Storage, Control and Communication Modules.

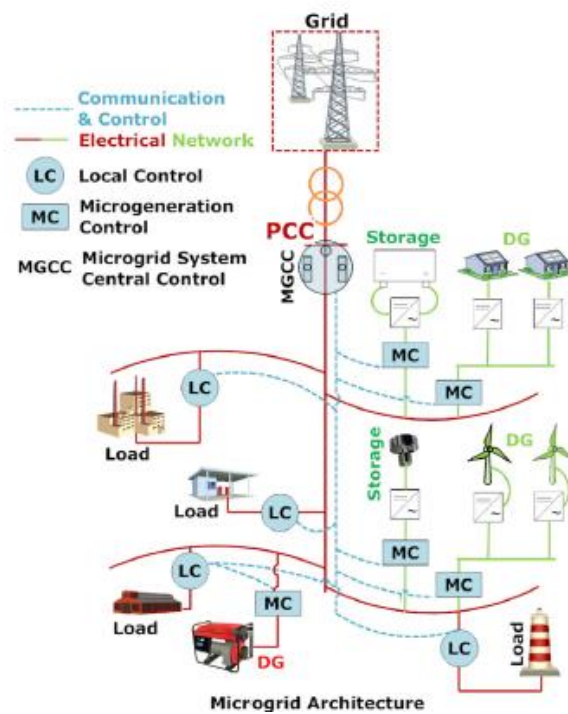


Figure 3 Microgrid Architecture [5] .

Classification of microgrid systems mainly based on the selection of the above components and the integration with the main electrical grid network. The classification which shows in Figure 4 as the primary structure of this classification which are:

- a) Distribution Systems: such as transmission line, distribution networks, and technologies. Available technologies for microgrid are studied in where the line frequency ac and dc technologies that consider for transmission and distribution system.
- b) Distributed generation resources: The technologies related for microgrid may include a sort of technologies such as (PV) system and wind turbine. Table 1 shows the difference of sources of distributed generation [6].

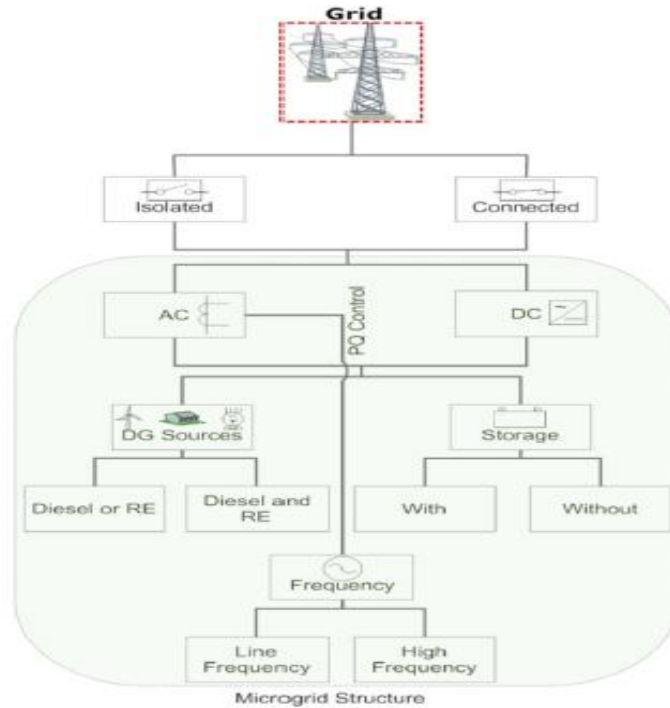


Figure 4 Microgrid Structure [5]

Table 1 Typical Characteristics of Common Distribution Generator Sources [7].

| Characteristics        | Wind                                   | Solar                                    | Micro-Hydro                        |
|------------------------|--|--|------------------------------------|
| Availability dependent | Cerographic location                   |  |                                    |
| Output power           | AC                                     | DC                                       | AC                                 |
| Control                | Uncontrolled                           |  |                                    |
| Converter              | (AC-DC-AC)                             | (DC-DC-AC)                               | Synchronous or Induction generator |
| Power Flow Control     | MPPT, Pitch and Torque control(+P, ±Q) | MPPT & DC link voltage controls(+ P, ±Q) | Controllable (+P, ±Q)              |

c) Storage devices: one of the primary requirement for efficient operation of a microgrid is the inclusion of energy storage device, which used as balances the power and energy demand with generation. There are three types of energy storage methods have been established so far, and they are flywheels, batteries and a super capacitor. Table 2 shows three of basic types of storage devices [7].

**Table 2 Basic Feature of Suitable Storage Devices in Microgrid System [7] .**

| Basic features          | Battery     | Flywheel | Super-capacitor |
|-------------------------|-------------|----------|-----------------|
| Continuous power [W/kg] | 50-100      | 200-500  | 500-2000        |
| Typical back up time    | 5-30 min    | 10-30s   | 10-30s          |
| Losses at standby       | Very low    | Variable | High            |
| Environmental Impact    | Medium High | Low      | Low             |

d) **Control and Communication Modules:** the communication systems for power control and protection. The primary communication technique with their characters shown in Table 3. There are different types of the communication systems using in the microgrid which are GPRS, 3G, WiMax, and PLC. There are various methods used to chose the communication network whcih are data transfer, cover range and limitations. WiMax, for instance, has fast data transfer ratio (up to 75 Mbps) and large coverage range, but the limitation is that spectrum fees are costly. In PLC communication systems, data rates are in the range of 2-3 Mbps and coverage ranges between 1 to 3 Km as shown in Table 3. For the long-distance communication, WiMAX and 3G used for short distance communication, PLC systems are preferable [7] .

**Table 3 Different Communication Systems Applicable in Microgrid [7] .**

| Technology | Spectrum          | Data Rate          | Coverage Range [Km] | Applications [AMI]   | Limitations              |
|------------|-------------------|--------------------|---------------------|----------------------|--------------------------|
| GPRS       | 900–1800MHz       | Up to 170 Kpbs     | 1–10km              | Demand Response, HAN | Low data rates           |
| 3G         | 1.92– 1.98GHz     | 384 kbps to 2 Mbps | 1–10km              | Demand Response, HAN | Costly spectrum fees     |
| WiMax      | 2.5, 3.5, 5.8 GHz | Upto 75 Mbps       | 10–50 km            | Demand Response, HAN | Not wide spread          |
| PLC        | 1–30 MHz          | 2-3 Mbps           | 1–3 km              | Fraud Detection      | Harsh, noisy channel env |

### 3 Comparison between Alternative Current and Direct Current Microgrid.

In this section, the comparison between two types of microgrids will be explained in different ways, from architecture difference, distribution lines, power electronic converter, and efficiency. The comparison will be based on the literature review and simulation using MATLAB/Simulink software tools to simulate ac and dc microgrids of the existing microgrid in Europe. Kythnos microgrids in Greece are considered to be the case study for the comparison over the project in terms of the simulation the network and analysis the result of the controlling.

### 3.1 Low Voltage Alternative Current (LVAC).

All the electricity generating units (for example DG units) with the ac power supply the output are directly connected to an ac bus line, which then connected to the main network through power converters . ac output power can be produced by DG units which include wind turbines, biogas, tidal and wave turbines. Those DG generally directly connected or might require the ac/dc/ac power converter which used to enable their stable coupling with the low voltage altranative current system [8].

Additionally, the ac load are directly connected to ac bus whereas the dc loads need power converters ac/dc to attach to the LVAC networks. Alternatively, any DG units which produce dc power output for example solar photovoltaic arrays (PV) and fuel cells with energy storage devices like battery chargers could be connected to the ac bus line by using the dc/ac inverters. The typical configuration of the DG units with the ac power output is a wind turbine, and dc power outputs are PV system and fuel cells which connected to the LVAC network as shown in Figure 5 [8] .

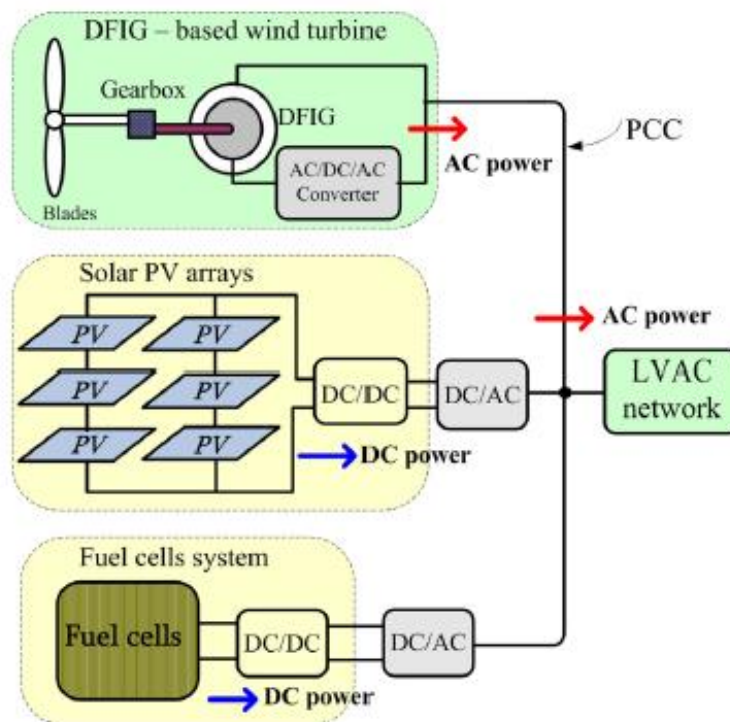


Figure 5 Typical Configuration of the DG units with LVAC network [8].



### 3.1.1 AC Microgrids

The standard ac microgrid system consistent with medium voltage system at the point of common coupling (PCC) is shown in Figure 6, which the primary system could be ac or dc bulk system. The distributed generation units and energy storage system (ESS) connected around points within the distribution networks. Then part of the network involving the DG units and load circuits could form a small isolated ac electric power system, which is known as ac microgrid [8].

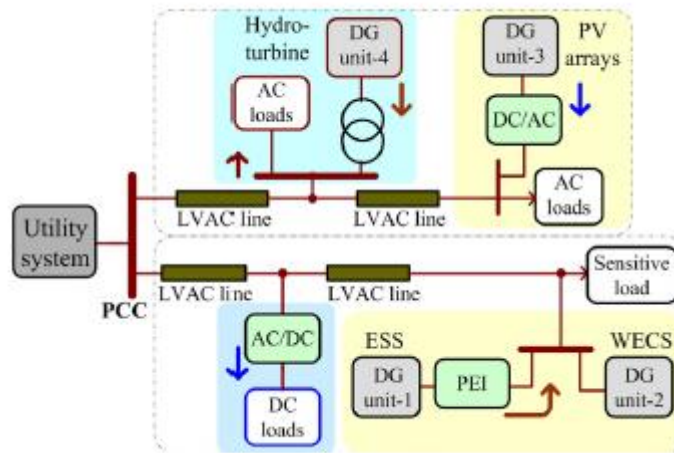


Figure 6 AC Microgrid Structure with the DG units [8].

During the normal operation conditions, both the networks are interconnected at the point of common coupling and the loads are supplied from the local sources, for example, the renewable energy sources (RES) based on the DG units.

In the case of the load demand power is less than the power which produced by the DG units, then the excess power can be exported to the main system. Table 4 indicates some of the typical examples of the ac power load that are in our homes.

Table 4 Typical Example of Home AC Powered Appliances [8] , [9]

| Sl.no | AC powered Loads       | Voltage Ratings(V) | Current Ratings (A) | Power Ratings |
|-------|------------------------|--------------------|---------------------|---------------|
| 1     | Microwave oven         | 240                | -                   | 8.3K          |
| 3     | Toaster                | 120                | -                   | 1050          |
| 5     | Electric clothes drier | 240                | -                   | 5600          |
| 6     | Electric cook-top      | 240                | -                   | 8.8           |
| 7     | Refrigerator           | 120                | 8.3                 | -             |
| 8     | Washing machine        | 120                | 7                   | -             |



Implementations of ac microgrid system over the world shown in Table 5. The voltage level is varying between one phase to three phase which is based on the DG units, and most of the microgrid using same frequency 50 Hz. As illustrated in Table 5. Kythnos microgrid in Greek Island the main DG unit is PV arrays with the Diesel Generators used as a backup in case of fault or maintenance in the PV arrays. The supply voltage is three phases but all the house in the Kythnos supply by one phase LVAC, more explanation will be in the simulation of ac microgrid.

**Table 5 Typical Example of AC Microgrid Systems [8] , [9] .**

| Locations             | AC microgrid Components                             | Voltage Level   | Frequency | Capacity  |
|-----------------------|---|-----------------|-----------|---|
| Kythnos, Greek Island | PV arrays, diesel generators, battery Banks         | One Phase LVAC  | 50 Hz     | 12 kWp from PV system, 85 kWh from battery bank |
| Hachinohe, Japan      | PV arrays & BESS- rural areas                       | Not specified   | 50 Hz     | 0.5–10kWperhousehold                            |
| Japan                 | Gas engines (GEs), wind turbine (WT), EDLC and BESS | 110, 230, 240 V | 50,60 Hz  | 50kW–2MW  |
| Porto, Portugal       | Fuel cells, PV arrays, WTs, ESSs and AC utility     | 400 V           | 50 Hz     | 50–200kW  |

## 3.2 DC Microgrids.

### 3.2.1 Low Voltage Direct Current (LVDC).

The LVDC network which used for business power supply and commercial buildings are increasing day by day. Moreover, in the future, the dc supply system will turn into an alternative way to provide all the electrical equipment connected to a bus system and optimally controlled through an energy management system (EMS). The PV system one of the primary example of the DG unit supply dc, which has an exceptionally modular structure with a lot of potential structure available in which the PV inverter could be connected [8].

The developed structures of LVDC networks designated as the central or string inverter. This way, the Direct current based on the DG unit and the energy storage system (ESS), which produced the dc Power, will be easily connected to the LVDC network or the bus line.

In the Energy storage system could be charged/discharged with the LVDC network and at different loads either ac load or dc load, which connected to the network [8] [10]. That in the case of the DG unit is based on the dc, but when the ac power generations units on the LVDC network then it required ac/dc power converter for their connection. In Figure 7 shows the LVDC network with the different types of DG units which are connected to it through the common bus bar at the point of common coupling (PCC). Based on the DG units that, for instance, ac based (Wind turbines) is connected to the network requires ac/dc inverters, while the dc-based (for example PV and fuel cells) are directly connected to the LVDC as shown in Figure 7.

