

# Key Performance Indicators Modeling for Optimized Microgrid Configuration

by  
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## Abstract

Distribution system is so vulnerable to failures. These failures can be the result of natural or manmade threats. Blackouts are one of the distribution systems failures. Many people can be affected by blackouts. Therefore, microgrids can be a suitable candidate to have a robust and secure distribution power system. Microgrids can support the distribution systems while they are having problems. Microgrids can be operated in small levels such as hospitals, government buildings, hotels and airports.

Microgrids need to be studied in details. Models must be developed and analyzed to see the effect of the microgrid on the overall grid system. Microgrids can play a significant role in reducing the distribution systems dependency on the main grid as they have local distributed energy resources (DER) such as wind turbine, solar photovoltaic, diesel generator, gas engine, micro turbine, fuel cells, etc.

In order to evaluate microgrids, key performance indicators (KPIs) need to be studied. These performance indicators are essential to evaluate and optimize the configuration of microgrids. These KPIs are reliability indicators, environmental indicators, economic indicators, and power quality factors.

This research consists of two parts. The first part is optimizing a hybrid system design using GA (PV panels, wind turbines, and storage devices) by minimizing the system cost and maximizing the efficiency. The second part of the thesis focuses on KPIs in order to evaluate the performance of the microgrid. The proposed microgrid is modeled in MATLAB. Different scenarios are analyzed and the results are captured. In addition, AHP is used to evaluate the KPIs in a microgrid to determine which KPIs are the most important ones.

Key words: Optimization, Microgrid, KPI Modeling

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# Nomenclature

A	Ideality factor
AC	Alternative Current
ACC	Annual Capital Cost
ACS	Annual Cost of System
AHP	Analytic Hierarchy Process
AOM	Annual Operation Maintenance
ARC	Annual Replacement Cost
ASIFI	Average System Interruption Frequency Index
B	Battery
C	Power Curtailed
$C_{\text{anncap}}$ (MG)	Capital Cost
$C_{\text{Gen}}$ (MG)	Generation Cost
$C_{\text{m}}$ (MG )	Maintenance Cost
CAIDI	Customer Average Interruption Duration Index
CRF	Capital Recovery Factor
D	Hours of Load Curtailment
DC	Direct Current
DER	Distributed Energy Resources
DG	Distributed Generator
E	Energy Curtailed
EENS	Expected Energy Not Served

ENS	Energy Not Served
EUE	Expected Unserved Energy
F	Frequency of Load Curtailment
FC	Fuel Cell
GA	Genetic Algorithm
GC	Grid- Connected
Ir	Irradiance
K	Boltzman Constant
KPI	Key Performance Indicator
LPSP	Loss of Power Supply Probability
LV	Low Voltage
MG	Microgrid
MG <sub>GR</sub>	Microgrid Generation Reliability
MG <sub>S</sub>	Microgrid Generation Shortage
MG <sub>T</sub>	Microgrid Total Generation
MG <sub>TCL</sub>	Microgrid Total Connected Loads
MT	Micro-Turbines
OC	Over Current
PCC	Point of Common Coupling
PG <sub>VS</sub>	Power Grid Voltage Stability
PQ	Real and Reactive Power
PV	Photovoltaic
Q	Electron Charge
R	Radius of a Wind Turbine Blade
RES	Renewable Energy Resources
SAI	Average Service Availability Index

SAIDI	System Average Interruption Duration Index
SFF	Sinking Fund Factor
SOC	State of Charge
T&D	Transmission and Distribution
THD	Total Harmonic Distortion
V/F	Voltage and Frequency
$V_{wind}$	Wind Speed
WT	Wind Turbine
$\beta$	Blade Pitch Angle
$\lambda$	Tip-Speed Ratio (TSR)/ Flux
$\rho$	Air Density

# Chapter 1- Introduction

## 1.1. Microgrid Concept

Future electricity distribution system will operate based on the smart grid concept. This intelligent system consists of advanced digital meters, distribution automation, communication systems, and distributed energy resources [1]. Self-healing, high reliability and power quality, providing accommodations to a wide variety of distributed generation and storage options are some of the functionalities for a desired Smart Grid [2]. Figure 1-1 demonstrates an average microgrid framework.

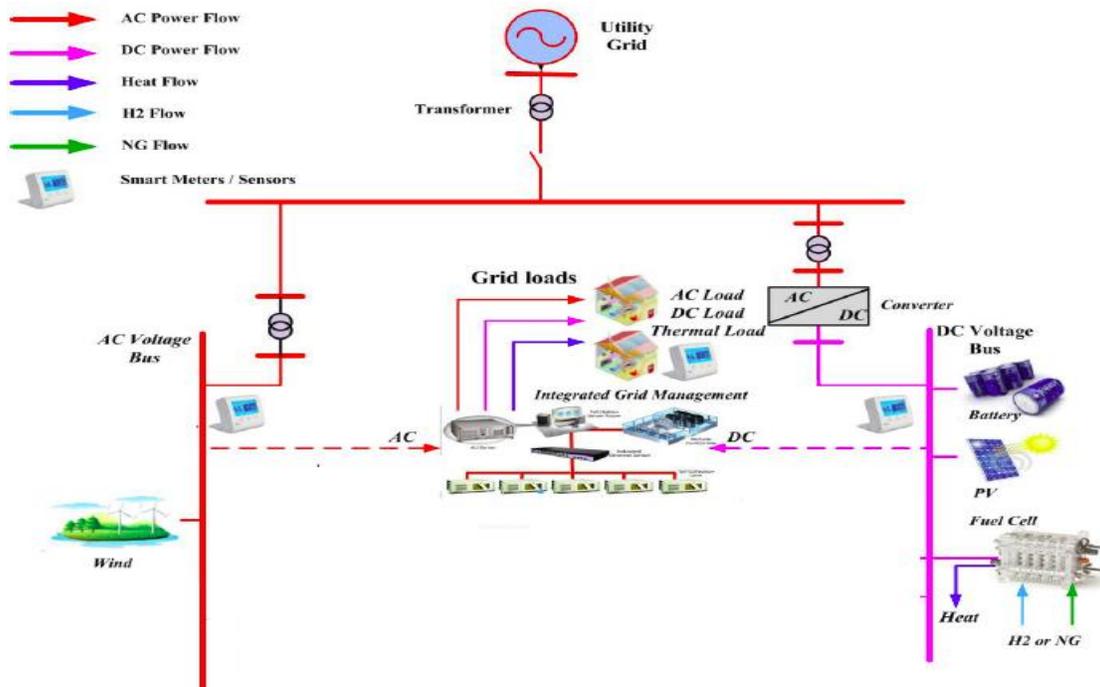


Figure 1-1: A typical microgrid System

Because of the ceaseless increment of DER infiltration levels, there have been a few changes in the way that the power system works. DERs may include generation in small scale (micro sources) and some of them take advantage of renewable energy resources

(RES) such as solar, wind. Transmission losses can be lessened by introducing micro sources near the load. By including RES, controllable loads, and energy storage systems, a microgrid can work in the islanded mode if there should be an occurrence of serious system disturbances. Thus, the chance of power supply interruption at the end-customers connected to a low voltage (LV) distribution grid can be reduced. The microgrid can supply power to the clients by gas turbines, energy components, photovoltaic (PV) frameworks, wind turbines, and so on. The energy storage systems for the most part incorporate batteries and flywheels. The storing device is necessary in the microgrid to balance between energy generation and consumption especially when there are rapid changes in load and/or generation [3].

Microgrids have several advantages such as enhanced reliability, reducing emissions, improving power quality, supportive voltage, reducing voltage dips, and low cost of energy supply. Utilities also can profit by utilizing microgrids. By utilizing distributed energy sources, the demand for distribution and transmission facilities can be reduced. By finding the appropriated location near loads, they can diminish streams in transmission and dispersion circuits. The two essential impacts of utilizing DG would be loss reduction and ability to potentially substitute for network assets. The administration quality can be expanded toward the end clients by finding the DG near interest. Microgrids can offer network support during the time of stress by relieving congestions and aiding restoration after faults. Microgrids can contribute to the reduction of emissions and the moderation of climate changes by using DG units that are based on clean renewable sources such as wind and solar [4-6]. Therefore, there are different favorable circumstances offered by microgrids to end-customer , utilities and society, for example, improved energy efficiency, minimized overall energy consumption, reduced greenhouse gases and pollutant emissions, improved service quality and reliability, cost efficient electricity infrastructure replacement [7].

From the other side, there are some specialized difficulties identified with the operation and control of microgrids. One of these difficulties would be guaranteeing a steady operation amid system aggravations. Likewise, keeping up steadiness and force quality

amid the islanding method of operation. Keeping in mind the end goal to accomplish every one of these objectives, there ought to be modern control systems for microgrid' inverters to maintain stability and power quality. Besides, there are different specialized issues connected with the combination and operation of microgrids alongside of the main grid [4, 6].

Protection system is one of the real difficulties for microgrid which must respond to both main grid and microgrid faults. The protection system ought to disengage the microgrid from the main grid quickly to protect the microgrid loads [4, 8]. Selectivity and sensitivity of protection system are the most critical parts of a protection system. One of the fundamental issues concerning protecting microgrids is identified with various introduced DER units in the microgrid. Actually the working states of microgrid are continually fluctuating in view of the microsources that are utilized (i.e., wind and solar) and load variation. Furthermore, the system topology can be changed every once in a while with a specific end goal to minimize loss and accomplish operational targets. With a specific end goal to have powerful protection system, guarantee that settings decided for OC (over current) protection relays are balanced by network topology and changes location, type, and amount of generation. To deal with bi-directional power flows in microgrids ruled by microsources with force electronic interfaces, another protection logic is obliged [4].

## 1.2. Motivation

In [62], four indices: the wind generation interrupted energy benefit (WGIEB), the wind generation interruption cost benefit (WGICB), the equivalent number of conventional generators (ENCG) and the equivalent conventional generator capacity (ECGC), were used to evaluate the reliability benefit on the addition of wind turbine generator to the rural distribution system. In [75, 76], the authors evaluated the performance and energy efficiency of PV generator in MG based on one year monitoring data, using IEA PVPS task 2 performance, reliability and analysis of PV systems that based on EU guide-lines and IEC 61724. A PV - wind - fuel cell - loads independent MG was used to study the cost benefit (fuel saving) and reliability (health state probability, loss of health expectation) [77]. In general, existing research focuses either on MG design or operation benefit, which

cannot give an overall view of a MG performance. Therefore, KPI modeling is necessary to evaluate the performance of the microgrid as a system.

The microgrid idea goes about as an answer for the issue of incorporating a lot of micro generation without disturbing the utility's operation system. With clever coordination of loads and DERs the distribution network subsystem or "microgrid" would be less troublesome to the utility system, than ordinary microgeneration. If there should arise an occurrence of unsettling influences on the principle system, microgrids could conceivably detach and keep on working independently. This operation enhances power quality to the client. From the network's observation, when the utilities utilize the DERs, the system capacity will be expanded and the loss will be less. The voltage profile will be made strides. Reactive power can be controlled in a better way. Clients can get profits by a microgrid in light of the fact that it is composed and worked to meet their nearby requirements for power and in addition give uninterruptible power, improve local reliability, decrease feeder losses and support local voltages/correct voltage sag.

In order to evaluate the performance of a microgrid, the analysis of different distributed energy resources within microgrid is essential. Distributed energy generations need to give steady yield power in a monetary and naturally qualified way. Solar and wind are great decisions as renewable vitality sources. Key performance indicators (KPIs) are critical to examine and evaluate the execution of the microgrid. Therefore, this thesis is focus on the comprehensive study of KPIs in the microgrid.

### 1.3. Objectives

The aim of this thesis is to present optimal configuration and evaluating the KPIs to ensure secure, reliable and efficient operation of a microgrid including photovoltaic (PV), battery energy storage system, wind turbine (WT) and fuel cell (FC). In order to achieve the stated goal, this study will cover the following objectives:

- Design of a typical AC/DC microgrid composed of wind turbine, fuel cell, PV, and Battery.
- Optimal sizing of microgrid based on minimum operating cost considering the operating conditions.
- Developing KPIs to improve the performance of microgrid.
- Analysis and evaluation of KPIs in dynamic and steady-state operation of microgrid considering high reliability and low emission.

## 1.4. Thesis Organization

The thesis includes six chapters. Following the chapter on introduction, the rest of the thesis is outlined as follows.

**Chapter 2** explains literature review. It explains detailed modeling of PV array with the implantation of maximum power point tracking. Also the battery model is studied. In addition, it explains the modeling of the overall DFIG system in detail. In this chapter the detail explanation is made using block diagrams and different algebraic equations. In addition to the microgrid structure and components, the microgrid operation and control strategies are discussed. Furthermore, the key performance indicators for microgrids are discussed. In addition, optimal sizing of a microgrid using GA are mentioned in this chapter as well. Furthermore, AHP is studied in this chapter too.

**Chapter 3** represents the framework and methodologies. In addition, it explains different analysis techniques. It explains the overall configuration of the hybrid microgrid system was implemented. It provides a detail study on microgrid KPI which are reliability indicators, economic indicator, environmental indicators, and power quality indicators. In addition, it explains the operational planning for microgrid in islanding and Grid-connected mode. Optimizing the microgrid using GA in islanding mode is discussed as well.

**Chapter 4** presents the modeling of the microgrid in MATLAB which includes modeling of WT, PV, FC and battery storage. In addition, microgrid control in Grid-connected mode and islanding are discussed.

**Chapter 5** presents the KPI modeling for steady state and dynamic.

**Chapter 6** presents the case studies that are used in this study in details. These case studies

are in Grid-connected and islanding mode.

**Chapter 7** presents all the simulation results which are found using MATLAB/SIMULINK environment. These simulation results include the microgrid data, Grid-connected and islanding mode analysis for different cases. The KPIs in the microgrid are evaluated as well. In the end, the KPIs are evaluated based on AHP.

**Chapter 8** presents the comprehensive summary and conclusions of the work undertaken in this thesis and also acknowledge about the future work.

**Summary:** In this chapter, introduction and background about the research work are described. In addition, research objectives, motivation, and organization of the thesis are presented. In the following chapter, a literature review will be analyzed in detail.

# Chapter 2-Literature Survey

## 2.1 Definition of Microgrid

Nowadays, renewable energy sources are getting more attention. One of the main reasons for that is the environmental concern. They can be used in the microgrid. There has been a shift the way that electrical power is being generated these days compare to traditional way. In the traditional way, there was no renewable energy source and the power was produced by generators that was power by non-renewable sources such as fossil [9].

Distributed generators make utilization of a few microsources for their operation like photovoltaic cells, batteries, small scale turbines and energy units. Microgrid is built up by combining cluster of loads and parallel distributed generation systems in a certain local area. Microgrids have expansive force limit and more control adaptability which achieves the framework's dependability and additionally the prerequisite of power quality. Microgrid can be associated with the low voltage system at the PCC (point of common coupling) that joined with the DER, storage system and loads. The microgrid loads are varied and may include residential, commercial buildings, campuses and industrial complexes [10-17].

In the event that photovoltaic eras, power devices, wind turbines and gas cogenerations are introduced into utility networks specifically then they can bring about an assortment of issues, for example, voltage rise and security issue in the utility grid [18-19]. The main microgrid was built by Thomas Edison in 1882. He made the first power plant in Manhattan Pearl Street Station. That power plant was basically a microgrid, since centralized grid had not yet been set up. 58 direct current (DC) microgrids had been introduced by 1886 [20].

The microgrid idea includes neighborhood control of distributed generation and thus

decreases the requirement for central dispatch. Amid aggravations by islanding mode and loads, local reliability can be higher in microgrid than the entire power system. In disasters, current distribution systems can face challenges to provide the required energy supply. Using the proposed microgrid in parallel with the grid, the distribution system can recover faster. Microgrids have the ability to be switched in and out of the transmission system. They can also operate independently from the system for a period of time. Therefore, microgrids can be either in grid-connected mode or islanding mode. Because of their ability to operate in islanding mode, the main use of microgrid can be providing power in an emergency to the residential community. Using the microgrids can improve the power delivery and allows the utilities grid to deliver power in urban areas [21]. The microgrid idea brings down the expense and enhances the unwavering quality of little scale circulated generators. From a network perspective, microgrid is an appealing choice as it perceives that the country's distribution system is broad, old and will change gradually. This idea allows high entrance of distribution generation without obliging upgrade of the distribution system itself. [22]. Using a microgrid in a distribution system can have a lot of advantages. The first advantage would be the environmental issues. They would have less environmental impact than the larger conventional thermal power stations. The next advantage would be operation and investment issues. The voltage profile would be enhanced because the reactive support of the whole system would be improved. In addition, transmission and distribution feeder congestion would be reduced and T&D losses would be decreased to about 3%. Furthermore, the investment for expending the transmission and distribution system would be reduced. The power quality and reliability would be improved due to “decentralization of supply, better match of supply and demand, reduction of the impact of large-scale transmission and generation outages and minimisation of downtimes and enhancement of the restoration process through black start operations of microsources”. The T&D costs are significantly reduced or eliminated because of using DERs in the system [23]. The microgrid idea goes about as answer for the issue of incorporating substantial measure of smaller scale era without intruding on the utility system's operation. The microgrid or conveyance system subsystem will make less inconvenience to the utility system than the routine miniaturized scale era if there is fitting and wise coordination of smaller scale era and burdens. If there should be an occurrence of

aggravations on the fundamental system, microgrid could conceivably detach and keep on working exclusively, which helps in enhancing force quality to the customer [3, 4, 24].

Microgrid works as a solitary controllable system which offers control its local area. To the utility microgrid can be viewed as a controllable cell of power framework. In the event of issues in microgrid, the main utility ought to be secluded from the dissemination area as quick as important to protect loads. The isolation depends on customer's load on the microgrid. [4, 16].

Diverse microgeneration advances, for example, micro-turbines (MT), photovoltaics (PV), fuel cells (FC) and wind turbines (WT) with a rated power going up to 100kW can be straightforwardly associated with the LV systems [4]. In addition, Energy storage devices are essential parts in microgrids since some of the generators can be based on renewable energy sources such as wind and sun. The reliability and efficiency of those renewable energy sources can be improved when the energy storage devices are used in microgrids. Furthermore, when the microgrid is not connected to the grid due to the power failure, the energy storage devices can provide power during the islanding mode [3]. As a result, microgrid operation turns out to be exceedingly adaptable, with such interconnection and can be worked uninhibitedly in the grid-connected or islanded mode operation. Each microsource can be worked like a present source with most maximum power exchanged to the grid for the previous case. During the islanded mode, the microgrid can deliver power to the customers. The islanded mode can occur due to the fault in microgrid or in main grid. In islanding mode, each microsource should now direct its own terminal voltage inside of a permitted extent, dictated by its inside produced reference. The microsource along these lines shows up as a controlled voltage source, whose yield ought to legitimately impart the heap interest to alternate sources. The sharing ought to ideally be in extent to their energy evaluations. [3, 4, 25].