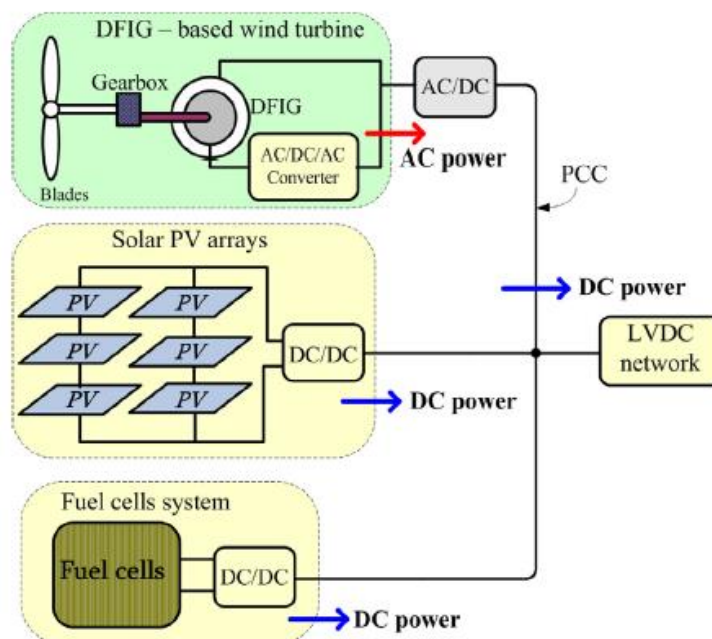


Figure 7 Typical Configuration of the DG units with LVDC network [8].

### 3.2.2 DC Microgrids.

The dc power systems have been utilizing in a different field for instance in manufacturing power distribution systems, telecommunication infrastructures, and point-to-point transmissions over long distances for interconnecting ac grids at a various range of frequencies. Moreover, most of today and future equipment’s are dominated by power electronic devices.

Different devices used the dc power for their operation, for instance, personal computer, variable speed drives, business and industrial application.

All these dc devices main supply is ac power then it required conversion of the available ac power into dc for use, and most of these conversions used inefficient rectifier [8]. Furthermore, the power from dc converted into ac to tie with the existing ac electrical network, which later converted to dc for the user, it will cause at some stage in substantial energy losses. The Low voltage direct current supply (LVDC) network is a new idea which is main option to challenge the current power supply issue and realize the future power system [8], [11]. The dc microgrid system interconnected shown in Figure 8 with the primary systems at the point of common coupling (PCC), which could be medium voltage ac network from the traditional power plants, with the different types of loads.

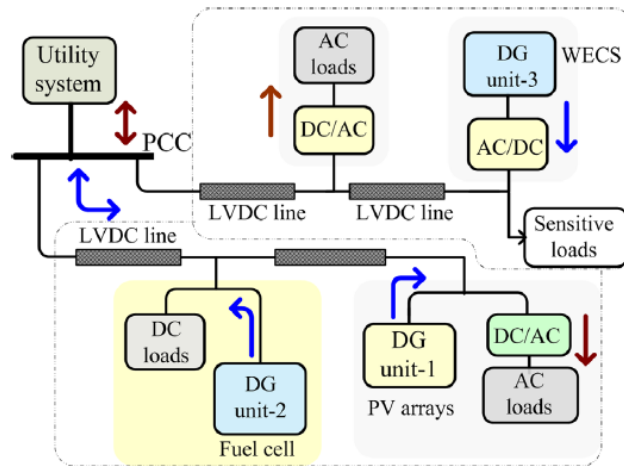


Figure 8 Concept of a DC Microgrid system with the DG [8]

Table 6 illustrates some of the examples using dc powered appliances at home. As a result from the Table that the voltage ratings from 5 to 20 volt. In Table 7 shows the typical example of the dc microgrid systems used as a testing model.

Table 6 Typical Example of Home using DC Power Application [8]

| Sl.no | DC powered Loads               | Voltage Ratings(V) | Current Ratings (A) | Power Ratings(w) |
|-------|--------------------------------|--------------------|---------------------|------------------|
| 1     | Laptop computer                | 20                 | 4.5                 | -                |
| 2     | Cell phone                     | 5                  | 550 mA              | -                |
| 3     | Wireless Phones                | 6.5                | 500 mA              | -                |
| 5     | Battery Powered Vacuum Cleaner | 10                 | 250 mA              | -                |
| 6     | Cable Modems                   | 12                 | 750 mA              | -                |
| 8     | USB Port                       | 5                  | 3.8 A               | -                |

**Table 7 Typical Example of DC Microgrid Systems [8].**

| DC Microgrid Components                | Voltage Range                  | Capacity |
|--|--------------------------------|----------|
| Sweden UPN AB for Data Center IBM      | 24–350/380LVDC(bipolarDC-link) | ≥5MW     |
| Japan NTT Group for data Center        | 380/400 LVDC (bipolar DC-link) | ≥5MW     |
| New Zealand Telecom NZ for data Center | 220 LVDC (bipolar DC-link)     | 0.5–5MW  |
| The US Intel Corp for data Center      | 400 LVDC (bipolar DC-link)     | ≥5MW     |

In the situation of dc microgrid arrangements, the low voltage dc (LVDC) links are based on a bipolar structure where the loads can be connected to the positive polarity and the ground or between the two polarities [8].

An improvement the efficiency of delivering power to the distribution system can be through by using the LVDC distribution network. It guarantees a higher power quality to the customers than in the present distribution network and assists more DG unit's connection [12].

### 3.2.3 Efficiency between AC and DC microgrid.

The most significant factor uses to measure the comparison between ac and dc microgrid is the efficiency, with the same DG unit but at different Load. There are two main differences which are the battery positions and electrical devices (inverter and converter) of loads. However, Figure 9 shows both off as efficiency measurement, the most impact of the energy calculations of the efficiency are:

- a) In ac microgrid battery bank located before the ac inverter, as using the inverter, there is the amount of source loss which happens on the inverter. In term dc micro-grid with distributed storage, this loss is mitigated throughout night time as the dc delivery is off at night. Most of the user applications are dc devices such as computers. The losses from the point of load (POL) which ac/dc converters have been assessed to be around 15% [13]. However, this energy which lost without any end user benefit.
- b) In ac microgrid, inverter losses could be control by a mismatch between the rated power to the actual load. The peak power load used to determine the size of the inverter (KVA-rating). There have been several microgrid studies, which show that peak loads are associated in time across many houses. For instance of such loads are electric kettles and electric rice cookers running at the same time of the day [14]. However, in the dc microgrid with the distributed storage, the batteries

function as remote energy buffers that filter variability in power request on upstream power converters [15].

- c) Inverter efficiencies suffer when the average power demand is significantly below the peak in an ac microgrid, which is because inverter efficiencies are highest when operation between 80-90% of the rated output capacity. Then operating the inverter at the low utilization rate (at average load/ rated capacity), it will affect the overall efficiencies of the ac microgrid suffer [15] .

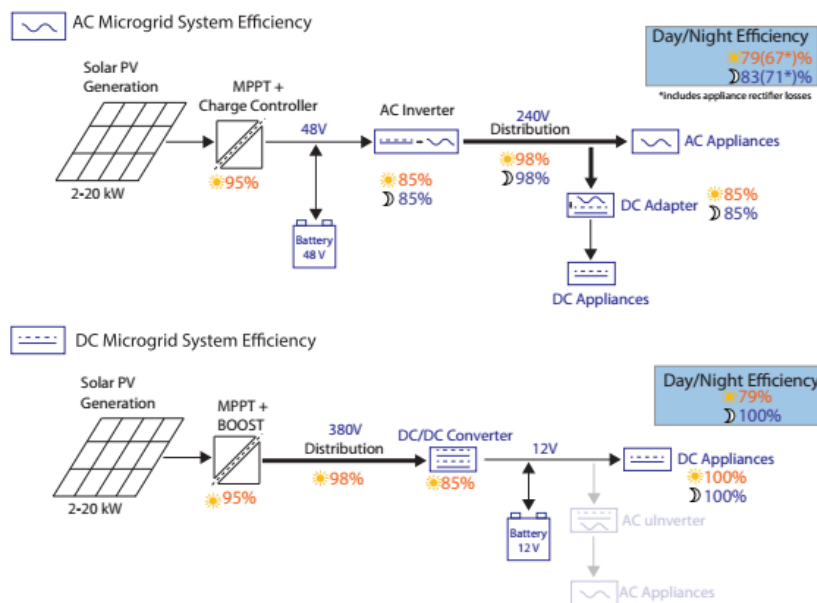


Figure 9 Efficiency of AC and DC Microgrid [15] .

### 3.2.4 Power electronic Converter in AC and DC Microgrid.

From the ac and dc microgrid structure that, dc microgrid need for the dc/dc converter to power the dc load, and dc/ac inverter to power ac loads.

- a) The inverter is used to supply ac load from the dc distribution system. Then conversion from the dc to ac is required. However, the output from the dc/ac converter having two options which can be made either single as shown in Figure 10 or three phases which could be decided based on the requirement of the system. In the simulation stage only considered being use single phase full bridge inverter.

- b) DC/DC converter which is mainly in the dc microgrid to, which used to obtain a desired dc voltage range for the supply load, a power electronic converter which converts a source voltage to another voltage level is needed. They are two type of dc/dc converter either boost or buck converters, in the boost converter the input voltage lower than the output voltage, but in the buck convert the input voltage is greater that output voltage.
- c) AC/DC Rectifier, which is mainly in the ac microgrid, the conversion from the AC/DC can be obtained through two options the active bridge or passive diode bridge. The main difference between them is the active bridge is a wide range of control in the active bridge, also can obtain a bidirectional power flow. In the passive diode bridge, the main disadvantage is that separate starting device is required, as its draws high charging current during the initial starting conditions. [16].

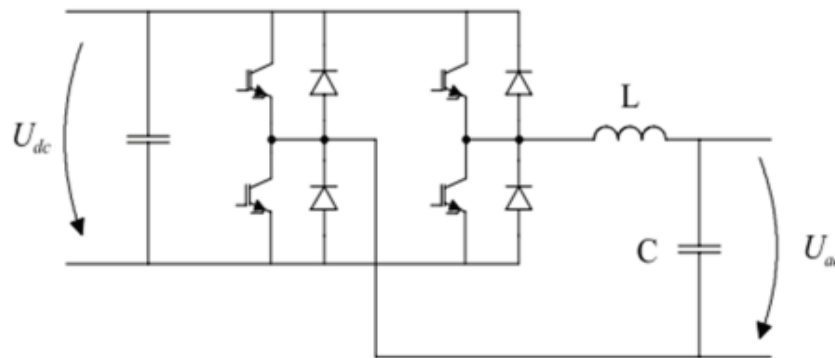


Figure 10 Single Phase Full Bridge Inverter with LC Filter [16] .

### 3.2.5 Comparison between AC and DC in distribution lines.

The Low voltage in both ac (LVAC) and dc (LVDC) distribution lines are characterized by different parameters, for example, power transmission capability, reluctance, frequency, susceptance's, line resistance and system stability. The comparison between the two ac and dc low voltage distribution lines shows in Table 8, and the operation of the ac and dc microgrid can also express in the form of the voltage.

**Table 8 Comparison between AC and DC distribution Lines [8] .**

| Effect Parameters | AC Distribution Line  | DC Distribution Line   |
|-------------------|---|--|
| Power transmitted | Due to high line loss, it is having the less efficiency. Require more Conductors. | Having more efficiency than AC, and more power transmission. Require few Conductors. |
| Frequency         | Frequency monitoring is Mandatory either 50 or 60 Hz.                             | Frequency is zero so no need of 50 or 60 Hz  |
| Reluctance        | Have Reactance on the line.   | No Reactance in the line and hence more power are transmitted.                       |
| Resistance        | Having the Line resistance and hence high losses.                                 | Have low line resistance.  |
| Analysis          | Involve Complex numbers and hence difficult to analyze                            | Involve Only real number.  |

The flow of the current and power transport in their distribution lines and circuit as shown in Table 9 [8]. The effect of the line parameters, in the both circuit, is to be considered with only the type of source that differentiates the two circuit.

**Table 9 Analysis of AC and DC circuit [8] .**

| Circuit      | DC circuit Analysis                                     | AC circuit Analysis   |
|--------------|---|---|
| Circuit      |   |   |
| Power Load   | $P_{LDC} = P_{LAC} = P_L$                               | $P_{LDC} = P_{LAC} = P_L$   |
| Voltage load | $V_{LDC} = V_{LAC} = V_L$                               | $V_{LDC} = V_{LAC} = V_L$   |
| Current      | $P_{LDC} = V_L * I_{DC}$ $I_{DC} = \frac{P_2}{V_{LDC}}$ | $P_{LAC} = V_L * I_{AC} \cos(w)$ $I_{AC} = \frac{P_2}{V_{LDC} \cos(w)}$ |

The following chapters will cover the different types of controllers used to control the microgrid. Then, explore the one which will be used in this report. There are many existing microgrid over the world, some of them dealing with ac power source and other with dc power source which is depending on the availability of the sources and the demand for it.

In this report, the case study will be about the Kythnos dc microgrid which is located in Greece Island. Kythnos microgrid is one of the most stable microgrid with the main distribution generation is PV array and diesel generator used as a backup in case of any fault occurs in the microgrid. Then over the report, it will explore in details about, the system configuration of the Kythnos microgrid network, cost rating, type of control used to control the microgrid.

MATLAB/Simulink is one of the software tools used in engineering to simulate the network of any system. In this case study MATLAB/SIMULINK used to simulate the network, and from that, the comparison between two networks will be carrying one and checking the efficiency between two types of microgrid network.

#### 4 Microgrid control

As microgrid contain different types of renewable distribution generators and the energy which produced by the energy source, it is difficult to be predicted. However, the power between the main grid and microgrid needs to be controlled in the grid-connected mode. Microgrid should have the ability to last when the main grid has been disconnected. Therefore, choosing the proper control techniques is a requirement to satisfy the issues that could face the microgrid [17]. Also, the control system maintains frequency and voltage level in island control of the operation [18]. The main objectives of microgrid controllers are:

- a) Having the ability to plug and play feature when connected new DG into microgrid.
- b) Dynamic load sharing as load suddenly increase or decrease in the islanded mode operation.
- c) Controlling the reactive power and distribution generator power flow to host grid under the demand of host network in a grid through connected mode [19] .
- d) Ability to manage the stability of the system in case of network disturbance [20] .
- e) Ensuring the power quality of microgrid within the standard, also keeping voltage and frequency fluctuation and phase angle within limits [19] .

The main principle method used to maintain the stability in MG is droop control which is classified as active power frequency P/F and reactive power-voltage Q/V.

These two controllers are the primary standard that could enable multiple synchronously rotating machines to control power sharing and maintain voltage/ frequency stability [19]



In the following section, more details about three types of control undertaken for a microgrid when its interfaces to the main utility grid are discussed.

#### 4.1 Hierarchical Control Levels in the Microgrid

There are three main hierarchical levels that can be applied in a microgrid network, as shown in Figure 11.



Figure 11 Hierarchical Control Level in the Microgrid [21] .

##### 4.1.1 Primary Control.

Primary control is the faster response, and first control compares to others level control [22]. In the microgrid, the main controller is the responsibility of the local voltage controller with power reliability, proper power sharing, and a stable microgrid operation [23]. Furthermore, the primary control is designed to satisfy the following requirements:

- a) Maintain the voltage and frequency following to an islanding even, the microgrid may lose its voltage and frequency stability due to the imbalance of the power generated and customer.
- b) Providing the reference points for the voltage and current control loops of Distributed Energy Resources (DER) [24].

Primary control normally results in differences to the setpoint of the frequency and voltage set points, then using the secondary control to correct this [24].