The establishment of distributed generators includes specialized investigations of two major fields. Initial one is the managing the impacts instigated by appropriated generators without making extensive adjustments to the control method of distribution system and the

other one is creating another idea for usage of distributed generators. The idea of the microgrid takes after the later approach. There incorporates a few focal points with the establishment of microgrid. It can likewise work freely in the event of any issue. Furthermore, microgrid includes distinctive DERs. “In summary, distribution grids are being transformed from passive to active networks, in the sense that decision-making and control are distributed, and power flows bidirectional” [4]. As a result of using this type of technology, combining DG (Distributed Generation), RES (Renewable Energy Sources) demand side integration (DSI) and energy storage technologies is much easier and more efficient. One of the advantages of having an active network is a better relationship between the power generation and customer demands. Active distribution network will allow both (the generation and demand sides) to operate better in real-time. [4, 26].

The need of client's for power quality and energy supply is satisfied by distributed energy supply. The distribution system can incorporate renewable energy resources, energy storage. These microsources can be introduced near the client's locales. The DERs' advantages incorporate force quality with better supply, higher unwavering quality and high effectiveness of vitality. These DERs are ecological cordial in light of the fact that they do not create CO<sub>2</sub>. Likewise it helps the electric utility by lessening clog on the network, diminishing requirement for new era and transmission and administrations like voltage bolster and request reaction. Microgrid is a coordinated framework and it comprise of distinctive DERs with capacity [27].

Incorporation of wind turbines and photovoltaic frameworks with the grid prompts instability. One of the answers for this issue can be accomplished by the usage of microgrid. Despite the fact that there are a few focal points connected with microgrid operation, there are high transmission line misfortunes. Renewable vitality assets, for example, sun based and stockpiling gadgets can be joined with DC transport with diverse converter topology from which DC burdens can get power supply. Inverters are actualized for force exchange in the middle of AC and DC transports. Amid deficiency in the utility network microgrid works in islanded mode. If there should arise an occurrence of crisis which can happen when renewable sources cannot supply enough power and condition of charge of capacity

gadgets are low, the microgrid detaches regular loads and supply energy to the delicate burdens [18, 19, 28].

In customary AC power systems, AC voltage source is converted into DC power utilizing an AC/DC inverter to supply DC loads. As a result of the environmental issues connected with conventional power plant, renewable resources are associated as distributed generators or AC microgrids. Long distance high voltage transmission is no longer necessary when power can be supplied by local renewable power sources. DC systems use power electronic based converters to convert AC sources to DC and distribute the power using DC lines. As a consequence of these changes, the efficiency is decreased in an AC or a DC system. Keeping in mind the end goal to have a more proficient system, a hybrid AC/DC microgrid is proposed which is the blend of AC and DC power system [29].

One of the main reason to use renewable power plants is providing power to rural areas which are far away from the main grid. Accordingly, there is probability of frail transmission line association. The microgrid idea gives a successful answer for such a weak system. By using a hybrid AC/DC microgrid not only the disturbances due to intermittent nature of energy from PV and wind generation can be minimized but also the microgrid can exchange power with the main grid when excess/shortage occurs in the microgrid [30].

Distribution energies can have benefits for both the utilities and the customers. When customers use the DGs, the power quality and reliability can increase. There will be less outages. The efficiency in using the energy can be increased. The energy cost will be less. In addition, the emission of greenhouse gases can be reduced significantly. When the utilities use the DGs, the system capacity will be increased and the reduction will be less. The voltage profile will be improved. Reactive power can be controlled in a better way. The customer-utility relation will be improved [7].

As it was shown in the previous chapter, a microgrid is for the most part associated with the utility grid through a solitary association point so it is effectively islanded by opening the electrical switch by then. The electrical association purpose of the microgrid to the

utility system, at the low-voltage transport of the substation transformer, constitutes the microgrid point of common coupling (PCC). In the case of islanding, the microgrid ought to keep on serving its loads without disturbance. The microgrid should likewise have the capacity to resynchronize with the grid when the condition that started islanding has been rectified [1, 2, 18, 31,32]. The operational, control and protection issues in microgrids have been addressed in many researches [2, 33-38].

## 2.2 Microgrid Structure and Components

This section will cover the microgrid components in details. As it mentioned before, a microgrid consists of PV, WT, battery and fuel cell. Each of these components will be examined in this section.

### 2.2.1. Photovoltaic System

Photovoltaics (PV) is the immediate change of daylight into power utilizing a semiconductor gadget called a sun oriented cell. A photovoltaic framework makes utilization of one or more sun based boards to change over sun based vitality into power. Photovoltaic modules, mechanical and electrical associations and mountings and method for directing and/or altering the electrical yield are the fundamental parts of PV. The utilization of photovoltaics is naturally well disposed. There are impressive points of interest of sun powered vitality like renewable source and no contamination. On the other hand, it can't give consistent electric force because of fluctuating yield profile which is brought about because of day night cycle, season change and climate condition [39].

As a result of the low voltage era in a PV cell (around 0.5V), a few PV cells are associated in arrangement for high voltage and in parallel for high current to frame a PV module for wanted yield. The proficiency of sun based cells diminishes as the temperature rises. For the most part there are of 36 or 72 cells when all is said in done PV modules. The modules comprise of straightforward front side, typified PV cell and rear. The front side is generally comprised of low-iron and treated glass material [40].

A photovoltaic cluster (PV framework) is an interconnection of modules which thusly is comprised of numerous PV cells in arrangement or parallel. In a cluster the modules' association is same as that of cells in a module. The modules in a PV exhibit are typically initially associated in arrangement to acquire the craved voltages. So as to create more present, the individual modules are then joined in parallel. Stand-alone PV frameworks and matrix associated PV frameworks are two PV applications [41].

## 2.2.2 Modeling of PV Panel

The photovoltaic framework can produce direct current power without ecological effect when is presented to daylight. The fundamental building piece of PV exhibits is the sun based cell, which is essentially a p-n intersection that straightforwardly changes over light vitality into power. The yield normal for PV module relies on upon the cell temperature, sun powered illumination, and yield voltage of the module [42].

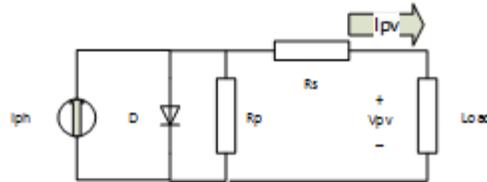


Figure 2-1: Equivalent Circuit of a Solar Cell

$$V_{OC} = \frac{nkT}{q} * \ln\left(\frac{I_L}{I_0} + 1\right) \quad (2.1)$$

$$I_{pv} = n_p I_{ph} - n_p I_{sat} \times \left[ \exp\left(\left(\frac{q}{AKT}\right)\left(\frac{V_{pv}}{n_s} + I_{pv} R_s\right)\right) - 1 \right] \quad (2.2)$$

$$I_{ph} = (I_{sso} + k_i(T - T_r)) \cdot \frac{S}{1000} \quad (2.3)$$

$$I_{sat} = I_{rr} \left(\frac{T}{T_r}\right)^3 \exp\left(\left(\frac{qE_{gap}}{kA}\right) \cdot \left(\frac{1}{T_r} - \frac{1}{T}\right)\right) \quad (2.4)$$

Table 2-1: Parameters for Photovoltaic Panel [42]

Symbol	Description	Value
$V_{oc}$	Rated open circuit voltage	
$I_{ph}$	Photocurrent	
$I_{sat}$	Module reverse saturation current	
$q$	Electron charge	$1.602 \times 10^{-19}$ C
$A$	Ideality factor	1.50
$k$	Boltzman constant	$1.38 \times 10^{-23}$ J/K
$R_s$	Series resistance of a PV cell	
$R_p$	Parallel resistance of a PV cell	
$I_{SSO}$	Short circuit current	3.27A
$k_i$	SC current temperature coefficient	$1.7e^{-3}$
$T_r$	Reference temperature	301.18 K
$I_{rr}$	Reverse saturation current at $T_r$	$2.0793e^{-6}$ A
$E_{gap}$	Energy of the band gap for silicon	1.1 eV
$n_p$	Number of cells in parallel	
$n_s$	Number of cells in series	
$S$	Solar radiation level	0-1000 W/m <sup>2</sup>
$T$	Surface temperature of the PV	
$I_o$	Dark saturation current	
$I_L$	Light generated current	
$n$	Ideality factor	

### 2.2.3 Maximum Power Point Tracking

By using maximum power point tracker (MPPT), the photovoltaic (PV) modules can produce the maximum power that they are capable of. Since MPPT is a fully electronic system, it varies the module's operating point so that the modules will be able to deliver maximum available power. MPPT is essential in PV systems since the outputs of PV system are dependent on the temperature and irradiation. MPPT allows the PV system to maximize the PV array output voltage [41, 43, 44]. The output power of the PV is calculated by  $P= VI$ . The voltage of the PV and the current are represented by  $V$  and  $I$  respectively. In order to get the maximum output power point the conventional MPPT

algorithms use  $dv/dp$ . The reference voltage is increased or decreased according to the operation region which is determined by measured  $\Delta P$  and  $\Delta V$ [45].

### 2.2.3.1 Incremental Conductance

There are different algorithms to track the peak power point of the solar PV module automatically. One of these algorithms is incremental conductance. In order to solve the problems regarding the tracking peak power under fast varying atmospheric condition, incremental conductance method can be used [46].

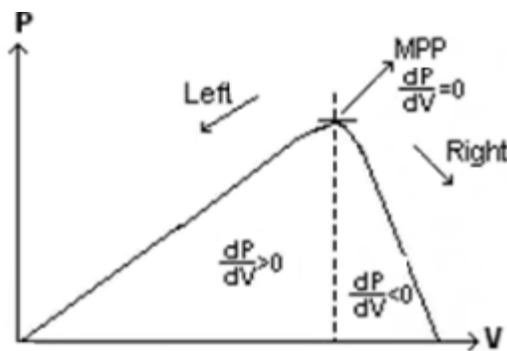


Figure 2-2: Incremental conductance [46]

The algorithm uses the equation

$$P = V * I \quad (2.5)$$

Where P=power of the module, V= voltage of the module, I= current of the module

Differentiating with respect to  $dV$

$$\frac{dp}{dv} = I + dI/dv \quad (2.6)$$

The algorithm works depending on this equation

At peak power point

$$\frac{dp}{dv} = 0 \quad (2.7)$$

$$\frac{dI}{dv} = -I/V \quad (2.8)$$

If the operating point is to the right of the power curve then we have

$$\frac{dp}{dv} < 0 \quad (2.9)$$

$$\frac{dI}{dv} < I/V \quad (2.10)$$

If operating point is to the left of the power curve then we have

$$\frac{dp}{dv} > 0 \quad (2.11)$$

$$\frac{dI}{dv} > I/V \quad (2.12)$$

The algorithm works using equations (2.8), (2.10), & (2.11).

At the point when the incremental conductance chooses that the MPPT has come to the MPP, it quits irritating the working point. On the off chance that this condition is not accomplished, MPPT working point course can be figured utilizing  $dI/dv$  and  $-I/V$  connection. This relationship is gotten from the way that when the MPPT is to one side of the MPP  $dP/dv$  is negative and positive when it is to one side of the MPP.

Battery is for the most part required when PV exhibit cannot be utilitarian, for example, during the evening or on a shady day. The significant elements of a stockpiling battery in a PV framework are: "energy storage capacity and autonomy, voltage and current stabilization and supply surge currents" are the real elements of utilizing batteries as a part of PV frameworks. Battery can store electrical vitality that is created by the PV. It additionally can supply vitality to electrical burdens. Battery can supply stable voltages and current to electrical loads [41].

## 2.2.4 Modeling of Battery

The battery is modeled as a nonlinear voltage source whose output voltage depends not only on the current but also on the battery state of charge (SOC), which is a nonlinear function of the current and time [26]. The following equations show terminal voltage and state of charge.

$$V_b = V_o + R_b \cdot i_b - K \frac{Q}{Q + \int i_b dt} + A \cdot \exp(B \int i_b dt) \quad (2.13)$$

$$S.O.C. = 100 \left( 1 + \frac{\int i_b dt}{Q} \right) \quad (2.14)$$

Where  $V_b$  is internal resistance of the battery,  $V_o$  is the open circuit voltage of the battery and  $i_b$  represents battery charging current. In addition,  $K$  is polarization voltage,  $Q$  is battery capacity,  $A$  represents exponential voltage, and  $B$  is exponential capacity [42]. Equations (2.13) and (2.14) are used in order to model the battery.

## 2.2.5 Wind Turbines

With the utilization of power of the wind, wind turbines produce power to drive an electrical generator. A wind turbine separates motor vitality from the cleared zone of the sharp edges. Normally twist ignores the cutting edges and makes the sharp edges turn. Pivoting cutting edges transform a pole then goes into a gearbox. The rotational rate can be expanded by the gear's utilization box. This can help the generator's operation. In addition, it utilizes magnetic fields to convert the rotational energy into electrical energy. The output electrical power goes to a transformer, which converts the electricity to the appropriate voltage for the power collection system [47-51].

The power contained in the wind is given by the kinetic energy of the flowing air mass per unit time [28, 47, 48, 50-52]. The equation for the power contained in the wind can then be written as

$$P_m = 1/2 C_p (\beta, \lambda) \rho \pi R^2 V^3 \text{wind} \quad (2.15)$$

Where  $C_p$  is a rotor power coefficient,  $\beta$  is a blade pitch angle,  $\lambda$  is a tip-speed ratio (TSR),  $\rho$  is an air density,  $R$  is the radius of a wind turbine blade and  $V_{\text{wind}}$  is a wind speed. Although Eq. (2.15) describes the availability of power in the wind, power transferred to the wind turbine rotor is reduced by the power coefficient  $C_p$ .

$$C_p = \frac{P_{\text{wind turbine}}}{P_{\text{air}}} \quad (2.16)$$

A maximum value of  $C_p$  is defined by the Betz limit, which states that a turbine can never extract more than 59.3% of the power from an air stream. In reality, wind turbine rotors have maximum  $C_p$  values in the range 25-45%.

$$P_{\text{wind turbine}} = C_p \times P_{\text{air}} \quad (2.17)$$

It is also conventional to define a tip speed ratio  $\lambda$  as

$$\lambda = \frac{\omega R}{V_{\infty}} \quad (2.18)$$

According to [63], in the condition of standard air density, the curve describing the correlation between the wind turbine power output and wind speed is called standard power output curve of the WTG. Figure 2-3 shows the standard power output curve of the WTG.

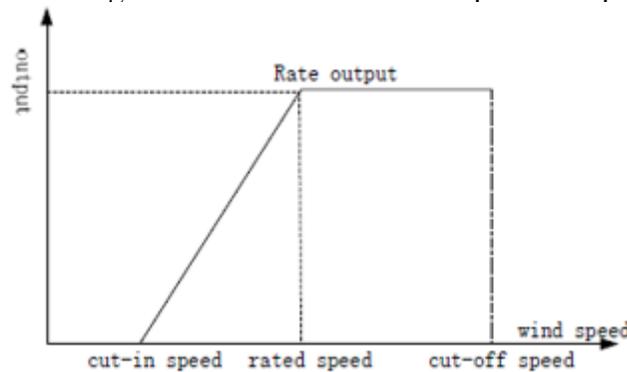


Figure 2-3: Standard power output curve of the WTG [63]

At the point when wind is up to the cut-in velocity, WTG begins working. The output power is straight with wind velocity till it ranges appraised yield. At the point when the wind velocity is equivalent or more prominent than the evaluated wind speed, the output power stays at rating output until wind rate is up to cutoff-speed. The calculation formula is shown as follows:

$$P = \begin{cases} 0 & 0 \leq V \leq V_{ci} \\ \frac{V-V_{ci}}{V_r-V_{ci}} & V_{ci} \leq V < V_r \\ P_r & V_r \leq V < V_{co} \\ 0 & V \geq V_{co} \end{cases} \quad (2.19)$$

### 2.2.5.1 DFIG System

The doubly fed induction generator is the most broadly machine in nowadays. The actuation machine can be utilized as a generator or engine. It is broadly utilized as a part of wind turbines because of adoptability limit and nature of tractability. This segment depicts the subtle element investigation of general DFIG framework alongside consecutive PWM voltage source converters. DFIG is an injury rotor sort instigation machine, its stator comprises of stator frame, stator core, poly phase (3-phase) distributed winding, two end covers, bearing, etc. The stator center is pile of round and hollow steel covers which are opened along their internal outskirts for lodging the 3-phhase winding. Its rotor comprises of openings in the external outskirts to house the windings like stator. The machine chips away at the rule of Electromagnetic Induction and the vitality exchange happens by method for exchange activity. This area clarifies the essential scientific displaying of DFIG. In this section the machine taking so as to demonstrate is clarified two stage parameters into thought [47].Figure 2-4 and 2-5 demonstrate the equivalent circuit diagram of an induction machine.

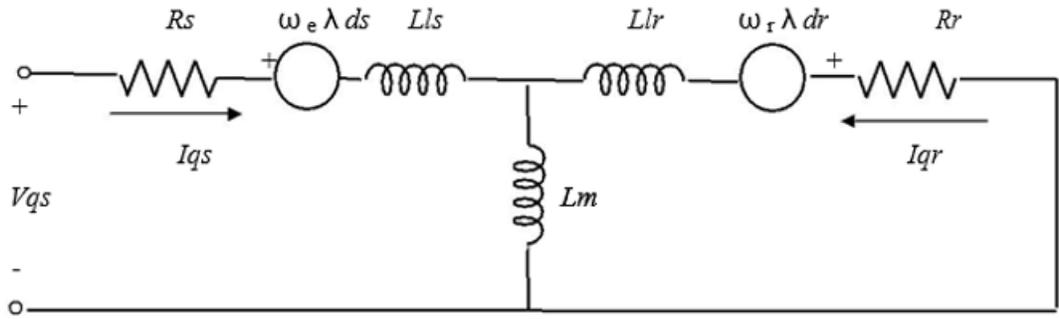


Figure 2-4: Q-axis circuit Equivalent Circuit on a Synchronous Frame [53]

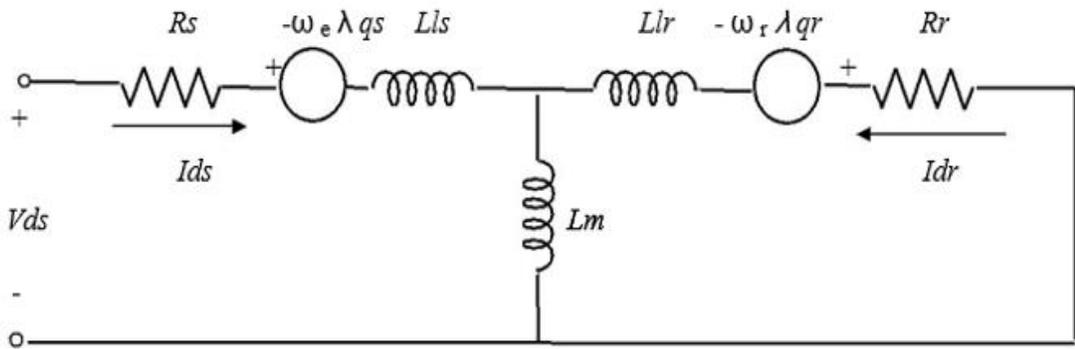


Figure 2-5: D-axis circuit Equivalent Circuit on a Synchronous Frame [53]

Equations for the stator circuit can be written as [53]

$$V_{qs} = R_s I_{qs} + p \lambda_{qs} + \omega_s \lambda_{ds} \quad (2.20)$$

$$V_{ds} = R_s I_{ds} + p \lambda_{ds} - \omega_s \lambda_{qs} \quad (2.21)$$

$$0 = R_r I_{qr} + p \lambda_{qr} + \omega_r \lambda_{dr} \quad (2.22)$$

$$0 = R_r I_{dr} + p \lambda_{dr} - \omega_r \lambda_{qr} \quad (2.23)$$

where flux linkage variables are defined by

$$\lambda_{qs} = L_s I_{qs} + L_m I_{qr} \quad (2.24)$$

$$\lambda_{ds} = L_s I_{ds} + L_m I_{dr} \quad (2.25)$$

$$\lambda_{qr} = L_m I_{qs} + L_r I_{qr} \quad (2.26)$$

Where  $R_s$  and  $R_r$  are stator and rotor winding resistances respectively.  $L_s$  and  $L_r$  are stator and rotor winding self-resistances respectively.  $L_m$  is magnetizing inductance and  $\omega_r$  is the rotor angular frequency.

## 2.2.6 Fuel Cell

General Electric in the United States presented PEMFC which is likewise called strong polymer power module amid the 1960s, for utilization by NASA. An exceptional polymer film that is covered with very scattered impetus particles is utilized as a part of this kind of power module. Hydrogen is encouraged to the film's anode side (conceivably at a weight more prominent than climatic weight) where the impetus causes the hydrogen molecules to discharge their electrons and get to be  $H^+$  particles (protons) [54].



The  $H^+$  particles can just go through the proton trade layer (PEM) while the electrons are gathered and used as power by an outside electrical circuit before they achieve the cathode side. In the cathode side, the electrons and the hydrogen particles are diffused through the layer join with the supplied oxygen (normally from air) to frame water. This reaction releases energy in the form of heat:



In order to prevent the cell from being flooded, this water needs to be removed. In addition, any unused hydrogen and oxygen (air) are exhausted from the cell anode and cathode outlets, respectively.

## 2.3 Microgrid Operation

According to [55], there are two operation modes of microgrid. The first one is Grid-connected Mode. In this mode, the microgrid is connected to the upstream network. The microgrid can receive totally or partially the energy by the main grid. In addition, when the total production is bigger than consumption, the power excess can be sent to the main grid.

The next mode is islanding mode which happens when the Grid has a failure, or there are some planned actions such as maintenance actions, the microgrid can smoothly move to islanded operation. Thus, the microgrid operate autonomously, is called island mode, in a similar way to the electric power systems of the physical islands.

## 2.4 Grid Connected Mode: PQ Control

PQ control strategy is used when the controllable inverter interfaced micro-sources are operated in grid-connected. In this mode, the micro-grid is regulated by the main grid when there are undulations in the loads, and disturbances in the frequency and voltage. The frequency and voltage of the system are not regulated by microsources and the frequency and voltage of the main grid are adopted directly by the microgrid. Voltage-mode control and the current-mode control are the two methods to control the active and reactive power flowing out of an inverter. In the voltage-mode control, the active and reactive power are controlled using the phase angle and magnitude of the inverter AC voltage side with respect to same quantities on the PCC side. In current-mode control approach the active and reactive power are controlled by controlling the phase and magnitude of the inverter AC side currents with respect to the PCC current quantities [56, 57]. Figure 2-6 shows the PQ schematic diagram.

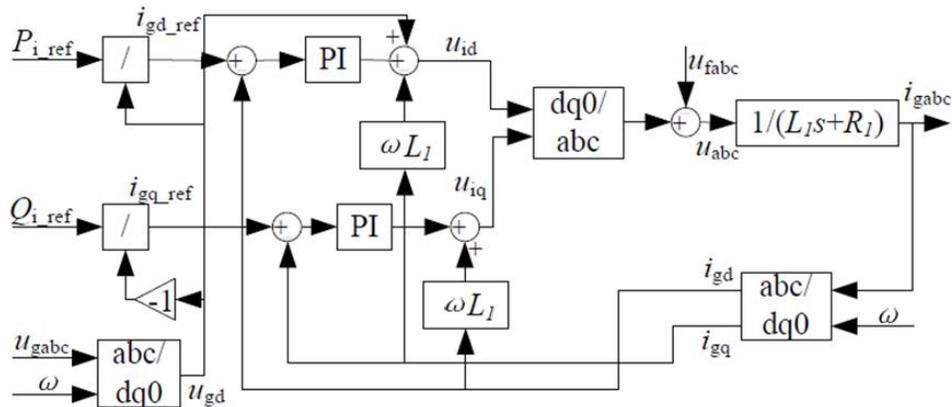


Figure 2-6: Schematic diagram of P/Q control [57]

Under the P/Q control condition, the inverters output voltage is changed from abc coordinate to dq0 coordinate in Park transform. In addition, the voltage of the q axis is changed to zero in the transition ( $u_{gq}=0$ ). The output power of the inverters are expressed as the following equations

$$P_{ref} = u_{gd} \times i_{gd} + u_{gq} \times i_{gq} = u_{gd} \times i_{gd} \quad (2.29)$$

$$Q_{ref} = -u_{gd} \times i_{gq} + u_{gq} \times i_{gd} = -u_{gd} \times i_{gq} \quad (2.30)$$

$u_g$  is the voltage and the  $i_g$  is the current of the grid at the PCC.

The voltage at the microgrid side can be written as

$$V_{sa}(t) = \hat{V}_s \cos(\omega_0 t \theta_0) \quad (2.31)$$

$$V_{sb}(t) = \hat{V}_s \cos(\omega_0 t \theta_0 - 2/3) \quad (2.32)$$

$$V_{sc}(t) = \hat{V}_s \cos(\omega_0 t \theta_0 - 4/3) \quad (2.33)$$

where,  $V_s$  is the peak phase-to-neutral value,  $\omega_0$  is the angular frequency at the microgrid side,  $\theta_0$  is the initial power phase angle.

## 2.5 Islanded Mode

When the microgrid is in islanding mode, the DGs that were operating with PQ control strategy lose their voltage and frequency references because the microgrid is no longer connected to the main grid. The storage device which was previously being operated with a PQ control changes to V/f control. The storage device provides the power difference that was being supplied from the main grid to the microgrid before the islanding mode. It is assumed that the storage device has an enough energy reserved to be able to provide the same power difference as the main grid [58].

### 2.5.1 V/f Control

The micro-grid can operate in the islanded mode when there is a power quality problem in the grid. In this mode, the microsourses are in charge of the voltage and frequency. The output of the inverters is detected in real time under the control of the PI controller, which

works via setting the reference value of the voltage and frequency. The V/f control strategy is a tight closed loop control with the reference values of voltage,  $V_{ref}$  and frequency,  $f_{ref}$ . The frequency is measured using a three-phase PLL. In the V/f control scheme two separate PI controllers are used to process the error caused by the difference of the measured value and the reference set-points and attempts to minimize the error by adjusting  $K_p$  and  $K_i$  values. Only the voltage, which is the output of the inverters, is detected in the V/f control and the frequency is kept as a constant value. [57, 59]. Figure 2-7 shows the schematic diagram of V/f control.

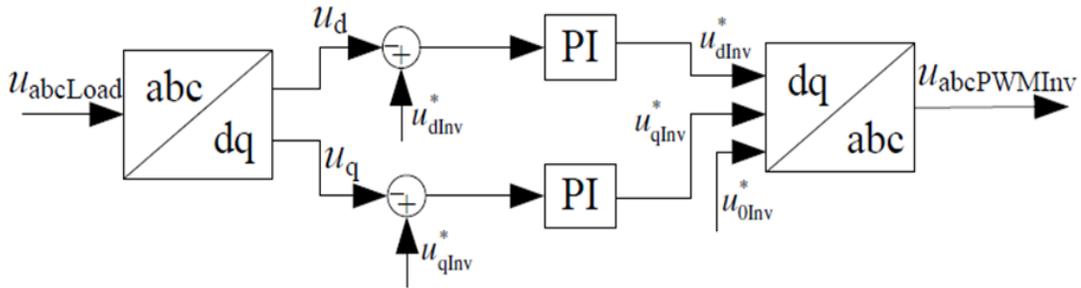


Figure 2-7: Schematic diagram of V/f control [57]

## 2.5.2 Master-Slave Operation

In master-slave operation of a microgrid during islanding period only one microsource acts as a reference DG to set the voltage and frequency constant while all the other sources operate in the same way as during the grid-connected mode. It is assumed that the storage device has enough capacity to provide the power imbalance and it has the ability to have fast response to power demand. In this control scheme, only one inverter behaves like a master to regulate the voltage and frequency and the other units keep the constant power. The master unit is V/f controlled and the remaining units are the P/Q controlled. The master/slave is shown in Figure 2-8 [60].

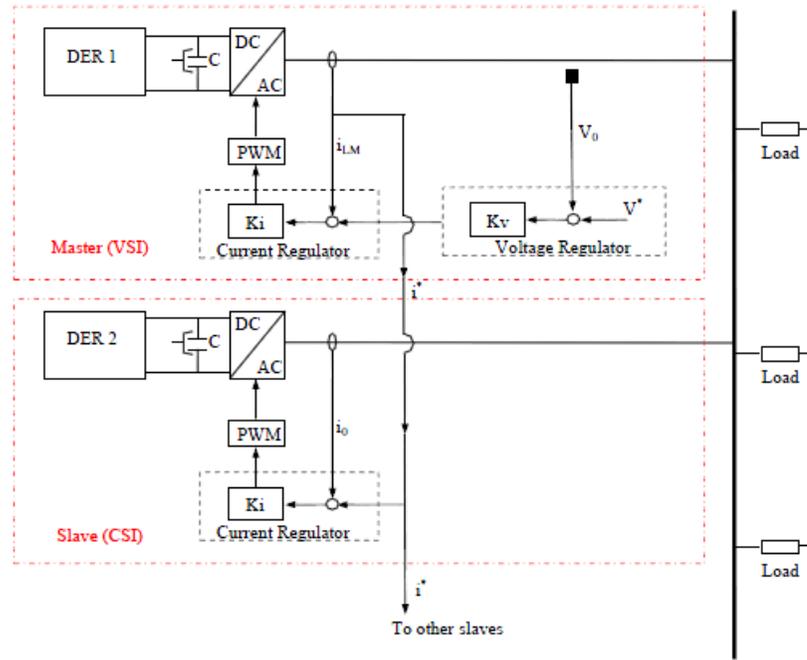


Figure 2-8: The master/slave control [60]

### 2.5.3 Droop Control

Figure 2-9 shows the droop control. In droop control, all the DGs within the microgrid during the islanding mode are transferred to droop control to share the load based on their respective droops  $V/Q$  droops. The  $V/Q$  droop control regulates the reactive power change based on their respective voltage droop characteristics [61]. In [60] mentioned that droop methods are based on the behaviour of synchronous generators in the power system. In this control technique, the active and reactive power sharing by the inverters are estimated by adjusting the output frequency and voltage amplitude. In addition,  $m$  and  $n$  are the droop coefficients.



In reality, waveform distortion varies a lot and it depends on both load levels and system conditions. The THD is fundamentally defined in Eq. (2-34).

$$THD (\%) = \frac{\sqrt{\sum_{i=2}^{\infty} F_i^2}}{F_1} \times 100\% \quad (2.34)$$

IEEE 519-1992 and IEEE 519A (draft) are the two IEEE documents that cover IEEE limits. According to these documents, the harmonics in the power system can be limited by two different methods. The first one is the harmonic limits for the harmonic current which a user can inject into the utility system at PCC. The second set of harmonic limits is for the harmonic voltage that the utility can provide to any customer at the PCC. Table 2-2 gives the IEEE 519-1992 voltage distortion limits. The acceptable distortion is decreased at higher voltage levels in order to minimize potential problems for the majority of system users [61].

*Table 2-2: IEEE 519-1992 Voltage Harmonic Limits [61]*

Bus voltage at PCC	Individual Harmonic Voltage Distortion (%)	Total Voltage Distortion-THD <sub>vn</sub> (%)
V <sub>n</sub> ≤ 69 kV	3	5
69kV < V <sub>n</sub> ≤ 161 kV	1.5	2.5
V <sub>n</sub> > 161 kV	1	1.5

If harmonics cause problems, two categories of solutions are available. The first one is reducing the harmonics at their point of origin (before they enter the system). In this method, various transformer connections can be used to cancel certain harmonics. This method can be used if a new facility is being built. The second method is applying filtering to reduce undesirable harmonics. For existing facilities, harmonic filters are cost effective method. There are two different types of harmonic filters. Active filters are only now becoming commercially viable products for high-power applications. Passive filtering is more cost effective for high power applications or for applications where power factor correction capacitors already exist [61].

### 2.6.1.2 Demand

According to [61] demand is a measure of the energy that loads require over short periods of time and it is expressed in terms of power (kilowatts or Megawatts). Demand, as commonly referred to in utility discussions as integrated demand, can be measured over 10, 15, or 30 min. The following formula shows the way of calculating demand.

$$\text{Demand} = \frac{\text{Energy Use Over Demand Interval}}{\text{Demand Interval}} \quad (2.35)$$

### 2.6.1.3 Demand Factor

In [61] mentioned that demand factor is a ratio of the maximum demand to the total connected load of a system or the part of the system under consideration. Utilizing demand factor permits power system equipments to be measured properly for the normal loads.

$$\text{Demand Factor} = \frac{\text{Maximum Demand}}{\text{Total Connected Load}} \quad (2.36)$$

### 2.6.1.4 Load Factor

Load factor is similar to demand factor and can be calculated from the energy use. If a load or group of loads operates near its peak most of the time, the load factor is high. It is the ratio of the energy use to the demand times time [61].

$$\text{Load Factor} = \frac{\text{Energy Use}}{\text{Demand} \times \text{Time}} \quad (2.37)$$

## 2.6.2 Reliability

The next KPI is reliability which can be subcategorized as wind generation indices and power system reliability indices.

### 2.6.2.1 Wind Generation Indices

According to [62], the index of the wind generation interrupted energy benefit (WGIEB) shows the reliability worth of adding wind generation as an alternative supply.

$$WGIEB = \frac{EENS_{bw} - EENS_{aw}}{\text{Incremental WTG capacity}} \quad (2.38)$$

where  $EENS_{bw}$  and  $EENS_{aw}$  represent the energy not supplied after and before adding WTG units respectively.

The index of wind generation interruption cost benefit (WGICB) can also represent the reliability worth of adding wind generation as an alternative supply.

$$WGICB = \frac{ECOST_{bw} - ECOST_{aw}}{\text{Incremental WTG capacity}} \quad (2.39)$$

where  $ECOST_{bw}$  and  $ECOST_{aw}$  are the expected interruption cost after and before adding WTG units to the system, respectively.

In order to find the number of WTG units required to replace a conventional generating unit of the same size for a specified system ECOST, the index ENCG (the equivalent number of conventional generating) is created.

$$ENCG = \frac{RNCG}{RNWTG} \text{ for a specified ECOST} \quad (2.40)$$

where RNCG and RNWTG are the required number of the CG and WTG respectively.

The equivalent conventional generating capacity (ECGC) is defined as following

$$ECGC = \frac{RCCG}{RCWTG} \text{ for a specified ECOST} \quad (2.41)$$

where RCCG and RCWTG are the required capacity of the CG and WTG respectively.

### 2.6.2.2 Power System Reliability Indices

According to [63] and [64], in the current distribution system reliability evaluation, the commonly used reliability indexes are divided into load point reliability indexes and system reliability indexes.

Load point reliability indexes, including the following three aspects:

- 1)  $\lambda$  :frequency of load interruptions (occurrences per year);
- 2)  $r$  :average duration of load interruptions(hours per occurrence);
- 3)  $U$  : average annual duration of load interruptions (hours per year).

A list of commonly used system indexes is as follows:

- 1) System Average Interruption Frequency Index (SAIFI);
- 2) System Average Interruption Duration Index (SAIDI);
- 3) Average Service Availability Index (ASAI).

$$SAIFI = \frac{\text{Total number of customer interruptions}}{\text{Total number of customer served}} \text{ per year or } SAIFI = \frac{\sum \lambda_i N_i}{\sum N_i} \quad (2.42)$$

$$SAIDI = \frac{\sum \text{Customer interruption durations}}{\text{Total number of customers served}} \text{ hours per year or } SAIDI = \frac{\sum U_i N_i}{\sum N_i} \quad (2.43)$$

$$ASAI = \frac{\text{Customer hours service availability}}{\text{Customer hours service demand}} = \frac{8760 - SAIDI}{8760} \text{ per unit or} \quad (2.44)$$

$$ASAI = (8760 \sum N_i - \sum U_i N_i) / (8760 \sum N_i) \quad (2.45)$$

where  $N_i$  represents the number of consumers at load point  $i$ ;  $\lambda_i$  represents the failure rate at load point  $i$ ;  $U_i$  represents the average annual duration of load interruption at load point  $i$ .

According to [65] Expectation Energy Not Supplied (EENS) is defined as following:

$$EENS = \sum L_i U_i \quad (2.46)$$

where  $L_i$  is the load. The unit is *MWh/year*. where  $U_i$  is the average annual outage time.

In order to find the failure of power system components, the following formulas are used.

$$f(t) = \lambda e^{-\lambda t} \quad (2.47)$$

$$g(t) = \mu e^{-\mu t} \quad (2.48)$$

where  $\lambda$  is the failure rate,  $\mu$  is repair rate,  $f(t)$  is probability of failure in time  $t$ , and  $g(t)$  is the probability of repair.