##### 4.1.2 Secondary control

The secondary control ensures that the electrical levels into the microgrid are within the required value [21] . This controller is designed to have slower dynamics response than that of the primary, which justifies the decoupled dynamics of the primary and secondary control loops, and simplifies their designs. Moreover, secondary control can also be aimed to satisfy the power quality requirements; for instance, the voltage balancing at critical buses.

Figure 12 illustrates how the secondary control removes voltage and frequency deviation caused by primary level in the microgrid units [25]. In Figure 12a, the performance of primary and secondary control for two distribution generator (DGs) with different droop measurement has been shown, that primary control just shifts by the secondary control response to allow the frequency to reach the nominal value, even DG is operating at different power rating [25].

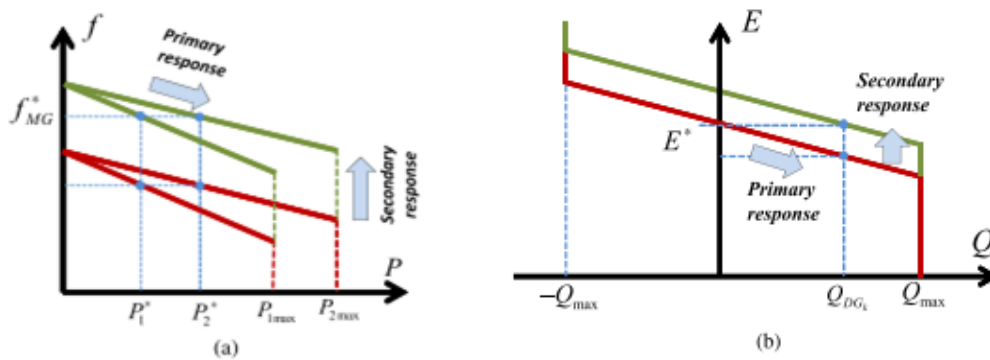


Figure 12 Secondary v Primary Control Responses (a)frequency restoration (b) voltage restoration [25] .

In the case of a control system using the droop control, if a DG is supplied to deliver a stable active and reactive power through Islanded mode. Then using the secondary controller to shift the droop curve vertically, so that the DG output proceeds to active and reactive power set points, as illustrated in Figure 13 [26].

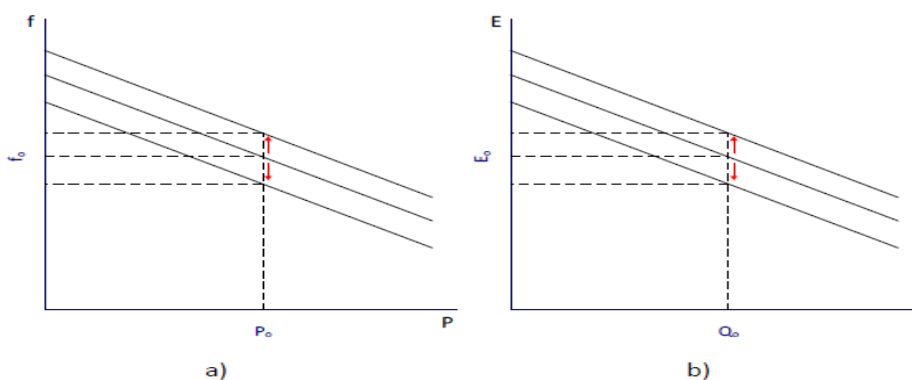


Figure 13 Secondary Control for Active and Reactive Power [26] .

### 4.1.3 Tertiary control

This control is the highest control level, and the main function of this control is to achieve power flow by controlling the voltage and frequency when the microgrid is in grid-connected mode. The network's grids active and reactive power can be compared besides the desired reference by measuring the real and reactive power through the point of common coupling (PCC). Hence, the active power at the grid can be controlled by adjusting the microgrid reference frequency [27]. In the case of any fault at the microgrid, the power transaction link between the grid and microgrid is disconnected and allowed to reduce the system frequency. Due to the issue, microgrid transfer to the Island mode and tertiary control will be disabled [27].

## 4.2 Droop Control

Mainly the droop control technique can be used to maintain load current sharing, which done by changing output voltage under both voltage and current droop characteristic [19]. Moreover, the relationship between reactive power and voltage, active power and frequency can be recognized by considering a simple microgrid with an interfaced inverter system as shown in Figure 14, that distribution generator connected to the load, with the impedance,  $Z$ . The active and reactive powers can express as following two Equations:

$$P = \frac{V_S^2}{Z} \cos\theta - \frac{V_S V_L}{Z} \cos(\theta + \delta) \quad (1)$$

$$Q = \frac{V_S^2}{Z} \sin\theta - \frac{V_S V_L}{Z} \sin(\theta + \delta) \quad (2)$$

Where,  $\theta$  is the angle of line impedance,  $Z = R + jX$ , then (1) and (2) can be rewritten as:

$$P = \frac{V_S^2}{R^2 + X^2} [R(V_S - V_L \cos\delta) + X V_L \sin\delta] \quad (3)$$

$$Q = \frac{V_S^2}{R^2 + X^2} [-R V_L \sin\delta + X(V_S - V_L \cos\delta)] \quad (4)$$

From Equations (3) and (4) show the dependency of the inverter output voltage and power angle  $\delta$  to the reactive and active powers.

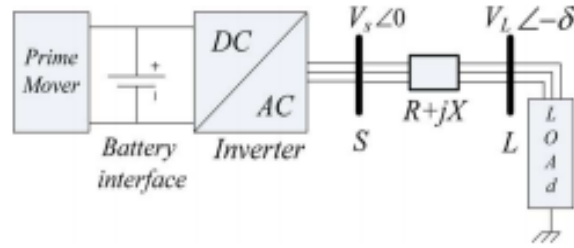


Figure 14 Simple Microgrid with an interfaced inverter system [28] .

From Figure 14, assuming that high voltage (HV) network has a low R/X ratio indicates that  $X \gg R$ , so R could be ignored. Also, assuming  $\delta$  is small then  $s\delta \approx 1$  and  $\sin\delta \approx \delta$ , so the result from Equations (3) and (4) can be expressed as two equations [28]:

$$\delta = \frac{XP}{V_S V_L} \quad (5)$$

$$V_S - V_L = \frac{XQ}{V_S} \quad (6)$$

From Equation (5), the active power  $P$ , controlled by the voltage angle, and the  $\delta$  referred to the power angle which is related to angular frequency ( $\frac{\text{rad}}{\text{second}}$ ). Then, from Equation (6), the reactive power ( $Q$ ) can be controlled by the difference between supply voltage ( $V_S$ ) and load voltage ( $V_L$ ). These strategies are known as P/F and Q/V controls [28].

Figure 15 shows the droop characteristics of frequency versus active power and voltage versus reactive power. In the case of the load change, this will cause a frequency change at the terminal of each synchronous generator, and the active power will flow from higher frequency regions to lower frequency which is shown in Figure 15 (a). Frequency change within the network will eventually drift to an average steady state value. Then, new steady state of frequency will be proportional to change in power as shown in Figure 15 (a) [26].

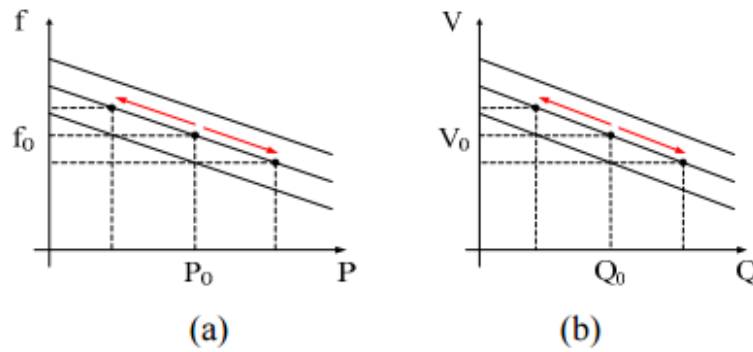


Figure 15 Droop Control (a) Active Power and Frequency (b) Reactive Power and Voltage droop control [26].

One of the primary example of the droop control shown in Figure 16 that two generators have similar power rating using the same droop, and during regular operating, each generator will deliver the same power with the same voltage to the load bus. When the load at the common indicate ( $V < 0$ ) increase, then the stored kinetic energy will be changed into electric power, which will cause the rotor speed to decrease.

As the rotor speed is related to the electrical frequency, any change occurring to the rotor speed governor’s control system will detect. Then the response of the mechanical power to the Synchronous generator will increase. The rotor speed and electrical frequency would continue to decrease if the mechanical power is not increased and the system will become unstable. [29].

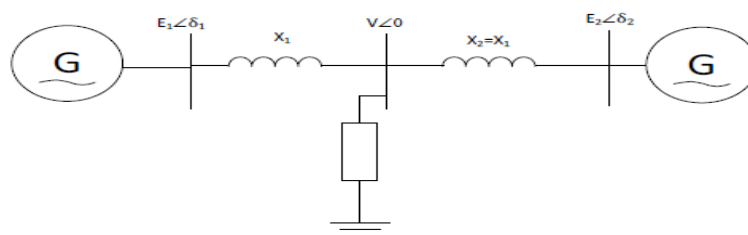


Figure 16 Load Sharing between two Generators [30].

#### 4.2.1 Voltage Source Inverter (VSI) with Droop control

Voltage source inverter (VSI) with droop control, the basic idea is that the input voltage and current are measured, which used later to measure the output power as shown in Figure 17.

Then by the measured reactive power, the voltage will be determined and by measuring the real power, the frequency is determined as shown in Figure 17. Moreover, the mathematical representation for the conventional VSI droop control is expressed into to Equations (7) and (8) [31].

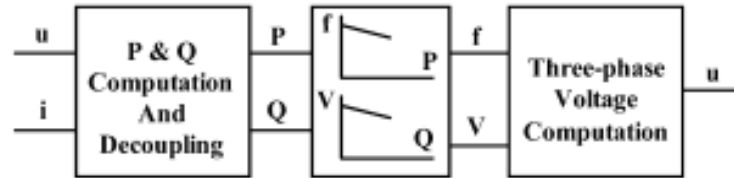


Figure 17 Voltage Source Inverter with Droop Control [31].

$$f - f_0 = -K_p(P - P_0) \quad (7)$$

$$V_S - V_{S0} = -K_q(Q - Q_0) \quad (8)$$

Where the  $f_0$  and  $V_{S0}$  are rated frequency and voltage of the microgrid,  $K_p$  and  $K_q$  are the droop control coefficients of distributed generator for the real and reactive power. Based on Equations (7) and (8) in case anything happens to the voltage and frequency of the inverter, the influence could be detected on the output real and active power of the inverter at self. However, the amount of suitable voltage and frequency deviation could be realized through droop characteristics [28].

#### 4.2.2 Active and Reactive (PQ) inverter with Droop Control

The main purpose of using PQ is to stabilize the output of active and reactive power distributed generation is same as the reference power, as Figure 18 shows the characteristics of PQ droop Controller [26].

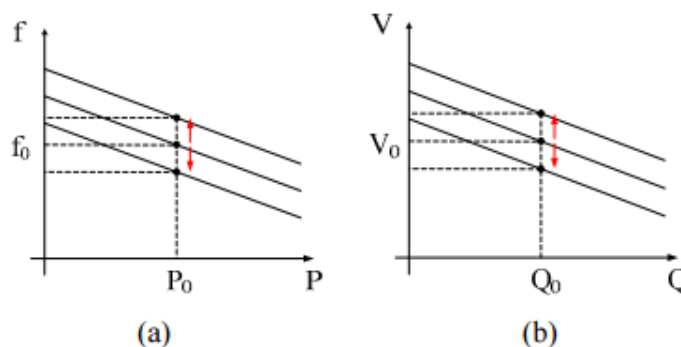


Figure 18 Active and Reactive Power (PQ) Inverter Control [26].

### 4.3 General Method of Control

In predictable power network, the synchronous generator (SG) is used for controlling the frequency and voltage of the whole system. During an islanded operation, the MG inverters should be responsible for controlling voltage and frequency. Then the MG could experience voltage and power fluctuations in case there is no controller. If a group of the micro source is operated within a MG and the main grid is available, providing voltage and frequency references, all the inverters can be operated in the PQ mode. In case the main grid is mislaid all the inverter will shut down as far there will not be any voltage reference within the microgrid, and it will cause unbalance between load and generation. This means that general voltage and frequency must follow to operate the microgrid.

There are three main strategies which combining the inverter control [32].

- a) Single-Master Operation (SMO).
- b) Multi-Master Operation (MMO).
- c) Secondary load-frequency control.

Voltage Source Inverter (VSI) is used by a single and multi-master operation to provide a reference for frequency and voltage, and secondary load frequency control must be measured to maintain the frequency between the specified bounds and to run distributed energy resources sparingly [33].

#### 4.3.1 Single Master Operation (SMO).

This method has one inverter acting as voltage source inverter and others as followers. When the main utility grid is disconnected or lost, then voltage reference will take by the followers from the voltage source inverter and operate in the PQ mode. However, to maintain the generation of active and reactive power at the specified values, the Local controllers (LCs) receives set points from the microgrid central controller (MGCC) [33]. Local micro sources (MS) controller can take information from the MGCC about the generation profile and control accordingly the corresponding micro source. Figure 19 illustrates the SMO scheme [31].

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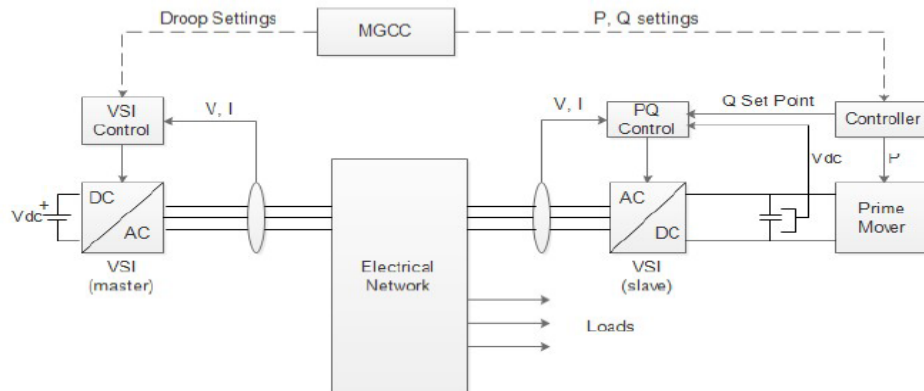


Figure 19 Control Scheme for Single Master Operation [31].

The main limitation associated with SMO control is it is required to locate a secondary load frequency control. This is required during islanded operation and needs to be installed in the micro source that can be controlled.

#### 4.3.2 Multi-Master Operation (MMO).

In the multi-master operation methods, several inverters are operating as voltage source inverter (VSI), either with predefined voltage/reactive power or with frequency/active power characteristics. The VSI can be attached to the micro source with storage devices in the dc link such as super capacitors, or to storage devices such as batteries which are continuously charged by the primary energy source.

Ultimately, other active and reactive power controlled inverters may also coexist; also, MGCC can change the generation profile by changing the idle frequency of VSI or by defining new set points for controllable micro source connected to the grid through PQ controlled inverters. Figure 20 shows the multi-master operation [31].