In [64] mentioned that the indices suitable for transmission system reliability evaluation are divided into system problem indices and load curtailment indices. System problem indices measure frequency, duration, probability, and severity of system problems. Some examples:

- Frequency of circuit overloads (overloads/year)

- Average duration of circuit overloads (hours)
- Probability of circuit overloads

Load curtailment indices measure severity in terms of load interrupted or curtailed. The three fundamental reliability measurements are frequency, duration, and load curtailment.

$$\text{Frequency of load curtailment } F = \sum_i F_i (\text{year}^{-1}) \quad (2.49)$$

$$\text{Hours of load curtailment } D = \sum_i F_i D_i (\text{hyear}^{-1}) \quad (2.50)$$

$$\text{Power curtailed } C = \sum_i F_i C_i (\text{MWyear}^{-1}) \quad (2.51)$$

$$\text{Energy curtailed } E = \sum_i F_i D_i C_i (\text{MWhyear}^{-1}) \quad (2.52)$$

$F_i$  = Frequency of event  $i$  ( $\text{year}^{-1}$ )

$D_i$  = Duration of event  $i$  (h)

$C_i$  = MW load curtailed for event  $i$  (MW)

$i$  = All events for which  $C_i > 0$

Energy curtailment (E), expressed in MWh not served, is often referred to as Energy Not Served (ENS), Expected Energy Not Served (EENS), or Expected Unserved Energy (EUE).

$$\text{Power interruption index } CN = C/\text{CMX} (\text{year}^{-1}) \quad (2.53)$$

$$\text{Energy curtailment index } EN = E/\text{CMX} (\text{h year}^{-1}) \quad (2.54)$$

where CMX = peak load for system, area, or bus.

Customer Average Interruption Duration Index (CAIDI)

$$CAIDI = \frac{\sum \text{Customer interruption durations}}{\text{Total number of customer interruptions}} = \frac{SAIDI}{SAIFI} \text{ hours per interruption} \quad (2.55)$$

The Average System Interruption Frequency Index (ASIFI)

$$ASIFI = \frac{\text{Connected kVA interrupted}}{\text{Total connected kVA served}} \text{ per year} \quad (2.56)$$

In [64] the author mentioned that underground cables and transformer failures are some of the utilities reliability problems.

### 2.6.3 The Economic Indicator

The economic indicator has five second-class indicators: capital cost, maintenance cost, generation cost, replacement cost, and power loss cost in US\$.

#### a) *Capital Cost*

Capital cost or lifecycle cost has been used to decide economic feasibility of a system [66]. Microgrid with lowest capital cost is always preferred.

$$\begin{aligned} C_{ann\_cap}(DGs) &= \sum [C_{cap,k} \cdot CRF(i, Y_{proj,k})] \\ &= \sum [C_{cap,k} \cdot \frac{i(1+i)^{Y_{proj,k}}}{(1+i)^{Y_{proj,k}} - 1}] \end{aligned} \quad (2.57)$$

Where  $CRF$  is the capital recovery factor that represents a ratio to calculate the present value of an annuity- a series of equal annual cash flow.

#### b) *Maintenance Cost*

Annualized maintenance cost of all DERs in microgrid can be calculated as a constant [66].

$$C_{ann\_main} = constant \quad (2.58)$$

#### c) *Generation Cost*

DGs generation cost or operation cost is related to fuel consumption and fuel price, mainly is related to DGs that consume coal or gas such as micro gas turbine and diesel engine [66]

$$\begin{aligned} C_{ann\_op} &= \sum_{t=1}^{8760} \sum_{i=1}^n \{C_{f,i}[P_{DG_i}(t)] + C_{o,i}[P_{DG_i}(t)]\} \\ &= \sum_{t=1}^{8760} \sum_{i=1}^n [K_{f,i} \times P_{DG_i}(t) + K_{o,i} \times P_{DG_i}(t)] \end{aligned} \quad (2.59)$$

#### d) Replacement Cost

Replacement cost refers to annualize replacement cost on batteries [66], which is usually thought as a constant.

$$\begin{aligned} C_{ann\_rep} &= C_{rep,battery} \cdot SFF(i, Y_{rep,battery}) \\ &= C_{rep,battery} \cdot \frac{i}{(1+i)^{Y_{rep,battery}} - 1} \end{aligned} \quad (2.60)$$

Where  $SFF$  is the sinking fund factor that is a ratio to calculate the future value of a series of equal annual cash flow.

### 2.6.4 Environmental Indicators

Environmental indicator refers to greenhouse emission produced by DGs [66]. It can be indicated as

$$E_{ann} = \sum_{t=1}^{8760} \sum_{i=1}^n [K_{e,i} \times M_e \times P_{DG_i}(t)] \quad (2.61)$$

## 2.7 Optimal sizing of a Microgrid Using Genetic Algorithm

Genetic Algorithms are inspired by Darwin's hypothesis about evolution. Algorithm is started with a set of solutions (represented by the chromosomes) called population. Solutions from one population are taken and used to shape another population. Solutions that are chosen to frame new solutions are chosen by wellness. They have a superior opportunity to repeat on the off chance that they have a superior wellness. The main elements of natural genetics used for the searching procedure are Reproduction, Crossover and Mutation. The production operation comprises of selecting individuals from the present population without changes to frame some piece of the new population. Meanwhile, the crossover operation comprises of making new individuals (offspring) from the present individuals (parents), as indicated by a crossover probability .The mutation

operation makes adjustments to a chose individual as per a change likelihood by altering one or more values in the binary representation [67-68].

## 2.8 Dispatch Optimization

Dispatching is the allocation of demand among electric power generators. The process determines the most cost-efficient operation of a power system. The main objective is the minimization of the operational cost of all committed units subjected to technical and capacity constraints. The selected optimization algorithm should have a good convergence speed and accurate results. Some of these optimization techniques are neural networks methods such as the one in [69], ant colony optimization [70] and particle swarm optimization [71]. In addition, methods such as genetic algorithms and the mesh adaptive direct search have been adapted to micro grid management simulations [72].

## 2.9 Analytic Hierarchy Process (AHP)

In [73] said that Analytic Hierarchy Process (AHP) is a standout amongst the most broadly utilized numerous criteria choice making instruments. This is an Eigen quality way to deal with the pair-wise examinations. It additionally gives a system to align the numeric scale for the estimation of quantitative and additionally subjective exhibitions. The scale ranges from 1 to 9. The mythology of AHP is the accompanying:

1. The issue should be characterized.
2. The criteria that impact the conduct is recognized.
3. The problem in a hierarchy of different levels constituting goal, criteria, sub-criteria and alternatives is structured.
4. Every component in the relating level is thought about and they are adjusted on the numerical scale. This requires  $n(n-1)/2$  examinations, where  $n$  is the quantity of components with the contemplations that corner to corner

components are equivalent or '1' and alternate components will just be the reciprocals of the prior correlations.

5. The procedure is done till the consistency index CI and normalized values for each criteria/ alternative are found.
6. The choice is taken in light of the standardized qualities.

*Table 2- 3: The Saaty Rating Scale [74]*

Intensity of importance	Definition
1	Equal importance
3	Somewhat more important
5	Much more important
7	Very much more important
9	Absolutely more important
2,4,6,8	Intermediate values

Summary: In this chapter, the literature review on microgrid and its advantage has been done. In addition, microgrid components were explained in details. Furthermore, controlling of microgrid in Grid-connected and Islanding has been mentioned. In addition, the KPIs that can be applied to microgrid were introduced. Optimal sizing of the microgrid by GA and dispatch optimization has been reviewed. In the end, analytical hierarchy process was explained.

# Chapter 3-Methodology

In this chapter, the methodology of the research is discussed. The aim of this thesis is to develop a feasible study of designing and evaluating a microgrid and its KPIs. The first part of the study is to optimize the size of the microgrid components in order to have an efficient system. In order to achieve this goal, Genetic Algorithm is used. For optimizing the size of the components, a good operational planning is needed. The second part of the thesis is evaluating the optimized microgrid based on its KPIs.

Figure 3-1 shows the framework of this thesis. The literature review was done in chapter 2. The data for analyzing the microgrid was gathered. Chapter 6 will explain the data in details. The operational planning for the islanding mode is introduced. There are six different scenarios in islanding mode operational planning. Chapter 6 will explain this operational planning in details. In Grid-connected mode, the microgrid is connected to the Grid and if there is a shortage, the Grid can provide the power. Therefore, there is no fuel cell in the Grid-connected mode. On the other hand, when the PV and WT power is superior to the load demand, the power excess can be sold back to the main grid or be stored to battery. The operational planning for Grid-connected mode is explained later in chapter 6. In addition, the microgrid is optimized by using the Genetic Algorithm. In order to optimize the microgrid, an objective function based on minimizing the operating cost is proposed. Chapter 5 will explain the KPIs modeling in details in dynamic and static (steady-state). After evaluating the KPIs for each case, AHP is used in order to evaluate the KPIs and determining which KPIs are the most important ones in case of evaluating the performance of the microgrid.

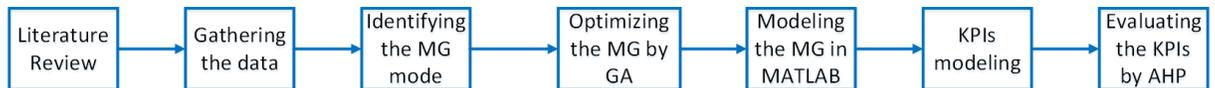


Figure 3-1 Framework

## 3.1 Optimizing the Microgrid using GA in Islanding Mode

Optimization model is developed for the considered unit commitment problem. The objective is to minimize operating costs while serving the total demand. The economic factor is one of the main factors to have a successful deployment of a microgrid. One of the main challenges in microgrid is finding the optimized size of the components. In order to optimize the system, a good operational planning is needed. As it mentioned earlier, the microgrid can be in Grid- connected mode or Islanding depending on the situation. The operational planning is needed when the microgrid is in Islanding. In order to optimize the microgrid the power demand by the load, locally available energy information such as solar irradiation data ( $\text{W}/\text{m}^2$ ), outside temperature ( $^{\circ}\text{C}$ ), wind speed ( $\text{m}/\text{s}$ ) have to be defined. In addition, operating and maintenance costs, initial cost need to be defined.

### 3.1.1 Proposed Objective Function for Islanding Mode

Precise selection of output power that can economically fulfil the load demand while minimizing the emission is one of the most important factor in designing an electrical system. Hence the system components are found subject to:

- Minimize the operation cost (\$/h).
- Ensure that the load is served according to the constraints.

The operation cost of the system can be calculated as the following:

$$\text{OC} (P) = \sum_{i=1}^N \text{OM}_i (P_i) \quad (3.1)$$

$\text{OC} (P)$  represents the operating costs in \$/h,  $\text{OM}_i (P_i)$  is the operation and maintenance cost of the generating unit  $i$  in \$/h and  $P_i$  is representing the real power output from generating unit  $i$  in kW.

The operating and maintenance costs OM are assumed to be proportional with the produced energy, where the proportionally constant is  $R_{OM_i}$  for unit  $i$ .

$$OM = \sum_{i=1}^N R_{OM_i} P_i \quad (3.2)$$

In addition, it should satisfy the constrains for the load. The system constraints are the following:

Power balance constraints are required to meet the active power balance.

$$P_L - P_{PV} - P_{WT} - P_{batt} - P_{FC} > 0 \quad (3.3)$$

Where  $P_L$  is the total power demanded in kW,  $P_{pv}$  is the output power of the photovoltaic cell in kW,  $P_{WT}$  is the output power of the wind turbine in kW,  $P_{FC}$  is the output power of the fuel cell in kW and  $P_{batt}$  is the output power of the battery in kW.

Generation capacity constraints have to be considered for stable operation, real power output of each generator is restricted by lower and upper limits as follows:

$$P_i^{min} \leq P_i \leq P_i^{max} \quad \forall_i = 1, \dots, N \quad (3.4)$$

Where  $P_i^{min}$  is the minimum operating of unit  $i$  and  $P_i^{max}$  is the maximum operating of unit  $i$ .

Table 3-1 shows the economic parameters of the microgrid. These parameters are considered in order to do the economic model of the microgrid.

### 3.1.2 Implementation of GA Algorithm

Figure 3-2 shows the implementation of GA Algorithm . The key characteristics of the proposed algorithm are the following:

- Power output of WT is calculated based on the wind speed.
- Power output of PV is calculated based on the temperature and the solar radiation.

- If the output from PV and WT is greater than the load, the excess power is directed to charge the battery.
- The power from the battery is needed whenever the PV and WT are insufficient to serve the load.
- The power from the fuel cell is needed whenever the PV and WT are insufficient to serve the load and the battery cannot provide enough power to cover the shortage.

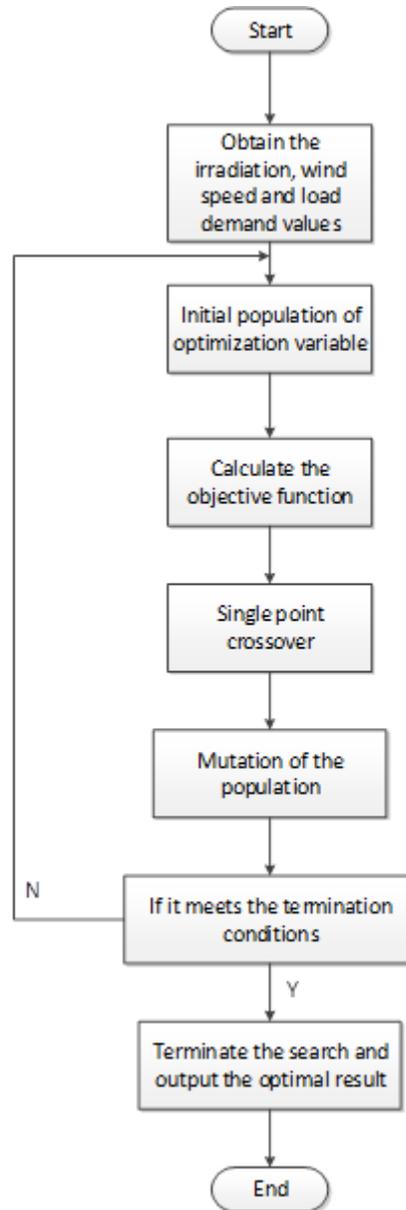


Figure 3-2: Implementation of GA Algorithm

## 3.2 Key Performance Indicators for Microgrid

The key performance indicators are defined for performance measurement. Using KPIs can be helpful to evaluate the microgrid performance. By calculating the KPIs, the sustainability can be increased. In addition, there would be adequate grid connections and all the grid users can have access to the grid. Analyzing the KPIs in the microgrid can help the smart grid in customer satisfaction and introducing different options for the grid customers. Sample quantitative KPIs are shown in Table 3-1.

Table 3-1: KPI

KPI Name	Formula
Power grid voltage stability	$PG_{VS} = \frac{V_s - V_L}{V_s} \times 100\%$
Microgrid total generation	$MG_T = \sum_{i=1}^n P_{DER_i}$
Microgrid total connected loads	$MG_{TCL} = \sum_{i=1}^n P_{CL_i}$
Microgrid generation reliability	$MG_{GR} = \frac{MG_T}{MG_{TCL}} \times 100\%$
Microgrid generation shortage	$MG_S = (1 - MG_{GR}) \times 100\%$
Capital Cost	$C_{ann_{cap}}(MG) = \left( \sum_{i=1}^n C_{capDG}(i) \right)$
Maintenance Cost	$C_m(MG) = \sum_{t=1}^{8760} \sum_{i=1}^n C_{mDG}(i)(t)$
Generation Cost	$C_{Gen}(MG) = \sum_{t=1}^{8760} \sum_{i=1}^n C_{DG}(i, t)$
Replacement Cost	$C_{rep}(MG) = \sum_{t=1}^{8760} \sum_{i=1}^n C_{repDG}(i, t)$
THD	$V_{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \%$ $I_{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \%$

Power grid voltage stability: The Power grid voltage stability is defined as the percentage of voltage drop from source to load terminal in a long transmission line.

Microgrid total generation( $MG_T$ ): It is defined as the sum of the individual available generation of distributed energy resource over time.

Microgrid Total Connected Load ( $MG_{TCL}$ ): Microgrid Connected Load is defined as total available load connected in microgrid. This load must be served by available DERs in microgrid or from the main grid.

Microgrid Generation Reliability ( $MG_{GR}$ ): Microgrid Generation Reliability is defined as a percentage of microgrid generation to support connected load.

Microgrid generation shortage: Microgrid Generation Shortage is defined as the difference of Microgrid Total Generation and Microgrid Total Connected Load.

Cost indicators are Capital Cost, Maintenance Cost, Generation Cost and Replacement Cost.

Environmental Indicators show that how much CO<sub>2</sub> is being produced for each DG in a microgrid.

Each microgrid component can be evaluated through different KPIs with respect to different indicators. Figure 3-3 shows the relationship between components and KPIs.

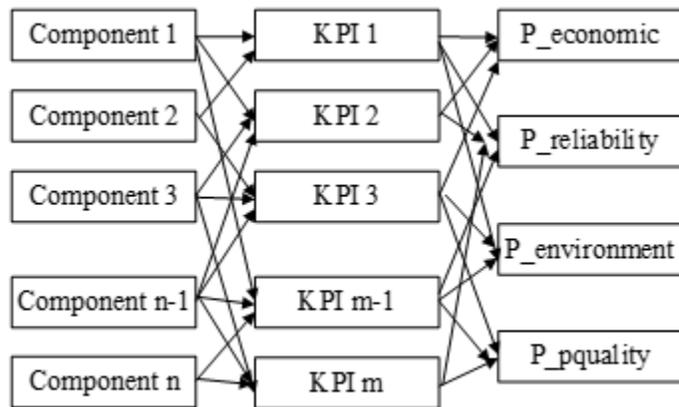


Figure 3-3 Relationship between components and KPIs

This relationship can be described as matrix

$$R = [R_{C,i}(component, kpi)]$$

$$R_{C,i}(component, kpi)$$

$$= \begin{cases} 1, & \text{the component contributes to the indicator} \\ 0, & \text{the component not contributes to the indicator} \end{cases}$$

The objective function of different components in microgrid can be obtained.

$$Objective_i = \sum_{j=1}^M R_{ij} \cdot KPI_j$$

The KPIs that are used in this thesis are can be categorized in two different parts. The first one would be the dynamic ones and the second category would be the static category. The KPIs are the reliability, power quality, economic and environmental indicators.

### 3.3 Methodology for Microgrid Performance Analysis

In order to analyze the microgrid, new methods and power system planning are developed. KPIs are necessary for evaluating a microgrid. In this thesis the AHP method is used for the evaluation of the microgrid. The AHP method involves the following steps:

**Step 1.** The overall goal (objective) is identified.

**Step 2.** The criteria, sub criteria are identified.

**Step 3.** The hierarchical structure is formed.

**Step 4.** Pairwise comparison is made using Saaty's evaluation scale.

**Step 5.** The priority weighting vectors are evaluated.

**Step 6.** Consistency of the judgments is checked by the consistency index.

**Step 7.** The final ranking of alternatives is defined.

**Goal identification:** The goal is to evaluate the performance of the microgrid.

**Identification of criteria, sub-criteria:** Criteria for microgrid are power quality, cost, customer satisfaction and environmental impact reduction. The power quality subcriteria are the power grid voltage stability, THD, loss of power supply probability (LPSP), microgrid total generation, microgrid total connected loads, microgrid generation reliability and microgrid generation shortage. The cost sub-criteria are Capital Cost, maintenance Cost, generation Cost and replacement Cost.

**Hierarchical structure formation:** The AHP method shows a hierarchal problem which the first level is the goal, the second level is relevant criteria and the third level is relevant sub-criteria.