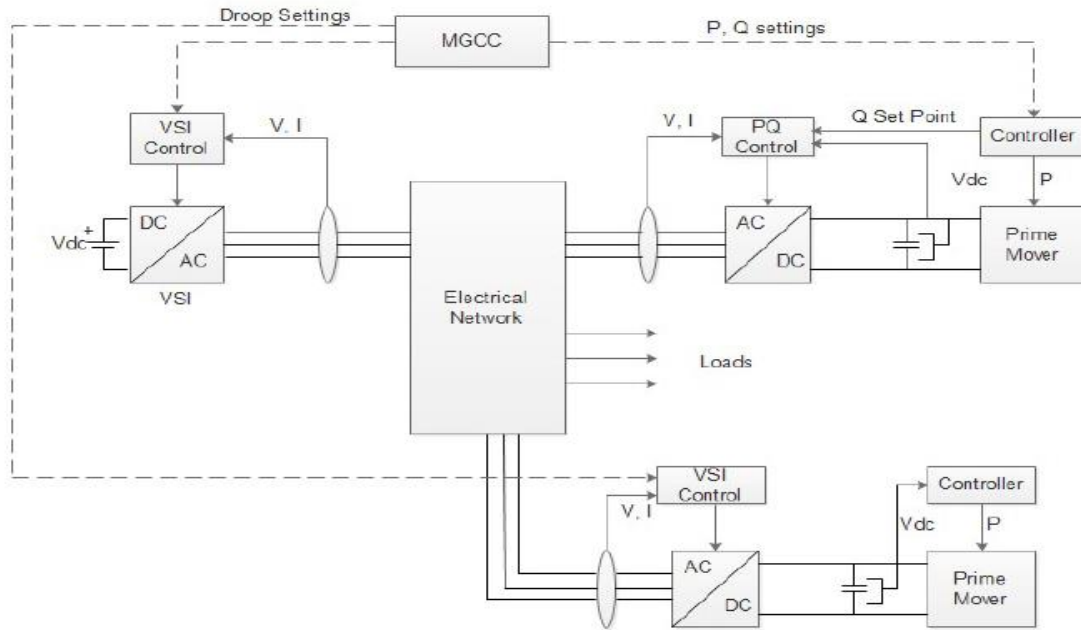


Figure 20 Control Scheme for Multi-Master Operation [31].

### 4.3.3 Secondary load frequency control

This method involved use of storage devices would keep on injecting or could be absorbing active power to maintain frequency stability. The storage devices such as batteries are responsible for load frequency control during the transient situations. Storage devices have a finite storage capacity, and then this method should be applied. Consequently, correcting the frequency deviations during an islanded operating condition should then be considered as one of the principal purposes of any control strategy.

Equation 9, shows that the VSI active power output is proportional to the MG frequency deviation

$$\Delta w = w_{0i} - k_{pi} \times P_i - [w_{0i} - k_{pi} \times (P_i + \Delta p_i)] = k_{pi} \times \Delta p_i \quad (9)$$

Where  $w_0$  = angular frequency of inverter,  $k_p$  = droop slope of inverter,  $p$  = inverter active power.

In order to develop secondary control aiming to restore frequency to the nominal value, two main approaches are available. Either local secondary control or by centralized secondary control mastered by the MGCC.

In the Local secondary control, using a PI controller at each controllable micro source as shown in Figure 21, other using a microgrid centralized controller (MGCC). Those two methods of the controller are partial to use during the transient stage as this is when the storage devices have responsibility for the load frequency primary control [31].

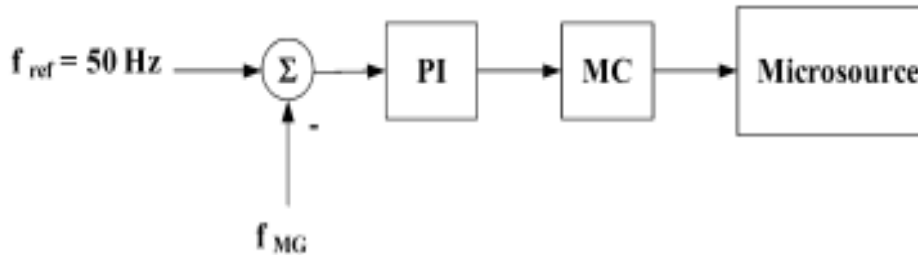


Figure 21 Local secondary load frequency control for controllable Micro sources [31].

## 5 Case Study of the Existing Microgrid in Europe

Kythnos Island microgrid is located in the Aegean Sea, close to Athens. The microgrid project at Kythnos was funded by the Europe FP 5 microgrid program, and the main propose of this project was to test centralized and decentralized control strategies for the island [34].

The system in Kythnos is 3 phase microgrid which is composed of overhead power lines [35]. It powers 12 houses with a single phase 230V (VAC) grid electrical service, and communication cable (RS485) running in parallel [36]. The power supply system represents of 10KW of PV, with 5 KW diesel generator set and a nominal of 53 KWH battery system. There is second 2KW PV array [36].

### 5.1 System Configuration

The microgrid power system at the Kythnos Island covers the need of 12 houses in the islands, and the main parts of the microgrid in this project are:

- a) PV generators: the network includes 7 PV arrays with the 10 KW of the total installed power. Figure 22 shows the overview of Kythnos microgrid with 7 PV arrays.
- b) Three Phases, 6 KVA diesel backup generators, those generators controlled by the Battery Management System (BMS).

- c) Two Lead Acid Battery Banks, first one which is the main with 1000Ah/48V is managed through three single phase battery inverters, Secondary with 480Ah/60V and is controlled with single phase battery inverters. Battery bank connects and disconnects depending on the day and nights, during night two banks are disconnected, while during the day, the two storages connected to the ac [35] .
- d) Each house connected to the microgrid, through Distributed Intelligent Load Controller (DILC), those types of controller operate in the frequency mode. For instance, if low battery State of Charge (SOC) overload by any house, then the controller will automatically disconnect a house when frequency drop below normal 49.14 Hz [37].
- e) Load Controllers used to protect against overloading or extreme battery discharge. When the frequency goes under 49.14 Hz, those controllers are triggered from shed loads and frequency [35].
- f) Three parallel-connected SMA batteries used to feed the local house facility, and those are controlled by master-slave control scheme at grid Frequency [38].

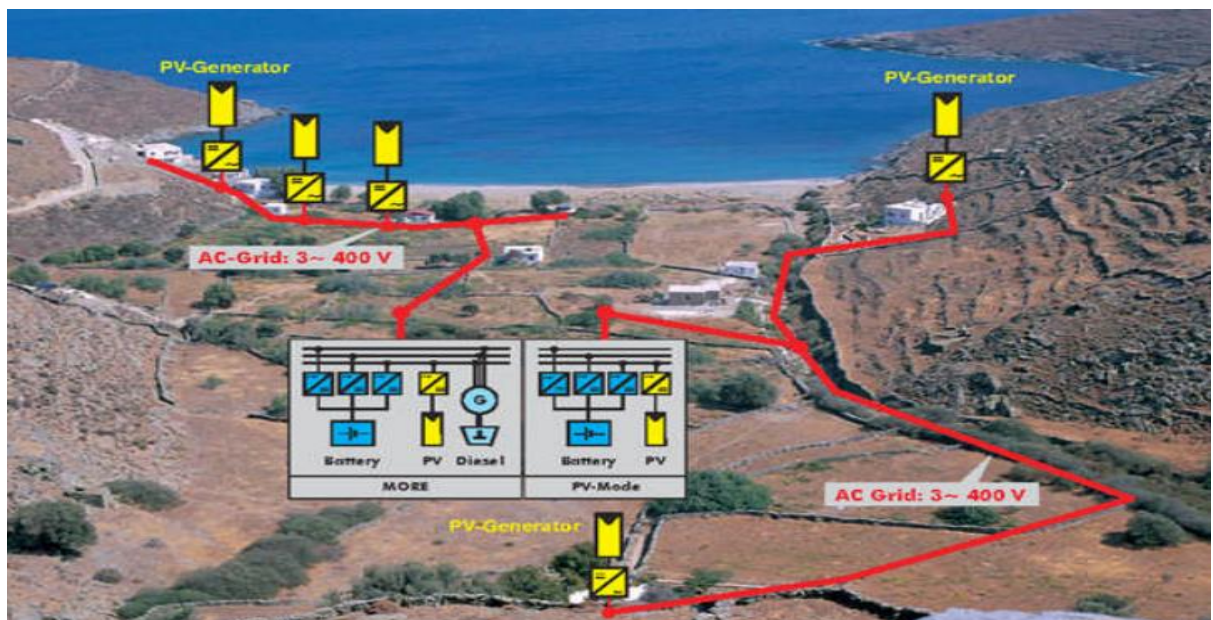


Figure 22 Overview of the Microgrid system on the Kythnos Island [37].

## 5.2 Battery Inverter Operation.

The most critical operating part in the microgrid is battery inverter as they perform the energy management which done by regulating frequency either by load shedding or by PV power derating. Also, they manage the diesel generator start-up [35]. Moreover, the battery inverter operates in multi-master configuration, by this way, the automatic load sharing is reached through the utilization of active power/frequency droop curves in the inverters control systems. The operation in frequency droop mode gives the technical opportunity to switch load controllers in case that the battery state of charge (SOC) is sensed low or limit the power output of the PV inverters. [37]. According to the battery state of charge, there are three states:

- a) When the State of Charge (SOC), falls below 30%, the diesel generator is automatically set in operation and charges the batteries. During this case is occurs in the grid then the battery inverter will follow the generator frequency.
- b) In order to trigger the load controllers and shut down the loads, which will happen when the state of charge falls under 15%, and the frequency became 47 Hz.
- c) When the battery voltage increases leading to a high state of charge, the frequency changes from 50 to 51Hz and then slowly according to the SOC from 51 to 52 Hz [35].

## 5.3 Cost

The cost of Kythnos microgrid was based on the initial cost estimate of the system from the maintenance and the service cost. The possible future solution for the electrification was considered as the many supply loads is ac. In Table 10, shows a list of the PV system components with a little description and their prices are listed. However, the monitoring equipment used in the Microgrid and their cost not included in the Table [39].

**Table 10 Investment Cost for the Farmer's PV System [39].**

| Component Description                                       | Cost in € with 18% VAT |
|---|------------------------|
| 36 Solarex MSX 60 $W_p$ PV Modules                          | 9400                   |
| 1 Sunny Boy 2500  | 2000 x3= 6000          |
| 1 Sunny Island  | 3500                   |
| Battery Bank, 30 X 2Volt cells of 800 Ah with Metallic Base | 4500                   |
| 1 Airlift Pump For the Batteries                            | 400                    |
| Electrical Board and Wires                                  | 1000                   |
| PV Module Support Structure Installed                       | 1000                   |
| Estimated installation cost                                 | 2500                   |
| Total System Cost   | 30300                  |

The PV system charge cost is per watt peak installed, which is approximately 11 €. This price is not an expensive cost for a stand-alone system, and the battery inverter can provide constant ac power up to 3.3 KW [39].

#### 5.4 MATLAB/Simulink: Simulation of Kythnos Island Microgrid.

In order to simulate Kythnos microgrid network, the whole work consists of several approaches and steps. Develop the simulation of the case study according to the following procedure:

- a) Kythnos microgrid is based on the three-phase power supply, but for the simulation and control propose, consider to be used as single-phase network.
- b) PV array represents the dc voltage source, and the dc output of the PV array is connected to a full-bridge Inverter to convert the dc into ac.
- c) The output of the inverter is a sine wave with appropriate frequency.
- d) The ac voltage source represents a diesel generator.
- e) At each four houses, there is one breaker used to protect the load in case anything happens to the network.
- f) From the controller, comparing the voltage reference and measurement voltage for the switching device of an inverter.

The system model, shown in Figure 23, is based on the solar cell array connected to a 50 Hz, 400 V which obtained from the dc/dc converter is applied to a single dc to ac inverter. The elimination of the harmonics which contained in the voltage and current of the inverter output, an inductor (L) filter inserted after the dc/ac inverter.

However, the grid connected with PV array system control is to be sure that the signals of the inverter output and grid signals have the same of the phase, frequency and RMS values.

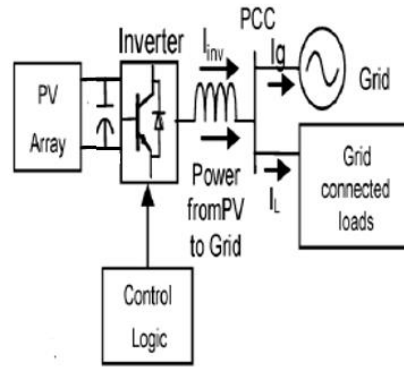


Figure 23 Kythnos Microgrid

MATLAB/Simulink platform for a complete micro-grid power circuit modelling for Kythnos Island microgrid is shown in Figure 24. Which consist of dc power supply of 400VDC represented by dc voltage source, three dc/ac inverters power electronic device with the type of Insulated Gate Bipolar Transistor (IGBT) switches and the frequency of 50Hz.

The transmission line between the inverter and the house as follows, for the houses 1, 2,3 and 4 the distance is 60 meters, and for house 5,6,7 and 8 the distance is 100 meters and 200 meters for the house 9,10,11 and 12. The Load at houses 1,2,5,6,8,12 is 2 KW, and the remaining houses 3,4,7,9 and 10 the load power is 3 KW. The maximum load located far away from the inverter by 200 meter which is close to the coast of the Kythnos Island. The resistance in the line is very small as the transmission line between the inverter and the load very close [37].

The IGBT switches are controlled using the bipolar pulse width modulation (PWM) refer to Appendix Part A for the inverter setup and each inverter supply voltage to four houses. The value for each L filter is varying depending on the distance between the inverter and supply house. In this network as shown in Figure 24, no voltage or frequency control is involved.