**Pairwise comparison:** Pairs of elements at each level are compared using Saaty's scale.

**Summary:** This chapter examined the methodology of the research. The first step was gathering all the microgrid data. The islanding mode operation planning was proposed. In addition, the size of the microgrid (Islanding mode) was optimized using GA by optimizing the annual cost. Furthermore, the operation of the microgrid in Grid-connected mode has been examined. In addition, KPIs that are used in this study were examined. In the end, methodology for microgrid performance analysis was done using AHP.

# Chapter 4-Microgrid Modeling

This chapter describes the Simulink modeling of the microgrid. This model consists of Wind turbine, PV, Fuel Cell and Battery. This model can be analyzed in two different modes. The first one is Grid-connected mode and the second one is Islanding mode.

## 4.1 Proposed Microgrid Architecture

The system is modeled using the MATLAB/Simulink SimPower Systems toolbox. Bus 1 is connected to the grid and Bus 2 is connected to AC distributed energy sources. Bus 3 is connected to DC distributed energy sources. The proposed hybrid microgrid consists of PV, wind turbine (WT), Fuel Cell (FC), Battery, AC loads, AC distribution lines, DC distribution lines, DC loads and DC-AC-DC converters. The energy that is produced by DGs is stored in the battery. Figure 4-1 shows the design of the microgrid.

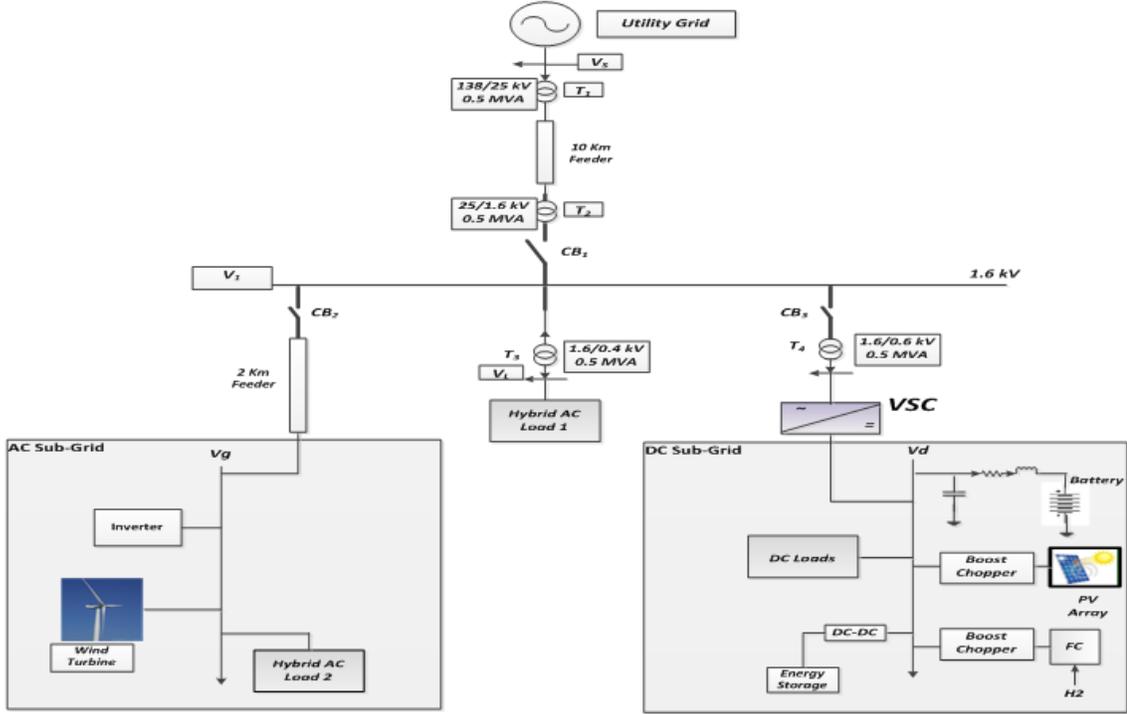


Figure 4-1: Proposed microgrid

## 4.2 Microgrid Technical Specification

The size of the microgrid average load is supposed to be approximately 1200 kW. This load can be a residential building. GA is used in order to optimize the size of the microgrid's components. When the PV and the WT can provide enough power to the load, the size of the PV is 100 kW and the size of the WT is 1.5MW. The irradiance of the PV is assumed to be 1000 W/m<sup>2</sup>. IM72C3-310-T12B45 is the module that is used in the simulation. In addition, GE 1.5 MW wind turbine is used in this study.

When the output power of PV and WT is not enough to provide power to the load, as it mentioned before, there are several cases. Based on the GA optimization, when the shortage in power is less than the minimum power of the fuel cell, the size of the WT and PV is 1.15 MW and 45kW respectively. The size of the fuel cell is 6 kW. When the shortage in power is bigger than the battery power, the size of the WT is still 1.15 MW but the size of the PV is 40 kW. The size of the battery is 3 kW. The next case is when the shortage in power is bigger than the minimum power of the fuel cell but it is smaller than the power of the battery. In this case, the size of the wind turbine is 1.15 MW, the size of the PV is 43 kW. The size of the battery is 8 kW and the size of the fuel cell is 6 kW. When the shortage in power is bigger than the minimum power of the fuel cell and the power of the battery altogether, the size of the wind turbine is 1.1 MW, the size of the PV is 80 kW, the size of the battery is 12 kW and the size of the fuel cell is 2 kW. The last case is when the shortage in power is bigger than the power of the battery and it is less than or equal to the minimum power of the fuel cell and the battery altogether. In this case, the size of the wind turbine is 1.15 MW, the size of the PV is 40 kW, the size of the fuel cell is 6 kW and the size of the battery is 7 KW.

## 4.3 Wind Energy Conversion System

Figure 4-2 shows the wind turbine model.

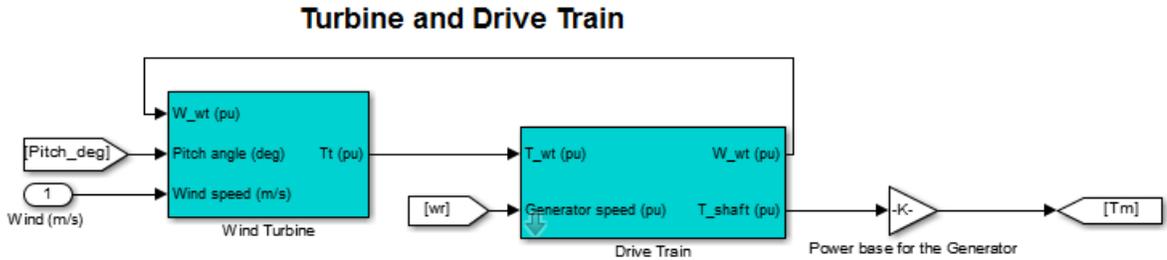


Figure 4-2: Wind turbine model in MATLAB

The inputs of the wind turbine are the initial speed of the wind turbine, the pitch angle and the wind speed. The output of the wind turbine is the torque. The inputs of the drive train are the initial output torque and the generator speed. The outputs of the drive train are the initial speed of the turbine and the shaft base speed.

According to [35], wind turbine controls are Grid-Side Converter Control System, Rotor-Side Converter Control System and Speed regulator & Pitch Control. In order to have a good control system for a wind turbine, the following criteria must be met. a) the wind power must be captured as much as possible, b) power quality standards such as power factor and harmonics should be met and c) must be able to transfer the electrical power to the grid for different wind velocities. Aerodynamic control, variable speed control, and grid connection control are the three subsystems of the control system. Pitch control is used to control the aerodynamics drive train. In addition, variable speed control is used to control the electromagnetic subsystem. Grid connection subsystem is controlled by output power conditioning.

In order to control the wind turbine, the control system is designed. The control system has three sub control systems. The first one is speed regulator and pitch control. The next one

is rotor side converter control and the last one is grid side converter control. Figure 4-3 shows the control of the wind turbine.

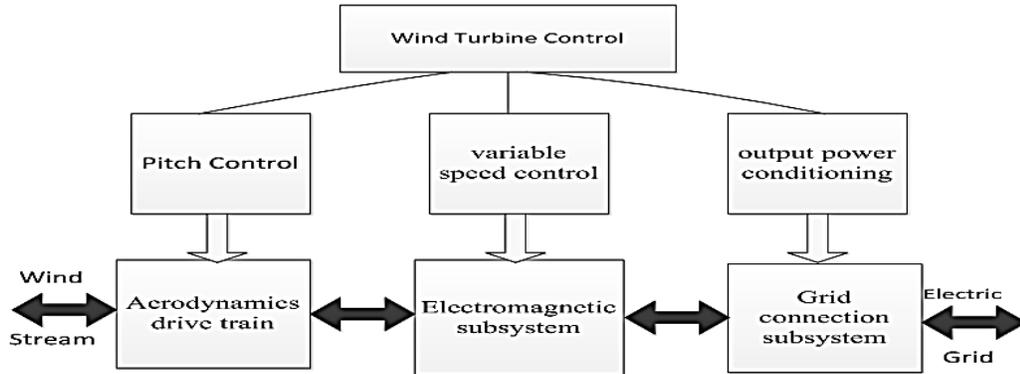


Figure 4-3: Wind Turbine Control Architecture

The Grid side converter control consists of two parts. The first one is  $V_{dc}$  regulator. Figure 4-4 shows  $V_{dc}$  regulator.

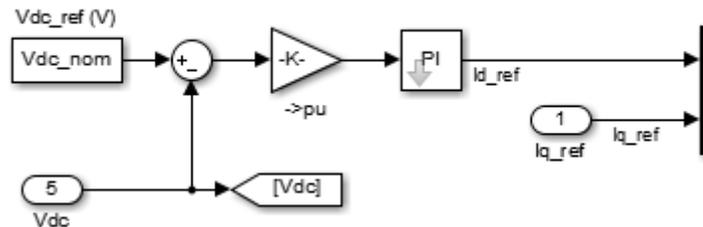


Figure 4-4:  $V_{dc}$  regulator

The  $V_{dc}$  is being compared to the reference DC voltage and that would be the input of the PI controller. The output of the PI controller is the reference current in d-frame.

The next part of this controller is current regulator. Figure 4-5 shows this part. The output of  $V_{dc}$  regulator would be one of the inputs of this part. The other input of this controller is

the stator voltage at d-q frame. The grid converter current at d-q frame is another input. The difference between the reference current at d-q frame and the current at grid converter would be the input of the PI controller and the output is the reference voltage at d-q frame. The control grid converter voltage at d-q frame is the difference between the stator voltage at d-q frame and the reference voltage. In the end the voltage at d-q frame is converted to abc frame.

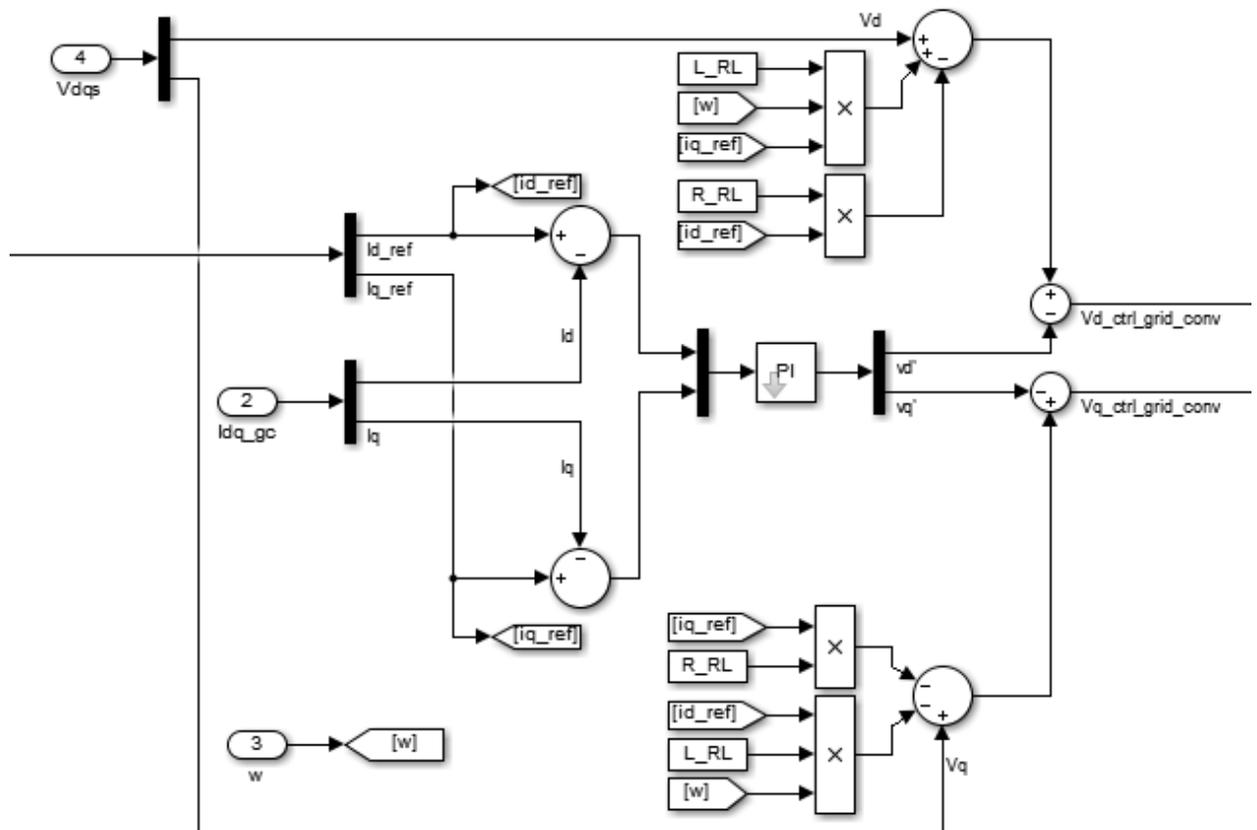


Figure 4-5: Current regulator

### 4.3.1 Speed Regulator and Pitch Control

Figure 4-6 shows this control. In this controller, the pitch angle is measured. The pitch angle should be kept constant at zero degree till it reaches to the point that the reference speed is on the tracking curve. The speed regulator is comparing the wind turbine speed with the reference speed and the pitch control is responsible of controlling the pitch angle to the reference pitch.

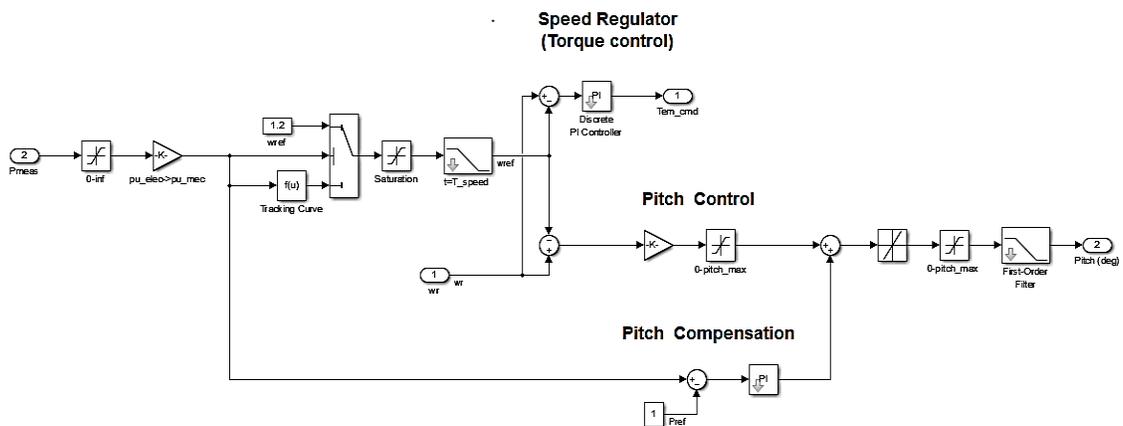


Figure 4-6: Speed regulator and pitch control

### 4.3.2 Rotor-Side Converter Control System

This control system consists of electromagnetic torque control, Var regulator and voltage regulator. In electromagnetic torque control (Figure 4-7), the stator voltage at d-q frame, the stator current in d-q frame and the rotor speed are the inputs of the stator flux estimator block and the output of this block is the rotor reference current in d axis. The Var regulator (Figure 4-8) is needed to keep the reactive power at the grid terminal constant. The output of the voltage regulator is the reference q-axis current  $I_{qr\ ref}$ . The outputs of the current regulator (Figure 4-9) are  $V_{dr}$  and  $V_{qr}$ .  $V_{dr}$  and  $V_{qr}$  are respectively the d-axis and q-axis of the voltage  $V_r$ .

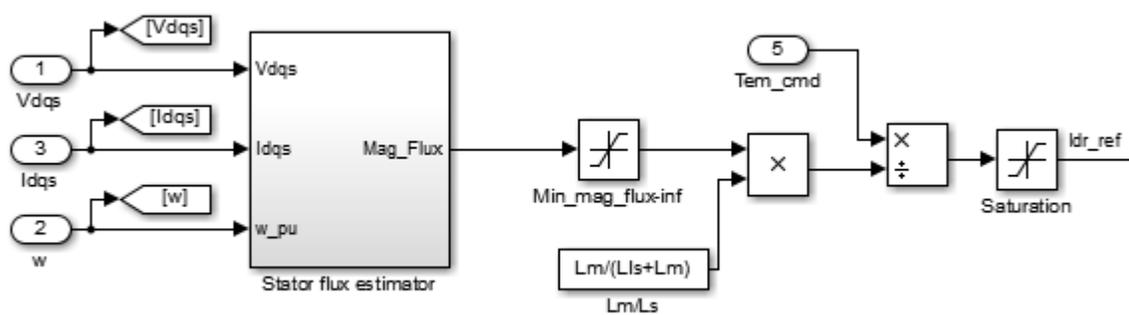


Figure 4-7: Electromagnetic torque control

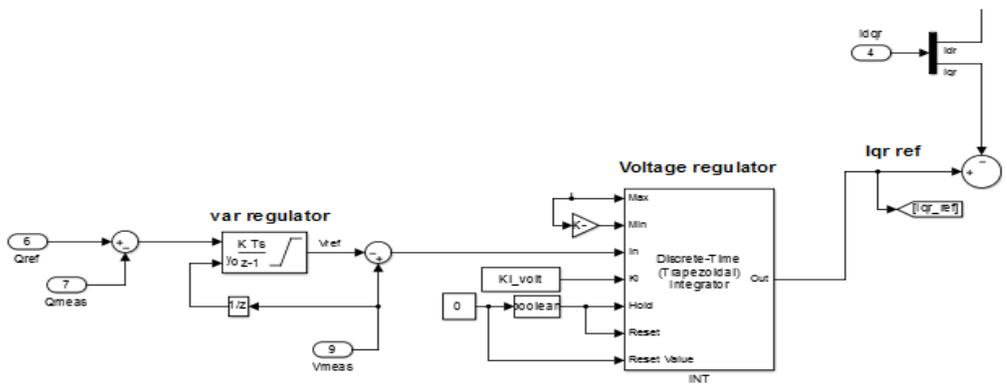


Figure 4-8: Var and Voltage regulator

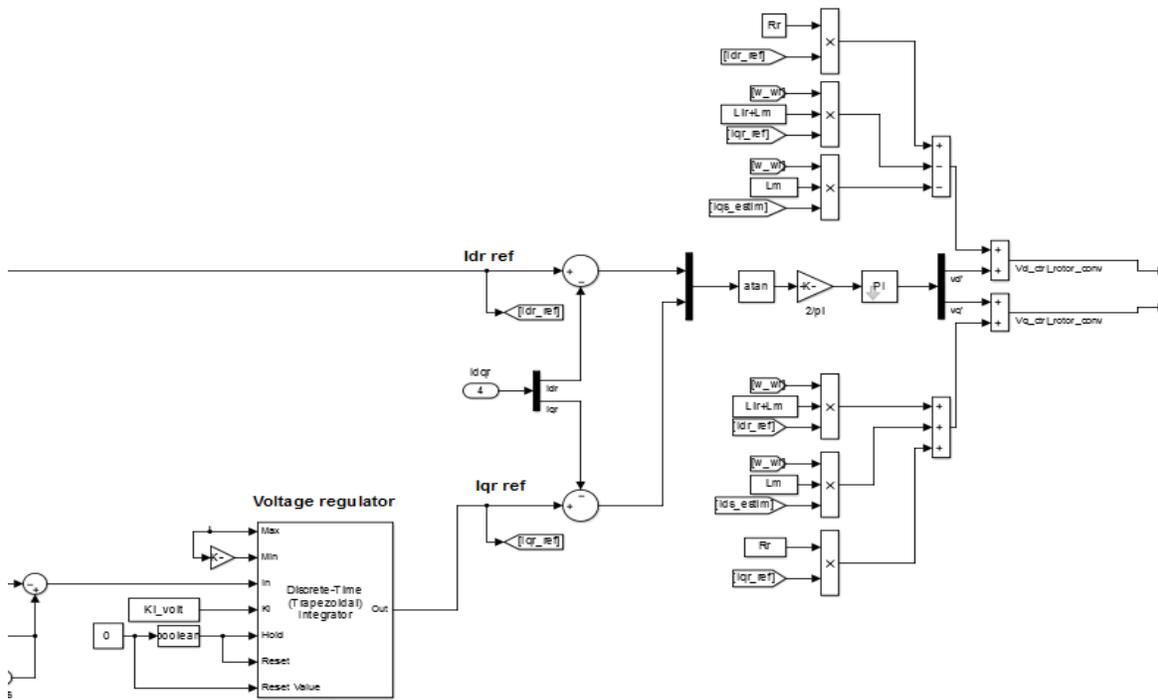


Figure 4-9: Current regulator

## 4.4 PV System

This section explains the PV system that is developed in this thesis. Figure 4-10 shows the PV system. It consists of PV arrays, a boost converter, the boost converter control and a voltage source converter. The output of this PV system goes to an inverter to be converted to three phase voltage.

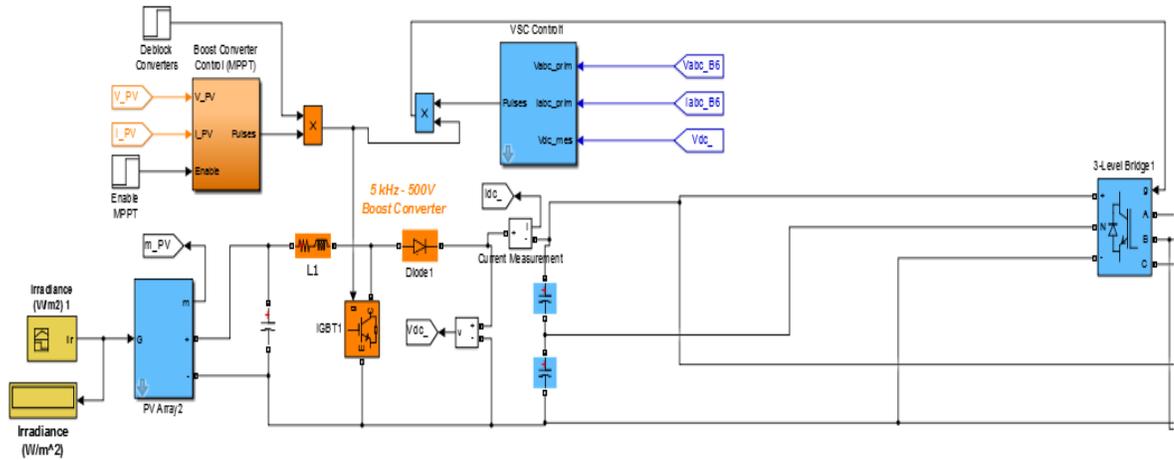


Figure 4-10: PV system

### 4.4.1 PV Array

Figure 4-11 shows the PV array model that was developed in MATLAB for this thesis. It is developed based on the literature review in chapter 2.

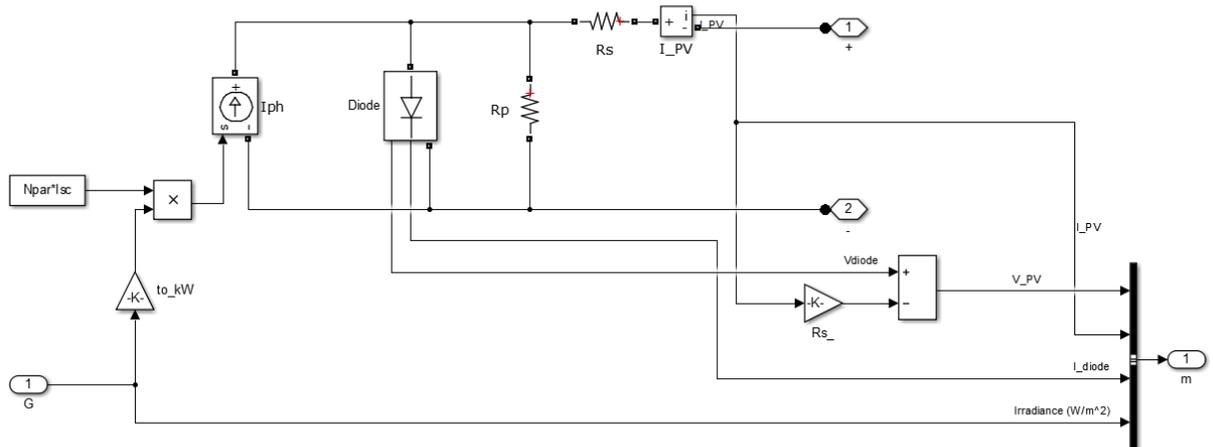


Figure 4-11: PV Array

PV array consists of  $N_{\text{par}}$  strings of modules connected in parallel, each string consisting of  $N_{\text{ser}}$  modules connected in series. The four PV model parameters (photo-generated current  $I_{\text{ph}}$ , diode saturation current  $I_{\text{sat}}$ , parallel resistance  $R_{\text{p}}$  and series resistance  $R_{\text{s}}$ ) are adjusted to fit the following four module characteristics measured under standard test conditions (STC: irradiance  $1000 \text{ W/m}^2$ , cell temperature =  $25 \text{ deg. C}$ ).  $V_{\text{oc}}$  is the open circuit voltage,  $I_{\text{sc}}$  is short-circuit current and  $V_{\text{mp}}, I_{\text{mp}}$  are the voltage and current at maximum power point respectively.

## 4.4.2 Boost Converter Control

In order to control the boost converter, it is necessary to control the PV system by using MPPT. Figure 4-12 shows the control block. The inputs of the MPPT block are the PV voltage, the PV current and the on/off switch for the system. The output would be the signal pulses that are used for the inverter. The MPPT method that is used is Maximum power point tracking by incremental conductance method with Integral regulator. Maximum power point is obtained when  $dP/dV=0$  where  $P= V*I$ ,  $d(V*I)/dV = I + V*dI/dV = 0$ ,  $dI/dV = -I/V$ . The integral regulator minimizes the error ( $dI/dV + I/V$ ). Regulator output is the Duty cycle correction.

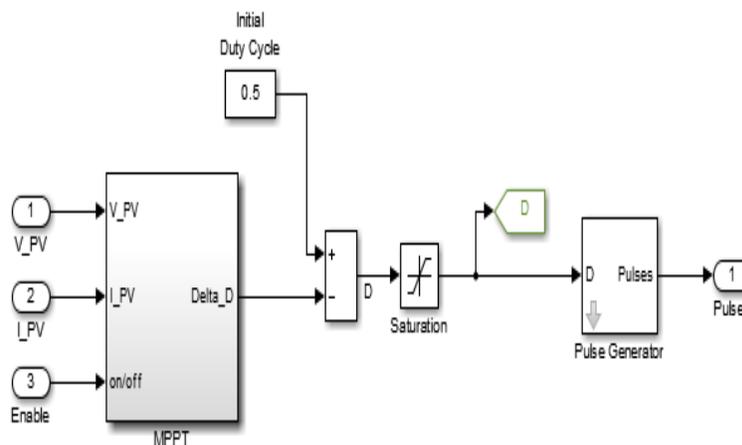


Figure 4-12: MPPT by incremental conductance method with Integral regulator

## 4.5 Fuel Cell

Figure 4-13 shows the Fuel Cell Stack block in matlab which can operate at nominal conditions of temperature and pressure. The detailed model represents a hydrogen fuel cell stack when the parameters such as number of cells, stack efficiency, pressures, temperature, compositions, and flow rates of fuel and air can be varied. The current increases until the value of nominal operating point. The nominal Fuel Cell Stack voltage and the nominal power can be chosen by the user. A flow rate regulator is used in order to make the utilization of the hydrogen constant.

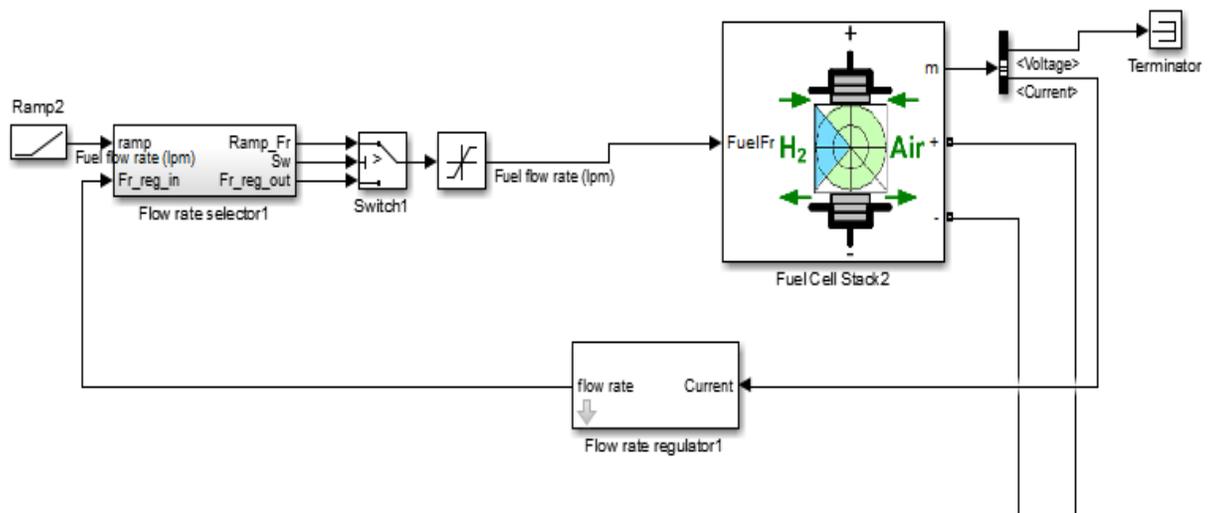


Figure 4-13: Fuel cell model

The fuel cell is connected to an inverter. The inverter is necessary to convert the DC voltage to AC voltage. This inverter is connected to the PV system as well. The following section explains the control system for the inverter that is used in this part of the thesis.

## 4.6 VSI Control for PV and Fuel Cell

In order to control the inverter, its controller has been modeled in MATLAB. It consists of PLL,  $V_{DC}$  regulator, current regulator and PWM generator. Figure 4-14 shows the control block.

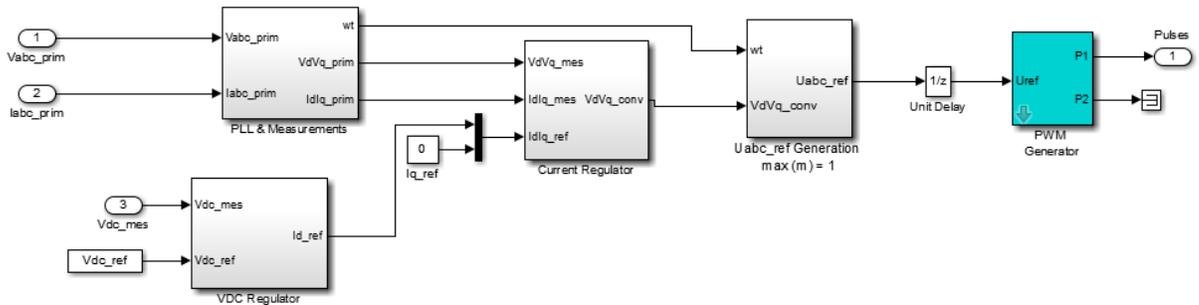


Figure 4-14: VSI control

The inputs of the PLL block are the three phase voltage and current. The three phase voltage and the current are transferred to d-q frame by Park transformation. The  $V_{DC}$  regulator block will compare the measured DC voltage to the reference voltage. In current regulator, the measured current in d-q frame is compared to the reference current in d-q frame. A PI controller is used to set the error to zero. A PWM generator is used to generate the pulses in order to control the inverter.

## 4.7 Battery System

Battery has been modeled in MATLAB and it was used along with Fuel cell and PV system. The control system that was used for the inverter is different from the control system that





## 4.8 Microgrid Control in Grid-Connected Mode

A PQ control strategy is used in order to control the microgrid when it is in grid-connected mode. This method controls the active and reactive power flowing out of an inverter. In order to control the active and reactive power, voltage-mode control is used. In this method, the active and reactive power are controlled using the phase angle and magnitude of the inverter AC voltage side with respect to phase and magnitude on the PCC voltage side. In addition to voltage mode control, the current-mode control is used in this control system. In this approach the active and reactive power are controlled by controlling the phase and magnitude of the inverter AC side currents with respect to the PCC current phase angle and magnitude. Figure 4-18 shows the PQ control strategy.

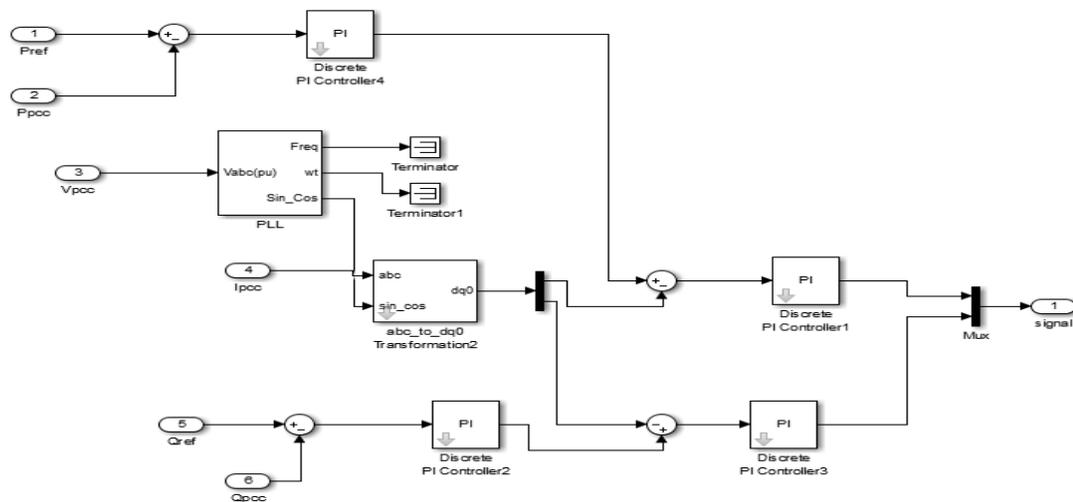


Figure 4-18: PQ control

## 4.9 Microgrid Control in Islanded-Connected Mode

The V/f control scheme is used for the islanded mode. The V/f control strategy is a tight closed loop control with the reference values of voltage,  $V_{ref}$  and frequency,  $f_{ref}$ . The  $V_{ref}$  is the voltage at the bus that is connected to the load. The  $f_{ref}$  is 60 Hz. The frequency is measured using a three-phase PLL. In the V/f control scheme three separate PI controllers are used to process the error caused by the difference of the measured value and the

reference set-points and attempts to minimize the error by adjusting the process control units. Figure 4-19 shows the V/f control scheme. The frequency of the microgrid is measured with a PLL and that is compared to the reference frequency which is 60 Hz. The difference is sent to a PI controller to minimize the error. The load voltage is compared to  $V_{ref}$  which is the rms value of the voltage at the bus that the load is connected. The difference is the PI controller input. The PI controller is used to set the error to zero. The output of the PI controller is converted to d-q frame by Park transformation. The  $V_d$  and  $V_q$  are compared to  $V_{dref}$  and  $V_{qref}$ .  $V_{dref}$  is set to 1 pu and  $V_{qref}$  is set to 0.