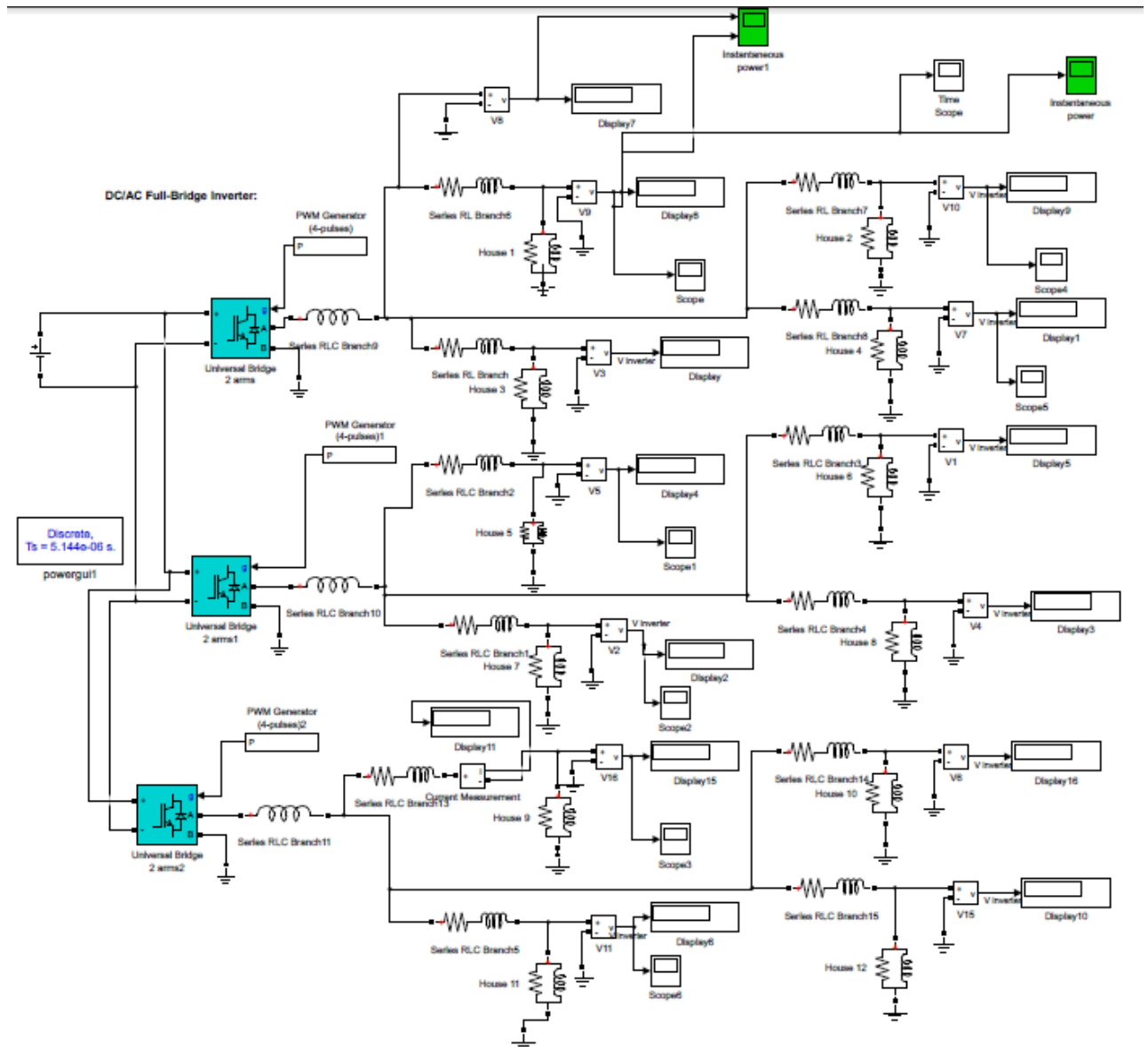


Figure 24 MATLAB/ Simulink Model of Complete Kythnos Microgrid power Circuit

Single -phase diesel generator (240VAC) used as a backup in case of any fault in the PV array or the supply power goes beyond the demand to the suppliers. The control method of the diesel generator in the island is based on the battery management system (BMS), whereas, in the MATLAB/Simulink simulation is controlled by the voltage controller based on the total load on the network.

Moreover, the breaker in the diesel generator used to simulate the fault that could happen to the generator refer to Appendix Part B. The setting timing for the breaker based on the running time of the simulation. The diesel generator is shown in Figure 25, that each four houses having breaker used to disconnect the load in case any fault occur to the network.



The output waveform of the inverter with L filter shown in Figure 26, that the pure sinusoidal waveform of frequency is 50 Hz and amplitude of 400 Voltage (Peak to Peak). In Figure 26 the y axis is the voltage (Volts) and in the x axis is the time (second).

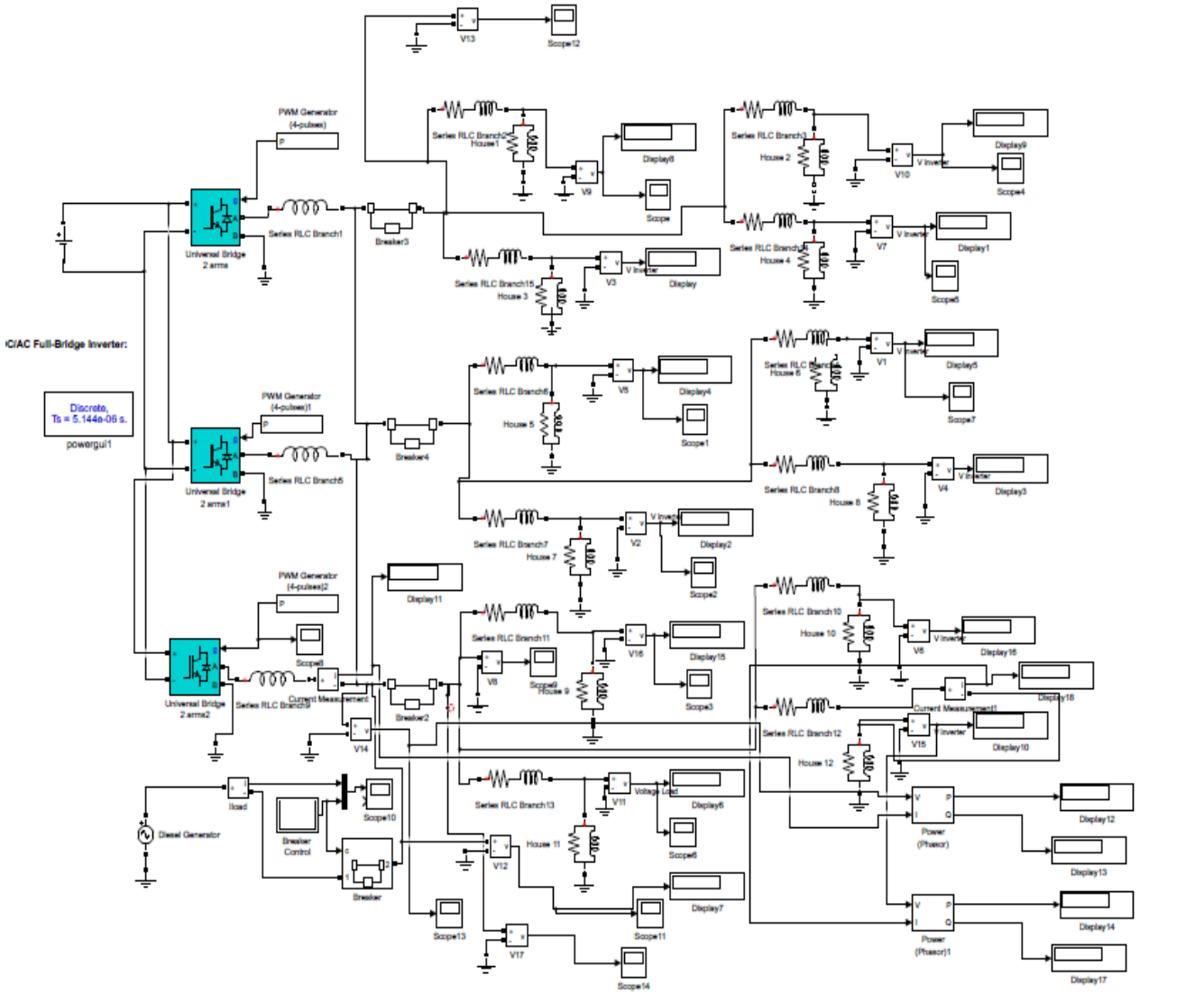


Figure 25 MATLAB/ Simulink Model of Complete Kythnos Microgrid power Circuit with Diesel Generator



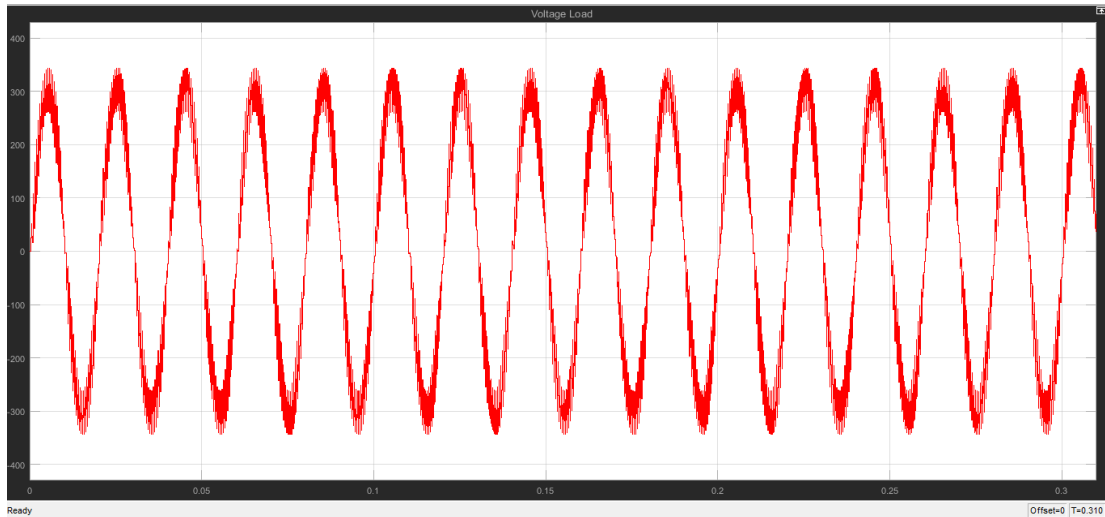


Figure 26 Output voltage waveform of a full bridge Inverter with L filter

When the diesel generator is supply voltage to the network as shown in Figure 27. If the fault occurs in the generator at the time dial setting (TDS) 0.025 second, then the fault will acknowledge at 0.05 second the generator will supply voltage to the network as shown in Figure 27. However, the breaker time dial setting will change based on the network configuration of fault.

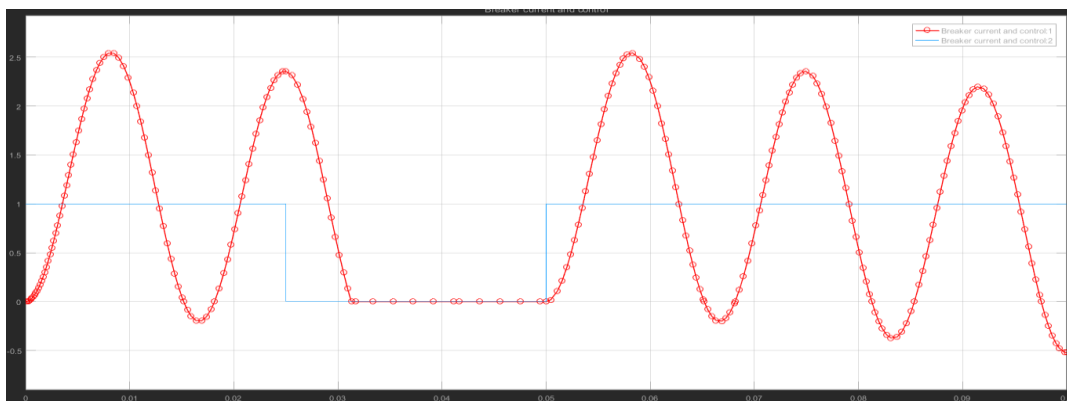


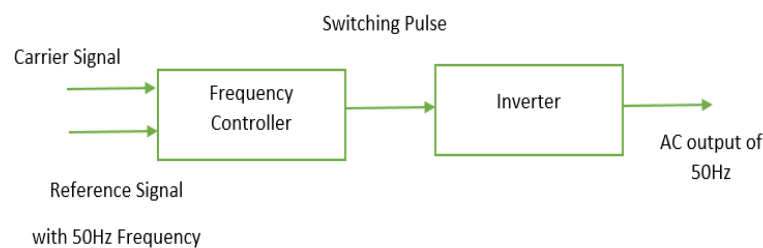
Figure 27 Diesel Generators in the Microgrid power Circuit

#### 5.4.1 Power and Voltage Control in the Simulation Network.

The inverter controls in the simulation could be broadly classified into two types: voltage and current controller. When the inverter is connected to the main grid, it controls the amplitude and frequency of the inverter output voltage. However, the inverter itself operates in the current control mode.

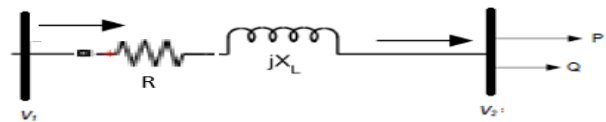
In this project, the grid is not connected to the network; only the load will supply through the microgrid or by the diesel generator which basically by the inverter, which can maintain the amplitude and the frequency by the utility interruption.

However, the inverter operates in voltage control mode providing the reference voltage and frequency. In the frequency controller, the output frequency of the inverter depends on the frequency of the reference signal. In this project 50 Hz used as reference signal. So, the output frequency of the inverter is 50Hz, the frequency control block diagram is shown in Figure 28.



**Figure 28 A Frequency Control Block Diagram**

In order to obtain the reference voltage by using single line Diagram(SLD), which representing a transmission line between two buses as shown in Figure 29, and the inductor is usually specified by its reactance value using Equation (10).



**Figure 29 Single Line Diagram of one phase.**

$$x_L = 2 \pi FL \quad (10)$$

As the inverter in the Kythnos microgrid operates in voltage control mode for such scenario, which provides the reference voltage and frequency. Then following obtain data required ( $V_1$  and  $\delta_1$ ) voltage and angle reference for the inverter. However, from the previous equation (1 and 2) in the section 4.2 that ( $Z = R + jx$ ).

The obtain active and reactive power as expressions in the following two Equations,

$$P_r = \frac{X_L V_1 V_2 \sin(\delta) + R(V_1 V_2 \cos\delta - V_2^2)}{X_L^2 + R^2} \quad (11)$$

$$Q_r = \frac{X_L(V_1 V_2 \cos\delta - V_2^2) - R V_1 V_2 \sin\delta}{X_L^2 + R^2} \quad (12)$$

Those two equations would be useful if they can be simplified by using a suitable approximation. There are two assumptions could be done, one assumption which assumes that the transmission line is lossless that meaning no power loss on the line, that implies the resistance will be zero. However, this assumption could often be being acceptable in a transmission line with high voltage network. This is form the following active and reactive power as shown in Equation (13) and (14).

$$P = \frac{V_1 V_2 \sin(\delta_1 - \delta_2)}{X_L} \quad (13)$$

$$Q = \frac{V_1 V_2 \cos(\delta_1 - \delta_2) - V_2^2}{X_L} \quad (14)$$

This pair of equation (13) and (14) can provide important clues into what causes certain network behaviour, and how to correct that behaviour of the controller. Then both equations can be written as:

$$\sin(\delta_1 - \delta_2) = \frac{p \cdot x_l}{V_1 V_2} \quad (15)$$

$$\cos(\delta_1 - \delta_2) = \frac{Q \cdot x_l + V_2^2}{V_1 V_2} \quad (16)$$

Then by rearranging the equation to calculate  $\delta_1$  and  $V_1$  as form a by the following equation shows:

$$\delta_1 = \delta_2 + \tan^{-1}\left(\frac{p \cdot x_l}{Q \cdot x_l + V_2^2}\right) \quad (17)$$

$$V_1 = \frac{p \cdot x_l}{V_2 \sin(\delta_1 - \delta_2)} \quad (18)$$

The second assumption that as the network is supplying by medium voltage, the resistance in the cable could be relatively large which will be affecting Equation (13) and (14), by considering the resistance in the equation and implies that inductivity in the line will be zero.

Then active and reactive power will be expressed in the following two Equations (19), (20) and as further explore into equation (21) and (22):

$$Q = \frac{V_1 V_2 \sin(\delta_1 - \delta_2)}{R} \quad (19)$$

$$P = \frac{V_1 V_2 \cos(\delta_1 - \delta_2) - V_2^2}{R} \quad (20)$$

$$\delta_1 = \delta_2 + \tan^{-1}\left(\frac{QR}{P.R + V_2^2}\right) \quad (21)$$

$$V_1 = \frac{Q.R}{V_2 \sin(\delta_1 - \delta_2)} \quad (22)$$

In the voltage control mode, the IGBT switches controlled using the Pulse Width Modulation (PWM) switching such, the inverter output voltage follows the reference voltage. A voltage control block diagram is shown in Figure 30 the voltage in the network across the load compares with the voltage references. The voltage reference is the  $V_1$ .

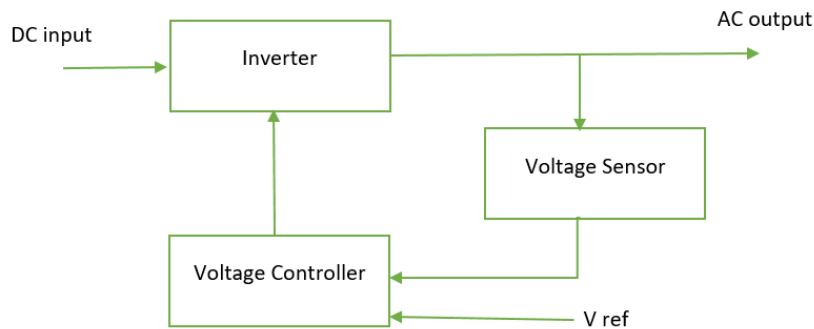


Figure 30 A voltage Control Block Diagram

Based on the last two equations (21) and (22), then by using the MATLAB/Simulink block function as shown in Figure 31 for the equation and Figure 32 for the MATLAB Code. The output of function generates a phase angle ( $\theta_1$  and  $V_1$ ), which is basically using the PWM generation to send single to the inverter. The active power (P) and reactive power (Q), putting it as constant block as easy to change it, Voltage Load is basically the voltage measured from the network.

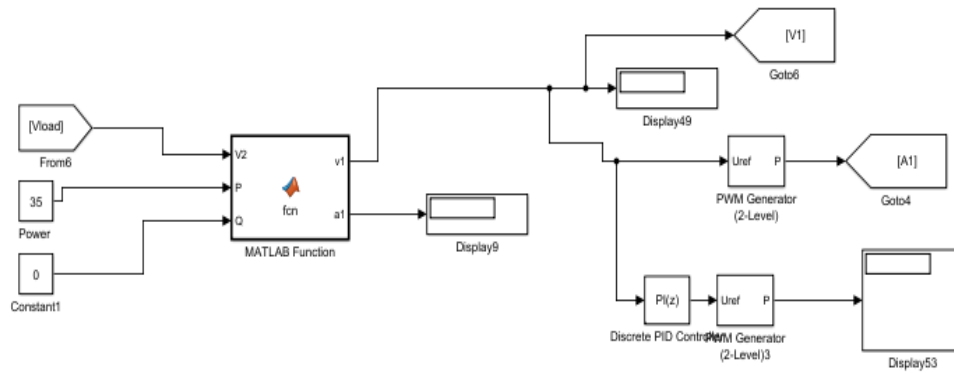


Figure 31 MATLAB Function for the voltage Controller.

```

MATLAB Function1*
1
2 function [v1, a1] = fcn(V2,P,Q)
3     % Q=5;
4     % V2=4;
5     % P=25;
6     % XL=2*pi*f*L
7     % XL=0.016*2*3.14*50;
8     % XL=0.01;
9     % R=0.016
10    % a2=75;
11    a1=a2+atan((P*XL)/(Q*XL+V2^2));
12    % a1=a2+atan((Q*R)/(P*R+V2^2));
13    % V1=(Q*R)/(V2*sin(a1-a2));
14    v1=(P*XL)/(V2*sin(a1-a2));

```

Figure 32 MATLAB Code for the voltage Controller

Based on PWM switching form, IGBT switches are turned ON and OFF in a bipolar fashion, such that two diagonally opposite switches in the H-bridge turn ON and OFF simultaneously. In the simulation of the Kythnos microgrid, the signal of the voltage controller will add with the repeating sequence before sending the signal to the inverter, as shown in Figure 33 to form ON and OFF simultaneously switching for the inverter.

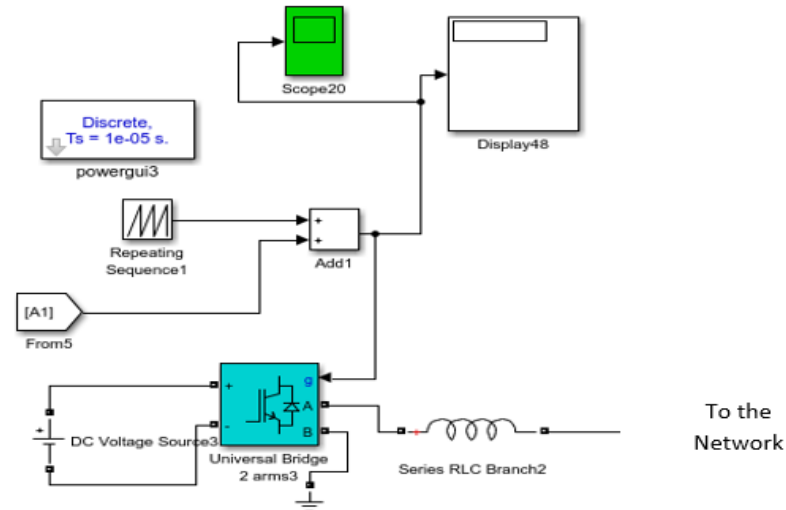


Figure 33 Voltage Controller with the Repeating Sequence

In the following Figure 34 shows the entire from the MATLAB function up to the signal pass through to the inverter, which implemented in the first four houses for obtaining the output voltage and current.

An example of the network the simulation of the controller, implemented in first four house of the network shown in Figure 34, with only one side of the inverter as to the network to obtain the output voltage and current.

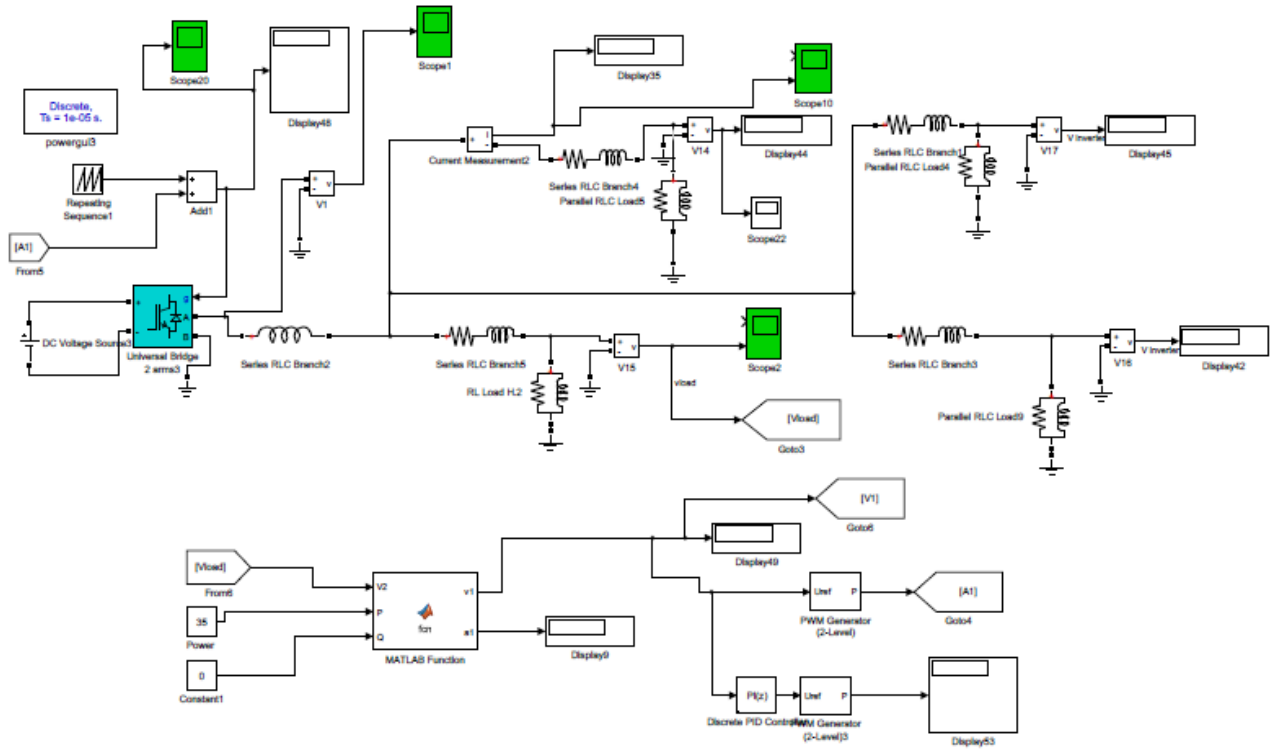


Figure 34 MATLAB Simulink Model for a Single Inverter of Microgrid Power circuit.

The whole network single phase of the Kythnos microgrid with the breaker, voltage controller and diesel generator is shown in Figure 35. The breaker is used to disconnect the load in case anything occurs in the microgrid, diesel generator the breaker time setting is 0.2 second, the other breaker setting time is 0.4s, 0.6s and 0.8 seconds for breaker one, two and three respectively. The behaviour of network under single phase voltage with the breaker around each four houses will be shown in the following section.

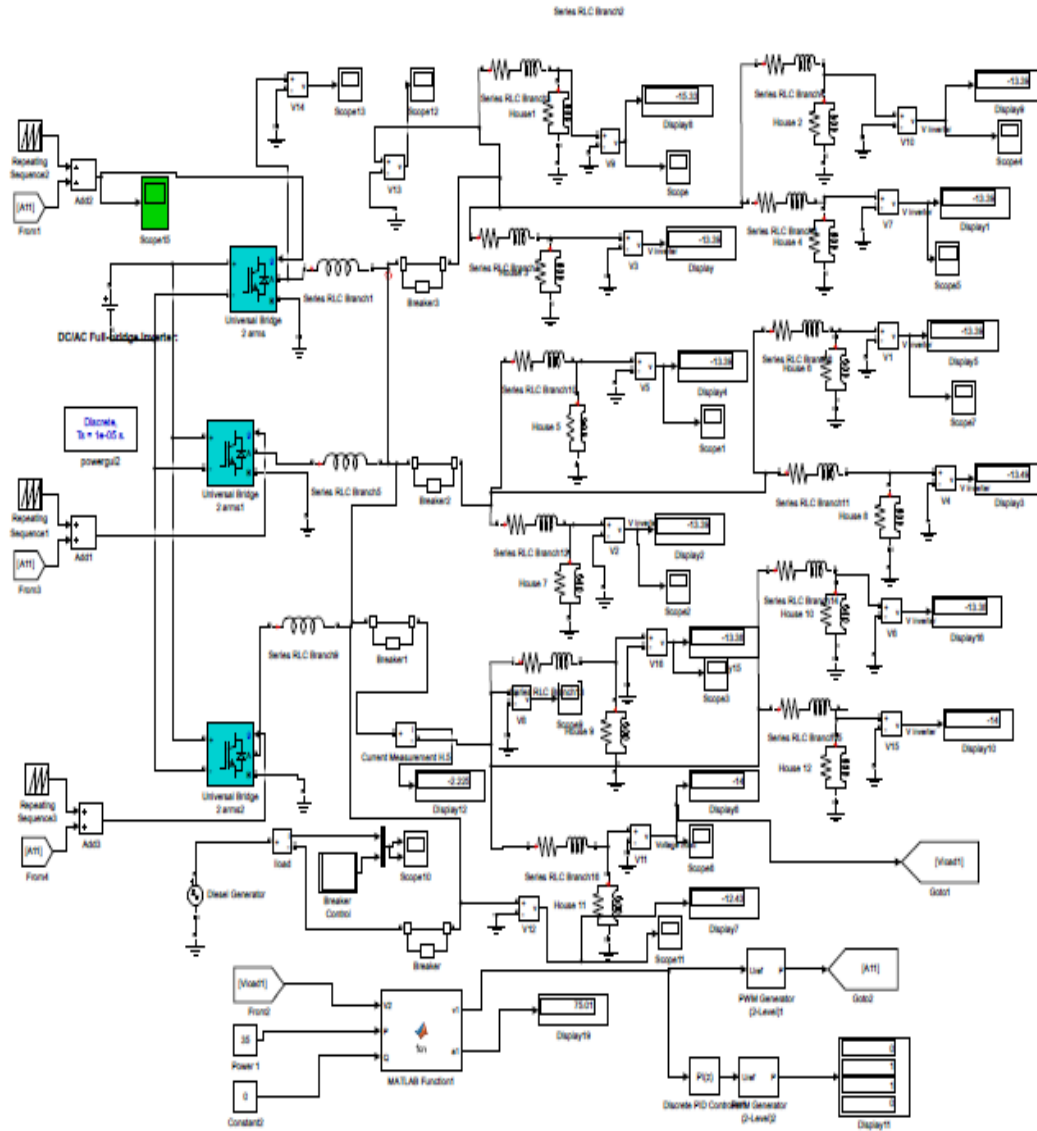


Figure 35 MATLAB Simulink Model of a Complete Microgrid Grid Power Circuit

### 5.4.2 Simulation Results for the network of the Alternative and direct current Microgrid

#### 5.4.2.1 Simulation Result for the DC/AC inverter network.

The output waveform of the inverter is a square wave which amplitude is 400 volts. The output voltage waveform of a single phase full bridge inverter is shown in Figure 36 which run for a short time, and Figure 37 run for a long time which is used in the simulation.