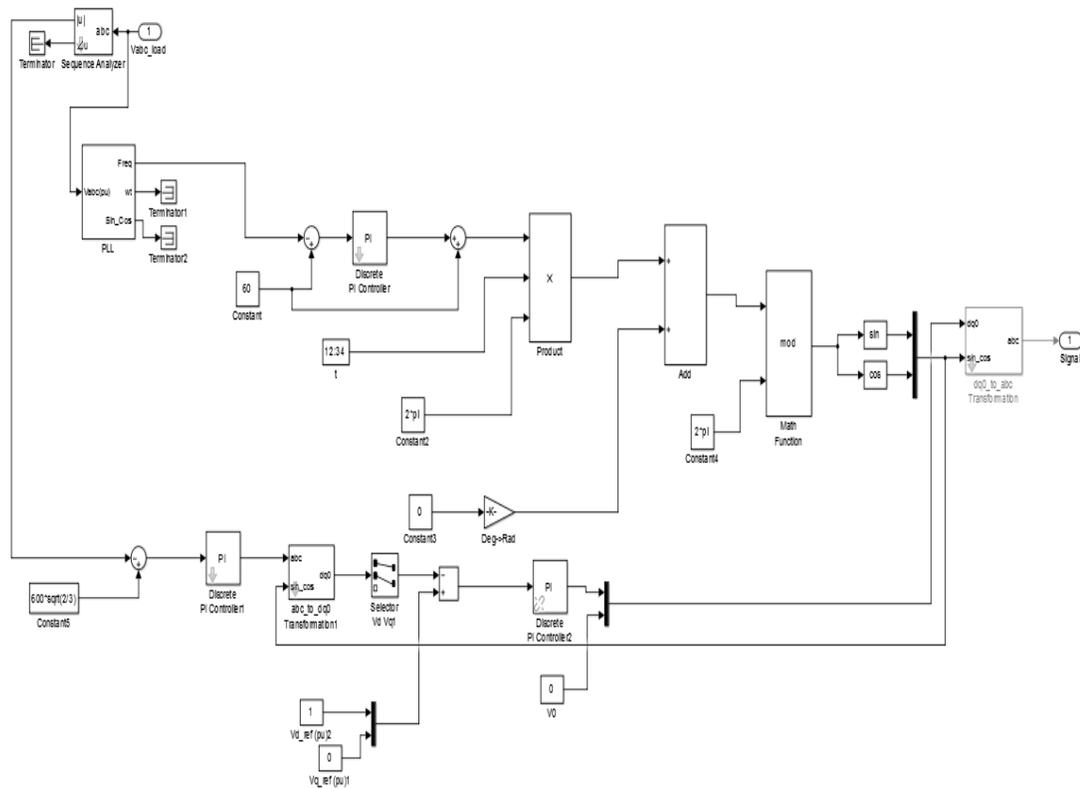


Figure 4-19: V/f control

Summary: The proposed microgrid was modelled in MATLAB. Each block was examined in details. The control system for Grid-connected and islanding mode was modeled in MATLAB.

# Chapter 5-KPI Modeling

This chapter will explain the KPI modeling for a microgrid. The KPIs can be in two different categories. The KPIs can be either in static (steady-state) or dynamic. The KPIs that can be used in order to evaluate the performance of a microgrid are environmental, economic, reliability, power quality, control and protection. The static KPIs could be environmental and economic indicators. The other KPIs can be categorized as dynamic since they are dealing with the dynamic behavior of the microgrid. These KPIs can be implemented on design or operation of the microgrid. The design category could consist of microgrid components such as load, PV, wind turbine, storage, fuel cell and power electronics devices. The operation category could consist of the two operational modes which are Grid-connected or islanding. Figure 5-1 shows the KPIs characteristics. This thesis will focus on the environmental, economic, reliability and power quality indicators. In addition, it will focus on the operation which are Islanding- and Grid-connected.

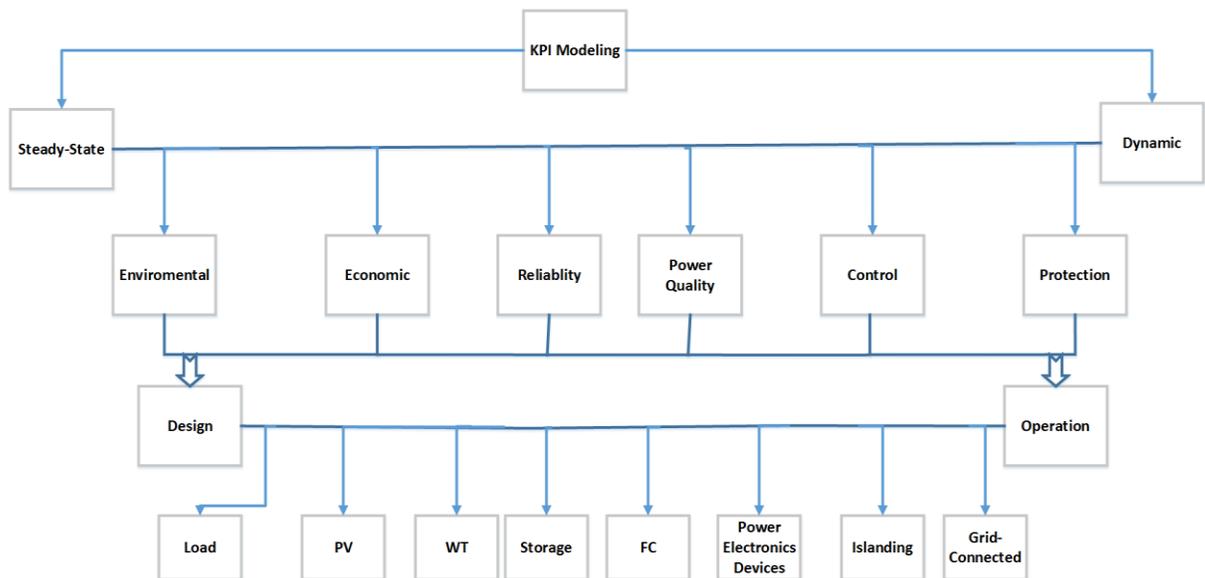


Figure 5-1: KPIs characteristics

Voltage breakdown is still the greatest single danger to the transmission framework. It is for the most part described by loss of a stable working focuses and by the crumbling of voltage levels in and around the electrical focal point of the locale experiencing voltage breakdown. Voltage fall, a type of voltage instability, regularly happens as a consequence of reactive power deficiency. The power grid voltage stability can be calculated as following:

$$PG_{VS} = \frac{V_s - V_L}{V_s} \times 100\% \quad (5.1)$$

The Power grid voltage stability is defined as the percentage of voltage drop from source to load terminal in a long transmission line.

Microgrid total generation( $MG_T$ ): It is defined as the sum of the individual available generation of distributed energy resource over time. Microgrid total generation is important to know the how much the power the microgrid can produce. Microgrid total generation can be defined as following:

$$MG_T = \sum_{i=1}^n P_{DER_i} \quad (5.2)$$

Microgrid Total Connected Load ( $MG_{TCL}$ ): Microgrid Connected Load is defined as total available load connected in microgrid. This load must be served by available DERs in microgrid or from the main grid. Knowing the microgrid total connected load is very important since it can affect the reliability of the microgrid. It can be defined as the following:

$$MG_{TCL} = \sum_{i=1}^n P_{CL_i} \quad (5.3)$$

Microgrid Generation Reliability ( $MG_{GR}$ ): Microgrid Generation Reliability is defined as a percentage of microgrid generation to support connected load. Microgrid Generation Reliability is very important in order to evaluate the performance of the microgrid.

$$MG_{GR} = \frac{MG_T}{MG_{TCL}} \times 100\% \quad (5.4)$$

Microgrid generation shortage ( $MG_S$ ): Microgrid Generation Shortage is defined as the difference of Microgrid Total Generation and Microgrid Total Connected Load. Microgrid generation shortage shows the shortage in power of the microgrid. The microgrid is

supposed to provide power to its loads when it is in islanding mode. Therefore the microgrid generation shortage shows how much shortage is in the power generation and can help the operation planning of the microgrid.

The capital cost distributed over the life time of the generator and is given by:

$$C_{ann\_cap} = \left( \sum_{i=1}^n C_{cap}(i) \times P_r(i) / N_i \right) \quad (5.5)$$

where  $P_r(i)$  is rating power (kW),  $C_{cap}(i)$  is capital costs for one kW unit, and  $N_i$  is the life time (years) of  $i^{\text{th}}$  generator.

The annual operational cost is given by:

$$C_{ann\_op} = \sum_{h=1}^{8760} \sum_{i=1}^n \left( C_f(i) \times P_g(i, h) + C_m(i) \times P_g(i, h) \right) \quad (5.6)$$

where  $P_g(i, h)$  is generated power (kW) at hour  $h$ ,  $C_f(i)$  is fuel cost and  $C_m(i)$  is the maintenance cost for  $i^{\text{th}}$  generator unit.

The maintenance cost for the microgrid is the summation of the maintenance cost of each DG in the microgrid over a year.

$$C_m(MG) = \sum_{t=1}^{8760} \sum_{i=1}^n C_{mDG}(i)(t) \quad (5.7)$$

The generation cost for the microgrid is the summation of the generation cost of each DG in the microgrid over a year.

$$C_{Gen}(MG) = \sum_{t=1}^{8760} \sum_{i=1}^n C_{DG}(i, t) \quad (5.8)$$

The replacement cost for the microgrid is the summation of the replacement cost of each DG in the microgrid over a year.

$$C_{rep}(MG) = \sum_{t=1}^{8760} \sum_{i=1}^n C_{rep\ DG}(i, t) \quad (5.9)$$

The CO<sub>2</sub> emission is the most important environmental KPI. The annual CO<sub>2</sub> emission can be calculated by the following equation:

$$E_{CO_2} = \sum_{h=1}^{8760} \sum_{i=1}^n K_{CO_2}(i) \times P_g(i, h) \quad (5.10)$$

Where  $K_{CO_2}(i)$  is the emission equivalent kg CO<sub>2</sub>/kW from  $i^{\text{th}}$  generator.

Energy deficiency is used to measure the ability of MG to produce required power whenever it is needed. It can be calculated by the following equation:

$$E_d = \sum_{h=1}^{8760} (\sum_{i=1}^n P_g(i, h)) - P_l(h) \quad (5.11)$$

where  $P_l(h)$  is the required load power profile.

The last KPI that is used in this study is THD. THD (Total Harmonic Distortion) can be calculated as following:

$$V_{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \% \quad (5.12)$$

$$I_{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \% \quad (5.13)$$

Summary: This chapter presented the different KPIs for steady state (static) and dynamic. The economic and environmental indicators are static. However, power quality and reliability indicators are dynamic.

# Chapter 6- Case Studies

## 6.1 Islanding Mode Operational Planning

There are different cases when the microgrid is in islanding mode. Figure 3-3 shows the flowchart of this operational planning.

- Case # 1: when the output power of the PV and the wind turbine is more than the load power. Therefore the battery is charging and the fuel cell is off.
- Case # 2: when the output power of the PV and the wind turbine is not enough. As a result, there is a shortage . If this shortage is less than the minimum power of the fuel cell, the fuel cell can be off and the battery can provide the remaining power to the load.
- Case # 3: when the output power of the PV and wind turbine is not enough and there is a shortage and it is bigger than the power of the battery.
- Case # 4: when the shortage power is bigger than minimum power of the fuel cell but it is smaller or equal to the charging power of the battery.
- Case # 5: when the shortage in power is bigger than the minimum power of the fuel cell plus the power of the battery. At this time, the battery is discharging and the new value of the fuel cell would be the difference of the shortage in power and the power of the battery.
- Case # 6: is when the shortage in power is bigger than the power of the battery but it is smaller or equal to the minimum power of the fuel cell plus the discharging power of the battery. At this point, the battery power would be the difference of the shortage in power and the minimum power of the fuel cell. The following flow chart shows the operational planning for the islanded mode. Figure 6-1 shows the flowchart of this operational planning.

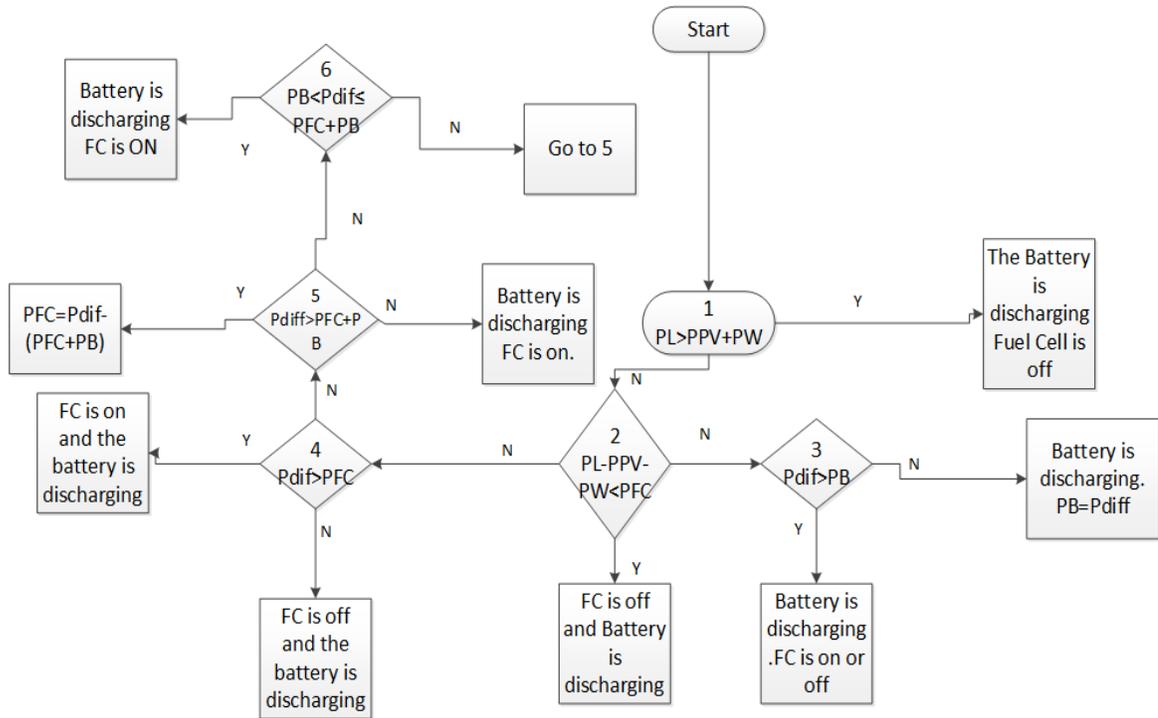


Figure 6-1: Islanding mode operational planning

## 6.2 Microgrid in Grid-Connected Mode

In this case, the fuel cell is not available; thus, the main grid will supply power whenever the load demand exceeds the PV, WT and battery power. On the other hand, when the PV and WT power is superior to the load demand, the power excess can be sold back to the main grid or be stored to battery.

### 6.2.1 Grid Power

Electric power can be purchased from the grid whenever the power of the PV system, WT and battery are not sufficient to meet the load demand. On the other hand, when the power

of PV and WT are more than the load demand, the power excess can be sold back to the grid or/and stored into the battery.

## 6.2.2 Operation of the Microgrid in Grid-Connected

The operation strategy of the microgrid in grid -connected is shown in Figure 6-2. The following are the

- $P_{PV} + P_W > P_L$

The power excess  $P_{PV} + P_W - P_L$  will be stored into the battery and can be sold back to grid as

$$P_{grid} = P_L - P_{PV} - P_W + P_B \quad (3.10)$$

- $P_{PV} + P_W < P_L$

The battery is discharging and the  $P_B$  is calculated as

$$P_B = P_L - P_{PV} - P_W \quad (3.11)$$

- $P_L - P_{PV} - P_W > P_B$

The battery is discharging.  $P_{grid}$  is calculated as

$$P_{grid} = P_L - P_{PV} - P_W - P_B \quad (3.12)$$

- $P_L - P_{PV} - P_W < P_B$

In this case, there are two scenarios. The first one is when feed-in tariff is less than feed-in tariff rate. At this point, the battery is discharging and  $P_B = P_L - P_{PV} - P_W$  (3.13). On the other hand if feed-in tariff is bigger than feed- in tariff rate, then the battery is discharging and the power can be sold to the grid as  $P_{grid} = P_L - P_{PV} - P_W - P_B$  (3.14).

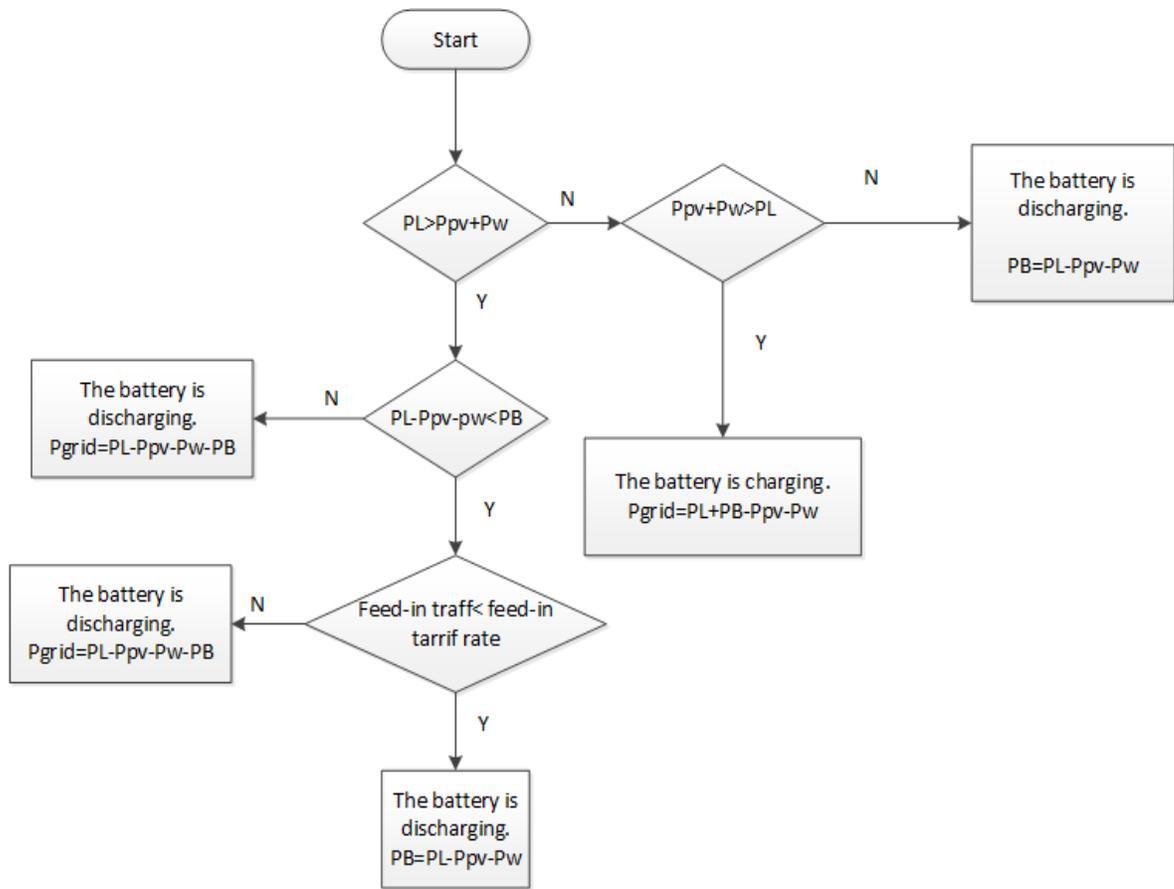


Figure 6-2: Operation of the Microgrid in Grid- Connected

## 6.3 Microgrid Data

The Figure 6-3 shows the daily profile of the load. Figure 6-4 shows the seasonal profile of the load. The location for this study is in Toronto, Ontario. Figure 6-5 shows the average wind speed (m/s) for different month. Figure 6-6 shows monthly average solar global horizontal irradiance (GHI) data. Figure 6-7 shows the load profile for a year. Residential load profile is chosen for this study. Figure 6-8 shows the solar irradiation data ( $W/m^2$ ) within a year. Figure 6-9 shows the wind speed (m/s) in a year. HOMER is used in order to obtain the data for Figures 6-3 to 6-6.