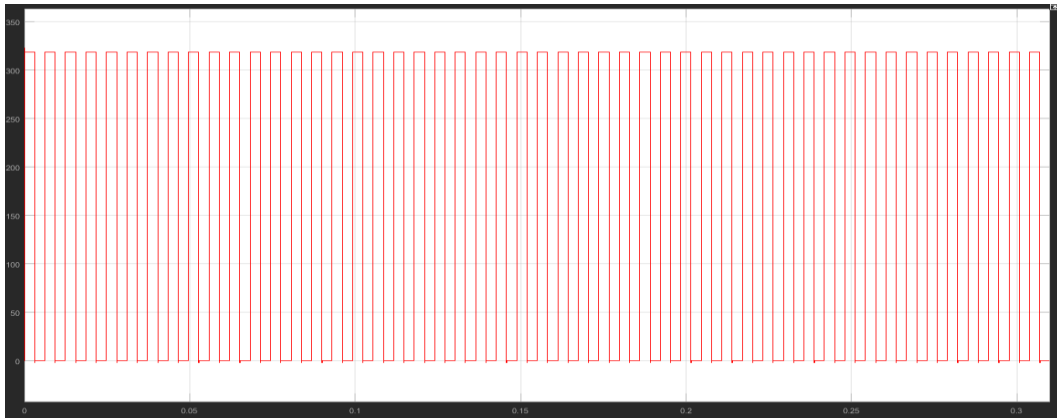


Figure 36 Output Voltage Waveform of full Bridge Single Phase Inverter

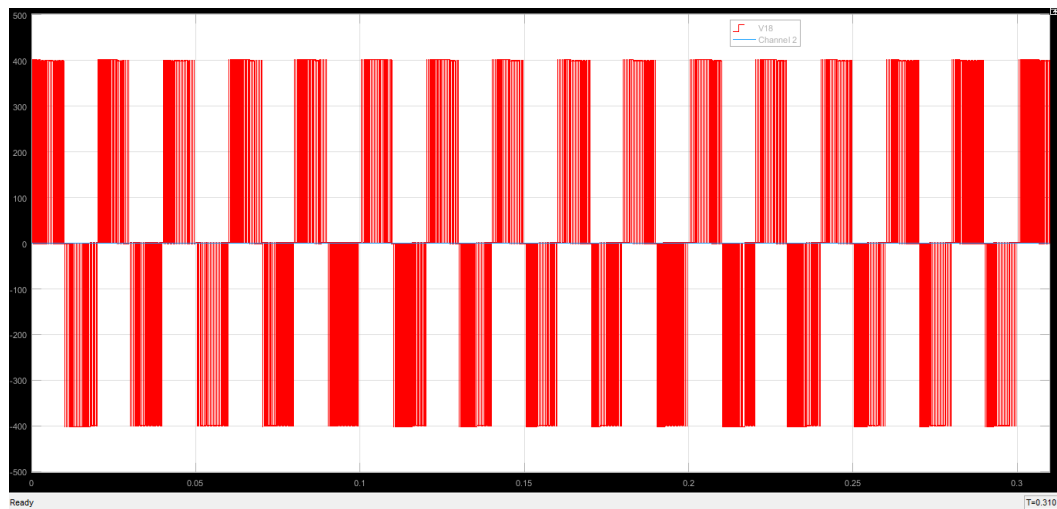


Figure 37 Output Voltage Waveform of full Bridge Single Phase Inverter for the simulation Used.

After filtering the output of an inverter, that obtains a pure sinusoidal wave of amplitude 400 and frequency of 50Hz. The full bridge inverter with L filter output voltage waveform of single phase inverter is shown in Figure 38, the simulation run for 1 second as shown in the Figures.

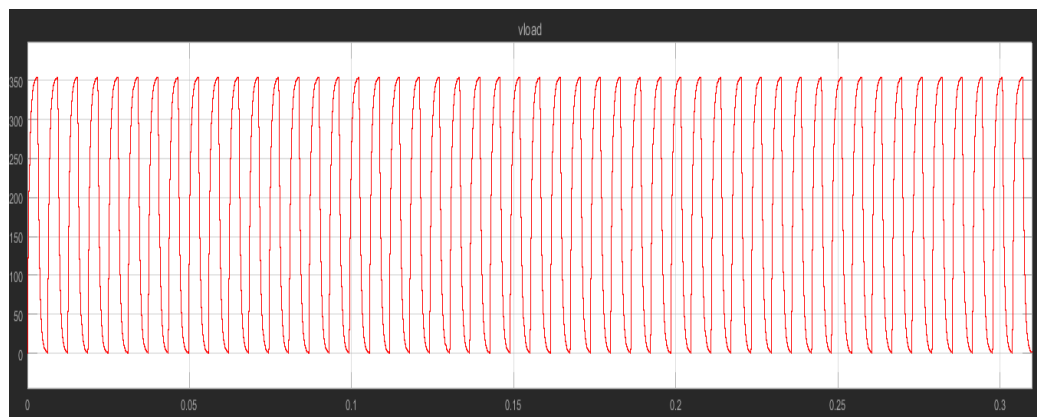


Figure 38 Output Voltage waveform of full bridge Inverter with L filter

In uncontrolled island mode of operation when diesel breaker is opened at 0.2 seconds, the supply from the generator is disconnected from the load. It will cause the load to be shared only by the microgrid. During this occasion, the voltage across the load is decreased significantly. Breaker 1, 2 and 3 from the Figure 35 which are used to disconnect load are opened at 0.4s, 0.6s, and 0.8s respectively as Figure 39.

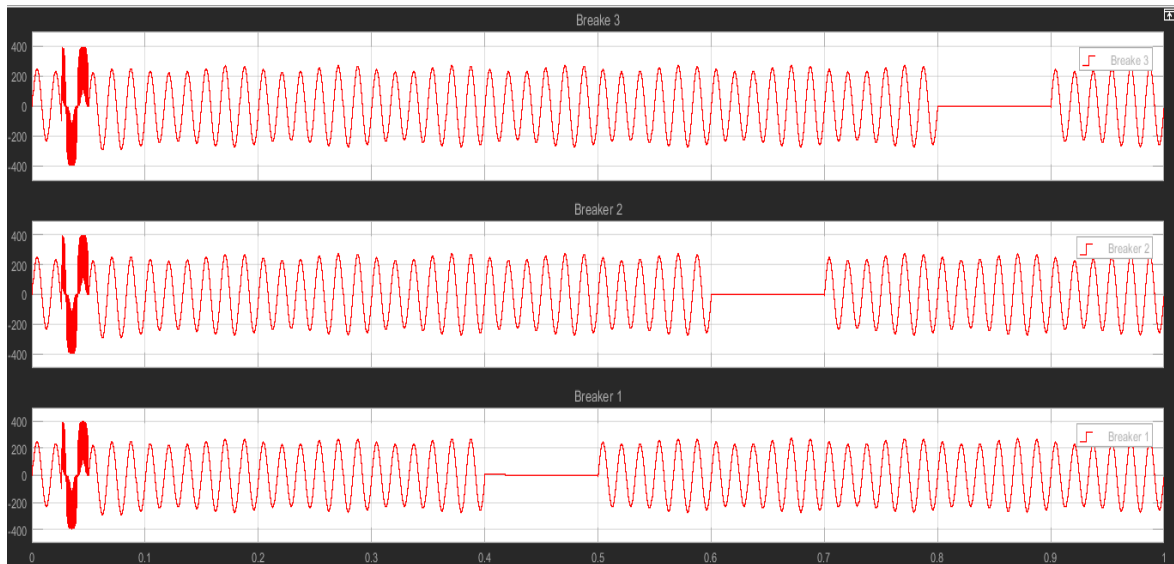


Figure 39 Breaker 1, 2 and 3 setting faults

The main purpose of those breaker is during any fault occurs in the network it will be disconnect the load. Due to the disconnect of load voltage across the load is increased. Thus, in uncontrolled island mode of operation voltage across the load is not constant. However, the output voltage waveform of a microgrid operated in uncontrolled island mode is exposed in Figure 40. The running simulation is one second as shown in the x axis of the figures

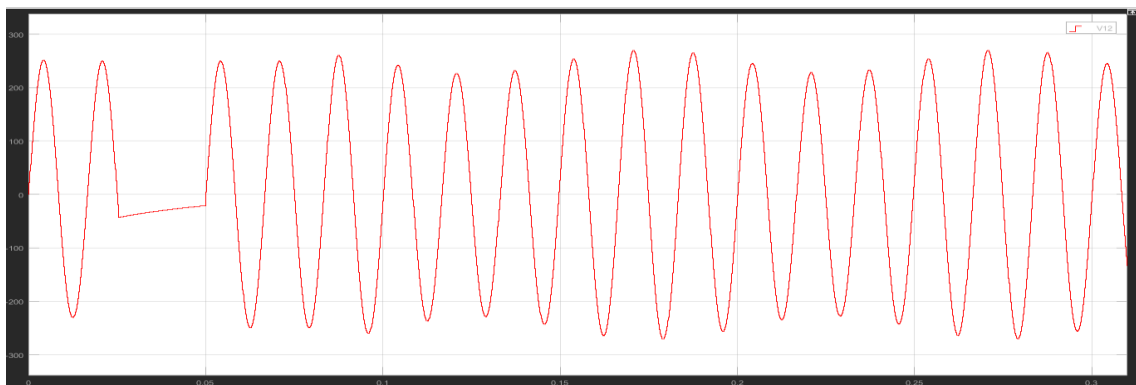


Figure 40 Output Waveform of Uncontrolled Island Mode of Operation of a Microgrid

In controlled island mode when diesel breaker is opened at 0.2second, the diesel generator disconnected from the load. When the generator is disconnected, then the load is shared only by a microgrid, but at this moment the voltage across the load is same as it remained at diesel generator. The main effect of that, because in the control mode using a controller which compares the inverter output with the reference signal. Which increase the output in the same proportion that decreases due to disconnection of a diesel generator.

The three breakers 1, 2 and 3 which are used to disconnect load are opened at time 0.4s, 0.6s and 0.8s respectively Those breakers operation causes discount of the load. However, voltage load remains constant despite disconnection of the load due to the controller operation. The output voltage waveform of microgrid operated in controlled mode is shown in Figure 41. The behaviour of the active and reactive power at the load during the control mode of the operation showing that the power is within 2KW as the supply power to the load as shown in Figure 42.

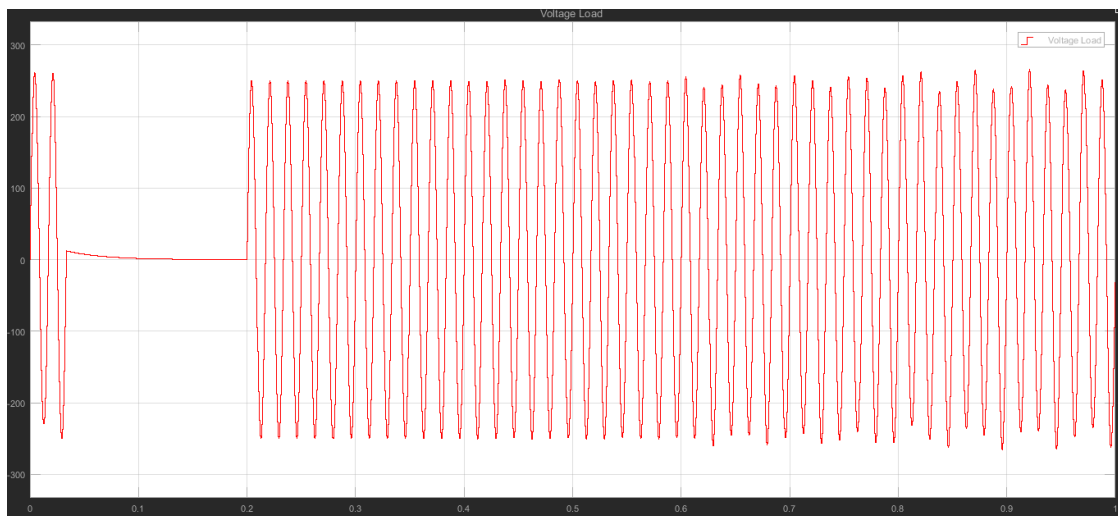


Figure 41 Output waveform of controlled Island Mode operation of a Microgrid using rectangular waveform as a carrier single of PWM

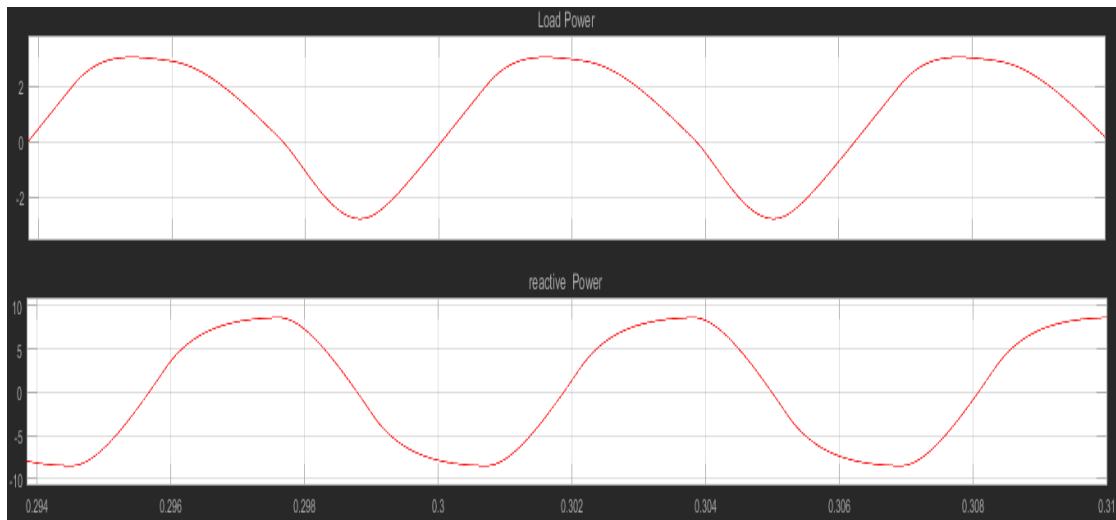


Figure 42 Real and Reactive Power During Controller Mode

To sum up in the dc voltage supply to the ac load (dc/ac) network simulation of the Kythnos microgrid that, in the case of uncontrolled island mode, the voltage across the load is not stable over running the simulation. Which is varies according to the load and generators; however, in controlled island mode a stable voltage is always maintained across the load, which it does not depend on the load variation and diesel generator.

#### 5.4.2.2 Simulation Result of the DC/DC converter network.

In the low voltage dc, there are several levels of voltage 326V, 230V, 120V, and 48V. The dc load could be supplied directly from the dc source, in the case of dc voltage is compatible with the device voltage level. The schematic diagram of the LVDC distribution systems at the Kythnos microgrid is shown in Figure 43. That the load voltage is 24V, which is required the dc/dc buck converter as shown in the schematic diagram to bring the voltage to the load voltage. [37].

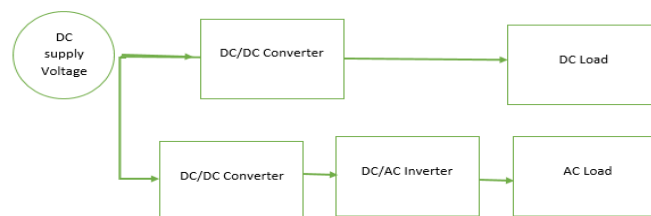


Figure 43 Schematic Diagram of the LVDC Distribution System

Kythnos microgrid of the dc/dc Load shown in Figure 44, that consist of three inverters and the load is varying between 12 houses with the maximum of 1 kW, the main power

supply step down from 240Vdc to 24Vdc as shown in Figure 45. The dc-dc PWM Generator Modulation choosing by the default from the Simscape MATLAB Modelling as shown in Figure 46.

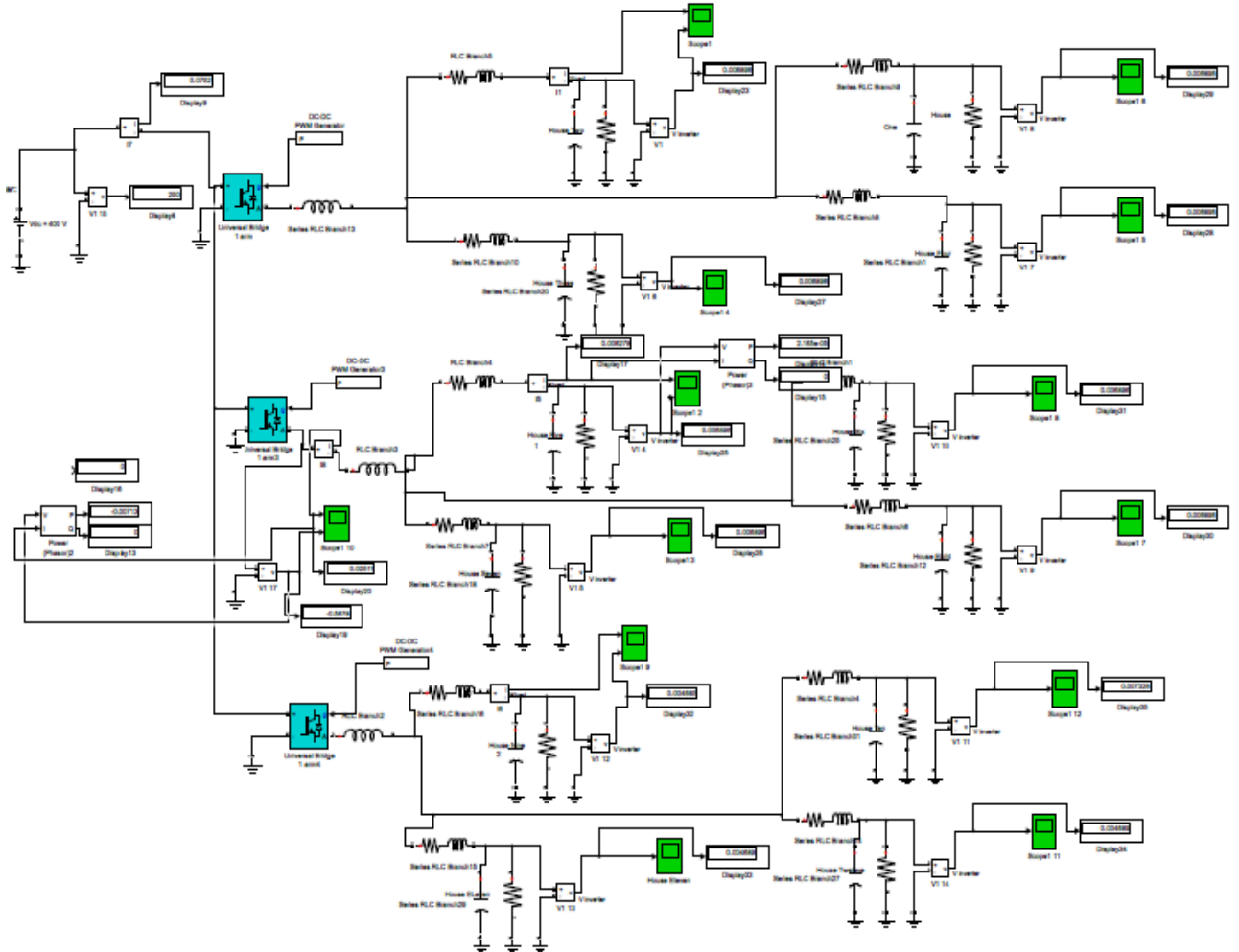


Figure 44 MATLAB/Simulink Model of a complete Microgrid Power circuit with DC Load

The output voltage and current waveform of the dc load, as shown in Figure 45, that the voltage in the load is 24V and load current is 22A for one example of the house.

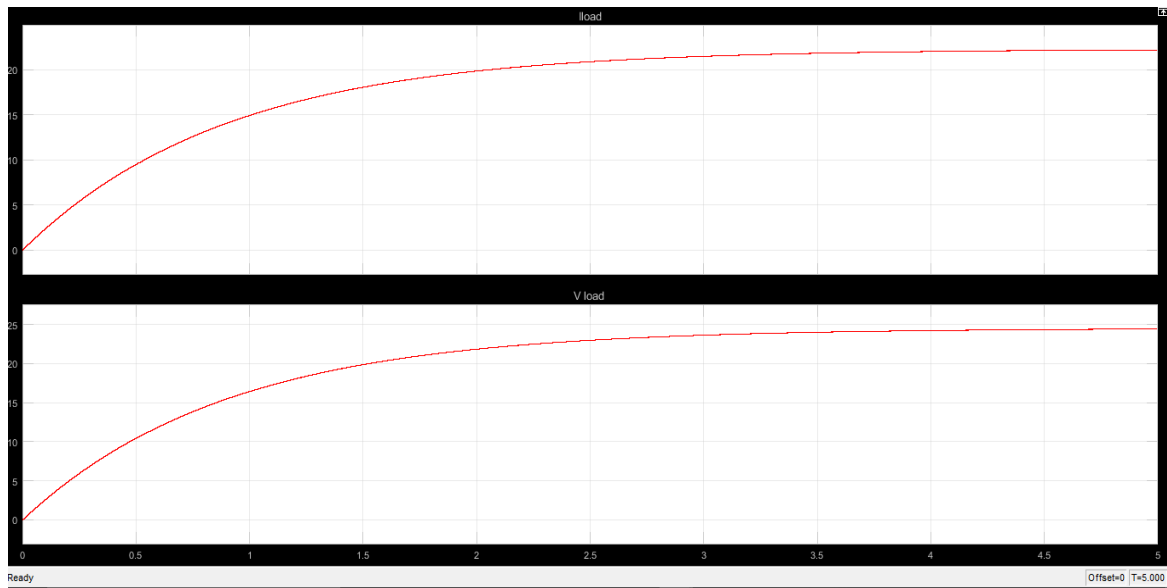


Figure 45 Output Voltage waveform of a full bridge converter with DC/DC buck converter

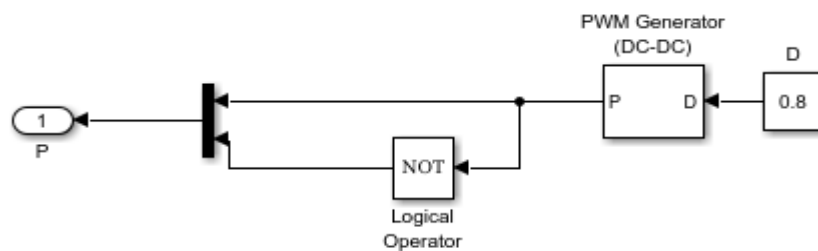


Figure 46 DC-DC PWM Generator with Modulation of 0.8

### 5.4.3 Comparison between AC and DC Microgrid simulation network.

After the comparison between the ac and dc microgrid in term of a block diagram, the efficiency is also playing main roles for the comparison. Table 11 shows the efficiency of the dc/ac inverter and dc/dc converter which taken based on the simulation of the network. By using the block diagram for measuring the power at the input and as output, refer to the Appendix Part C for the block using to measure the current, voltage and power for the two networks. As a result, shows in the Table 11 that the efficiency of the dc/ac is 90 %, is greater than the efficiency of the dc/dc converter which might be lossless in the network compared to the dc/ac network.

Table 11 Result of the Efficiency between AC and DC Microgrid with LV

| Components   |            | DC/AC inverter | DC/DC Buck Converter |
|--------------|------------|----------------|----------------------|
| Input/ Value | Voltage    | 400 V          | 250V                 |
|              | Current    | 86.2A          | 23.59A               |
|              | Power      | 5379W          | 4006W                |
|              | Efficiency | 90%            | 85%                  |

## 6 Conclusion.

The project, in general, was successful through the new area of understanding the operation and control of the microgrid, which based on the literature review, application and simulation of the microgrid. Also, the result of the literature review proves that the viability of droop controller as viable options for controls of microgrid when it is in island mode. The comparison between two networks which are alternating current and direct current with the low voltage (LVDC) distribution system at different load condition presented in this report. The case study of Kythnos Island microgrid was a success after the approach to simulate the network using MATLAB/SIMULINK for twelve houses with different ac and dc Loads. Disconnect mode of the microgrid having an advantage compare to connect to the utility grid, for instance, protect the electrical device from any fault in the network. The inverter control success under the disconnect mode of the microgrid by achieving the stability of the power in the load.

Analysing data shows that higher efficiency in dc/ac distribution system compares to the dc/dc with implementations inverter control in the microgrid. Also, the result indicates that a microgrid can be controlled as island mode with good stable output voltage to the system. The application of the dc distribution system could be extended if the integrate the renewable energy and energy storage devices in the dc system. As to be considered future improves the overall system, not only by the efficiency comparison between ac and dc microgrid of the Kythnos microgrid, it is better to include the cost. However, without cost comparisons, it is insufficient to state that the dc/ac with the LVDC is more beneficial than the dc/dc converter in terms of simulation network. It is indicative that the dc/ac could improve and optimize the future power distribution scenario.

### 6.1 Future scope of work for the DC Microgrid simulation and control

The dc voltage source could be made after the modelling of the PV array or any types of the renewable energy source. The network simulation microgrid is used as single-phase supply to the house, the future scope of work could be done by using three phase voltages. As the efficiency of the single phase determined that the dc/ac efficiency is higher than the dc/dc converter. The distributed generation source and energy storage could be integrated to have the better utilization of the dc load compare to the ac load. Moreover, consider using a single breaker for each house instead of using one for all four houses.

Also, the comparison between the LVAC and LVDC could be considered instead of LVDC voltage only. This will give a better comparison in terms of efficiency even, as the Kythnos microgrid having the wind turbine. In the future works, the cost estimation of the replacement of the existing technology with the LVDC can be evaluated with the simulation result of the efficiency.



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## 8 Appendix.

### 8.1 Appendix Part A. Simulink, Simscape™ and SimPower Systems™.

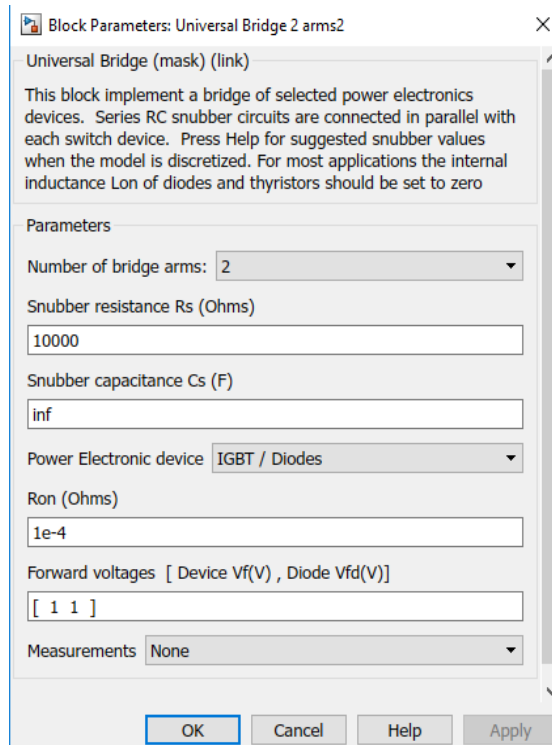


Figure 47 IGBT Switch for the Network.

Block Parameters: PWM Generator (4-pulses)2

PWM Generator (2-Level) (mask) (link)

Generate pulses for PWM-controlled 2-Level converter, using carrier-based two-level PWM method. The block can control switching devices of single-phase half-bridge, single-phase full-bridge (unipolar or bipolar modulation) or three-phase bridge.

When the Synchronized mode of operation is selected, a second input is added to the block, and the internal generation of modulating signal is disabled. Use input 2 (wt) to synchronize the carrier.

Generator type: Single-phase full-bridge (4 pulses)

Carrier

Mode of operation: Unsynchronized

Frequency (Hz): 1080 Initial phase (degrees): 90

Minimum and maximum values: [ Min Max ] [ -1 1 ]

Reference signal

Sampling technique: Natural

Internal generation of reference signal

Modulation index: 0.8 Frequency (Hz): 50 Phase (degrees): 0

Sample time (s): Ts

Show measurement port

OK Cancel Help Apply

Figure 48 Bipolar Pulse Width Modulation (PWM).

Block Parameters: House 8

Parallel RLC Load (mask) (link)

Implements a parallel RLC load.

Parameters Load Flow

Nominal voltage Vn (Vrms): 400

Nominal frequency fn (Hz): 50

Active power P (W): 2e3

Inductive reactive Power QL (positive var): 55

Capacitive reactive power Qc (negative var): 0

Set the initial capacitor voltage

Set the initial inductor current

Measurements None

OK Cancel Help Apply

Figure 49 Load Parameters for the Network

## 8.2 Appendix Part B

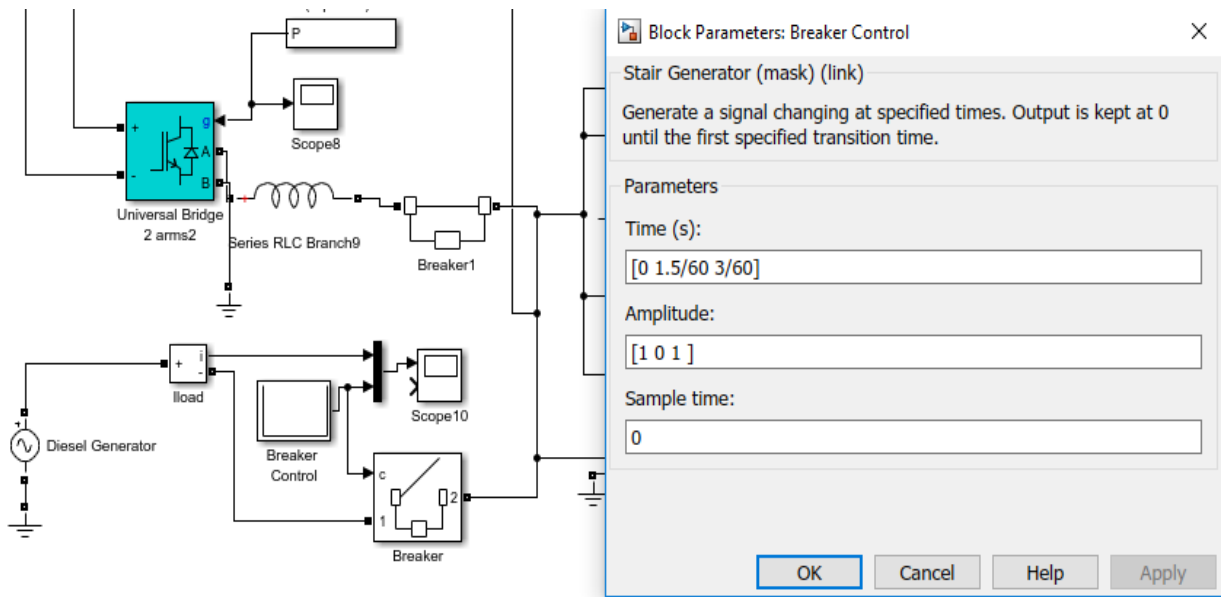


Figure 50 Diesel Generator Control Through Breaker Control