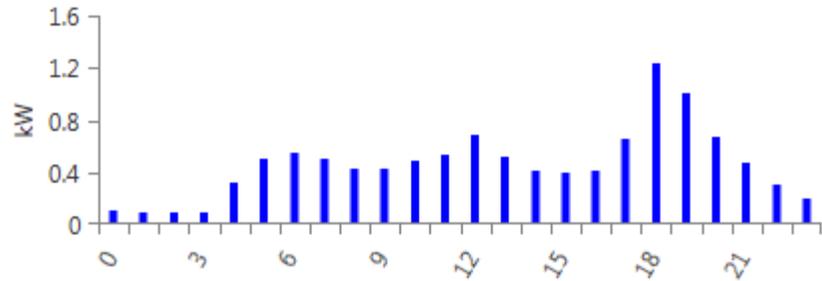


Figure 6-3: Daily profile of a residential load

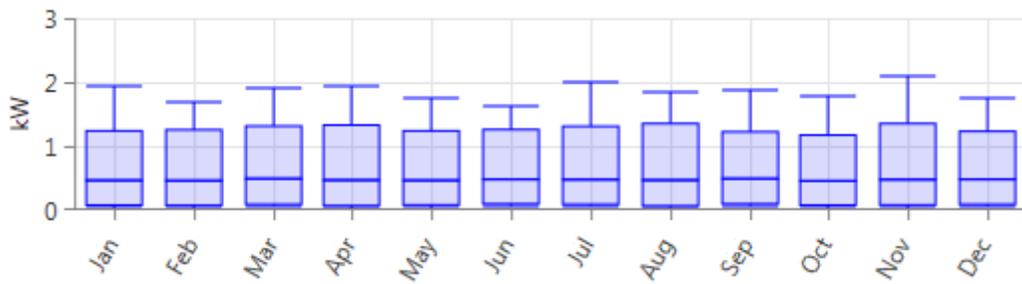


Figure 6-4: Seasonal profile

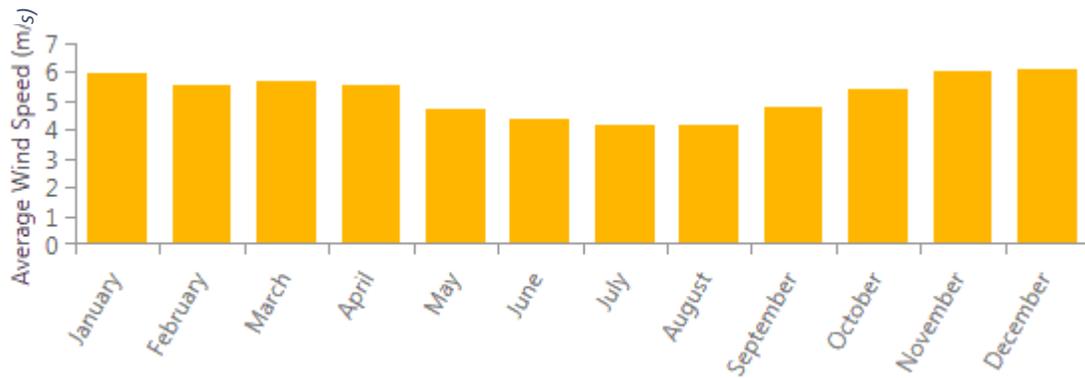


Figure 6-5: The average wind speed (m/s) for different month

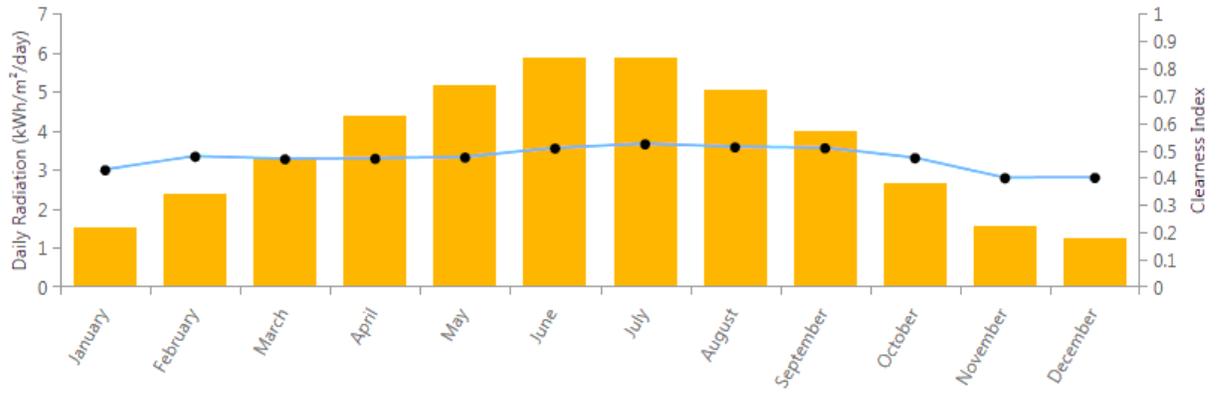


Figure 6-6: Daily Radiation for different month

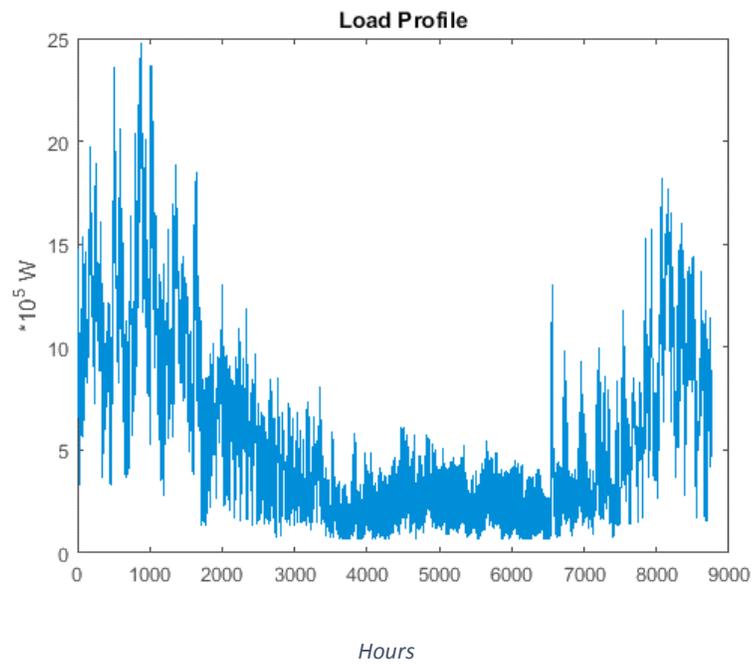


Figure 6-7: Load profile

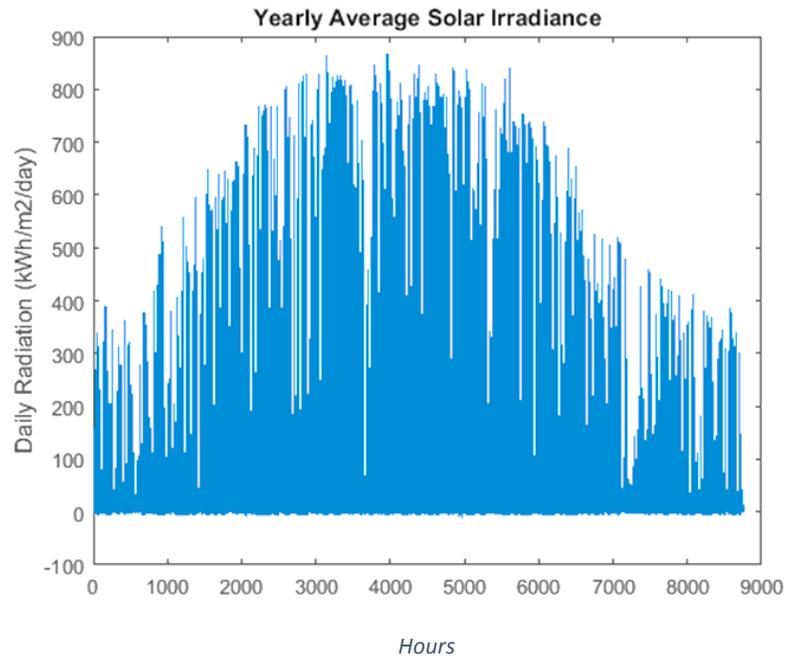


Figure 6-8: Monthly average solar global horizontal irradiance (GHI) data

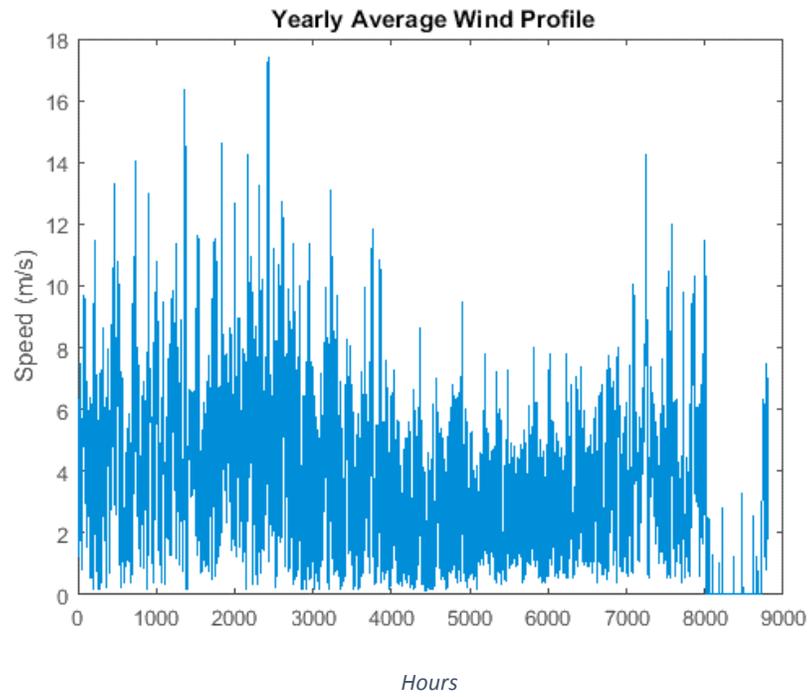


Figure 6-9: Yearly average wind profile

Summary: This chapter presented the case studies that are used in this thesis. The islanding mode operation planning was introduced and different cases have been analyzed. In addition, this chapter presented the Grid-connected mode operation planning as well. Furthermore, this chapter discussed the data that was used for the microgrid such as the wind speed, solar irradiance and load profile.

# Chapter 7-Results and Discussion

This chapter will discuss the simulation results for residential load in Grid-connected and Islanding mode. The optimization algorithm defines how to meet the power demand. This depends on the microgrid's mode of operation which may be islanded or Grid-connected. In this chapter the proposed microgrid is analyzed based on its KPIs.

## 7.1 Grid-Connected Mode

In this scenario, the microgrid is connected to the Grid. The Grid can supply enough power to the load and therefore, there would be no shortage in power. The average load for the microgrid is 1.2 MW. The size of the wind turbine is 1.5 MW. In addition the size of the PV is 100 kW. Furthermore, the size of the battery is 3 kW.

### 7.1.1 Electrical Analysis

Figure 7-1 shows the three phase voltage (V) and current (A) of PCC .As it is shown in this figure, the voltage and the current at PCC is without any distortion. In addition, the graph of the three phase voltage and current at the bus that is connected to the wind turbine are shown. It is shown that the real power of the WT is 1.2 MW and the reactive power of the WT is almost zero. Figure 7-2 shows the three phase voltage and current at the load bus.

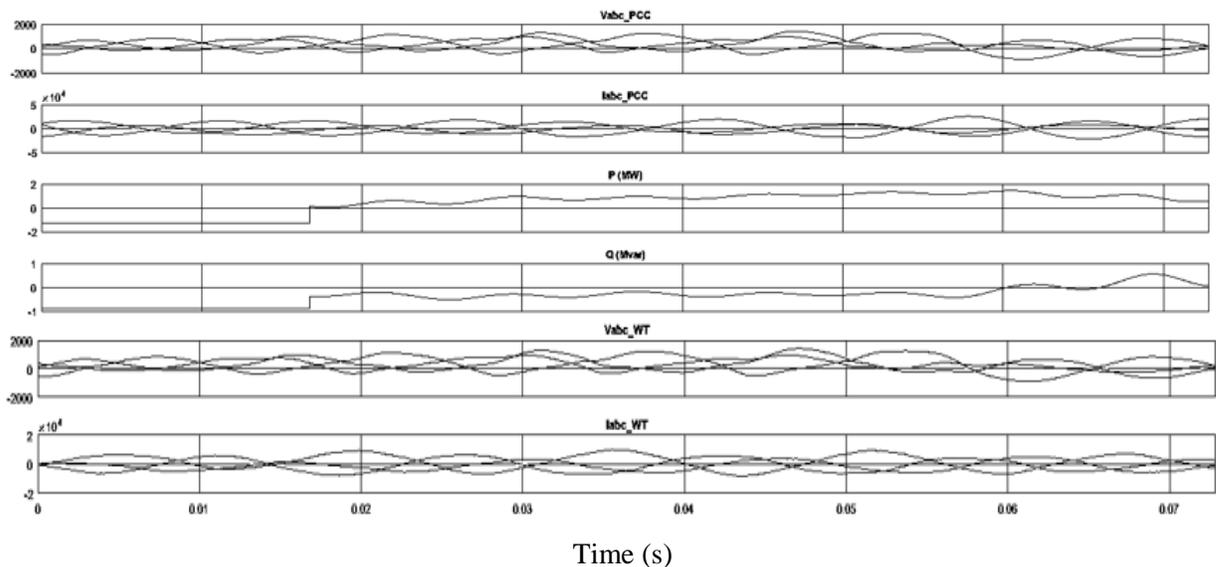


Figure 7-1: Voltage and current of PCC, WT; Real and reactive power of WT in GC

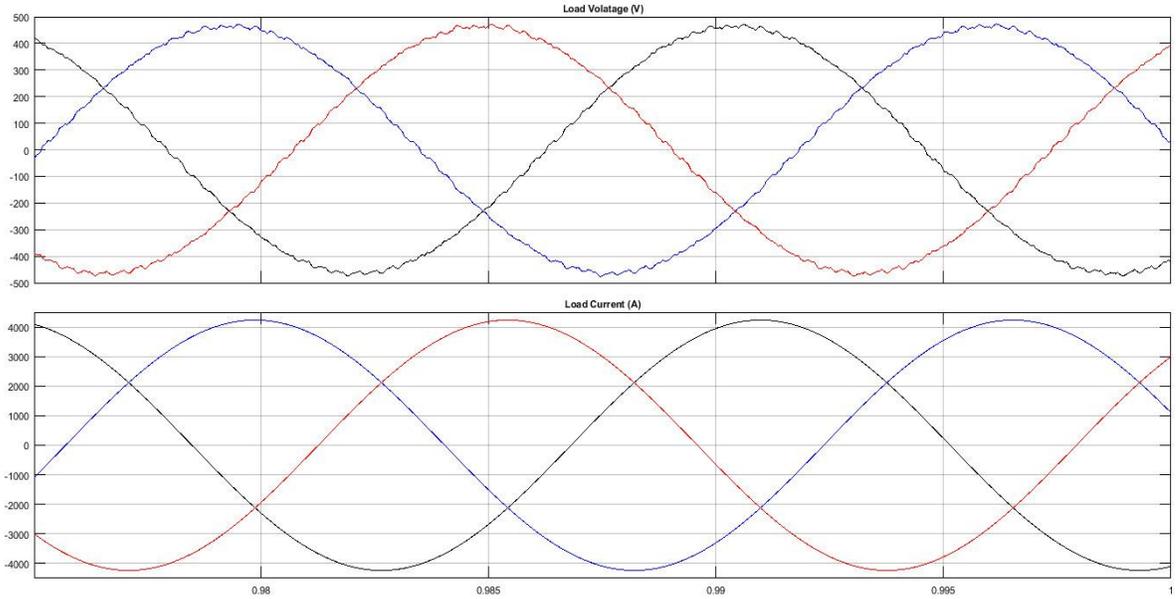


Figure 7-2: Voltage and current of the load in GC

The DC side of the microgrid consists of PV, fuel cell and battery. Figure 7-3 shows the irradiances ( $\text{W}/\text{m}^2$ ), duty cycle, and the power of the PV and the DC voltage of the PV. The irradiance is  $1000 \text{ (W}/\text{m}^2)$ , the duty cycle is 0.5, the power of the PV is 100 kW and the DC voltage of the PV is 300 V. The voltage of the inverter is 499.78 V. Figure 7-4

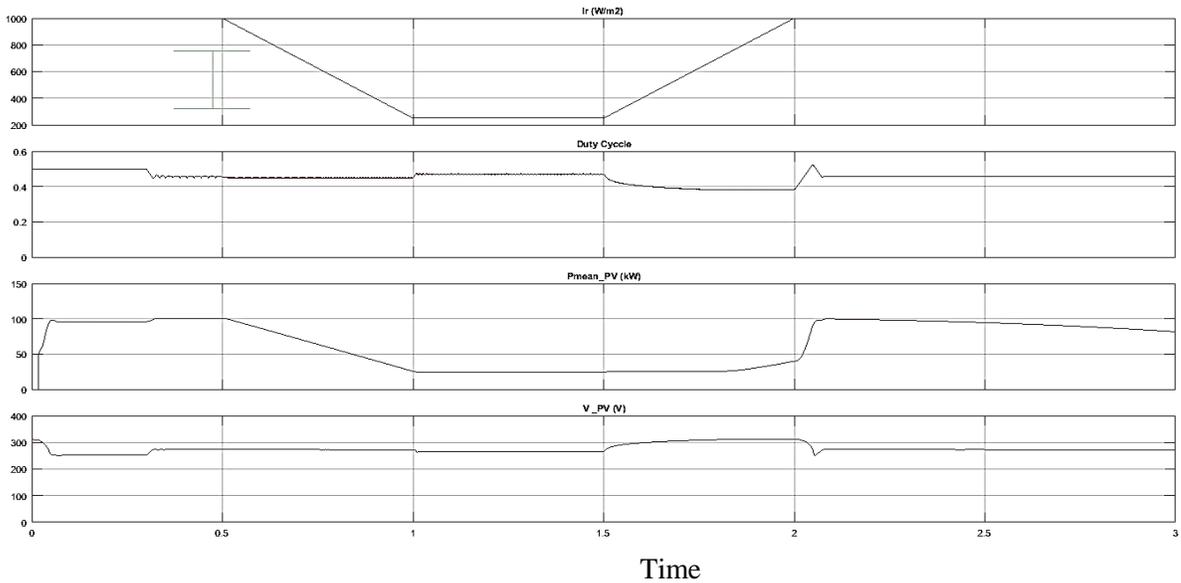


Figure 7-3: Ir, duty cycle, power and the voltage of PV in GC

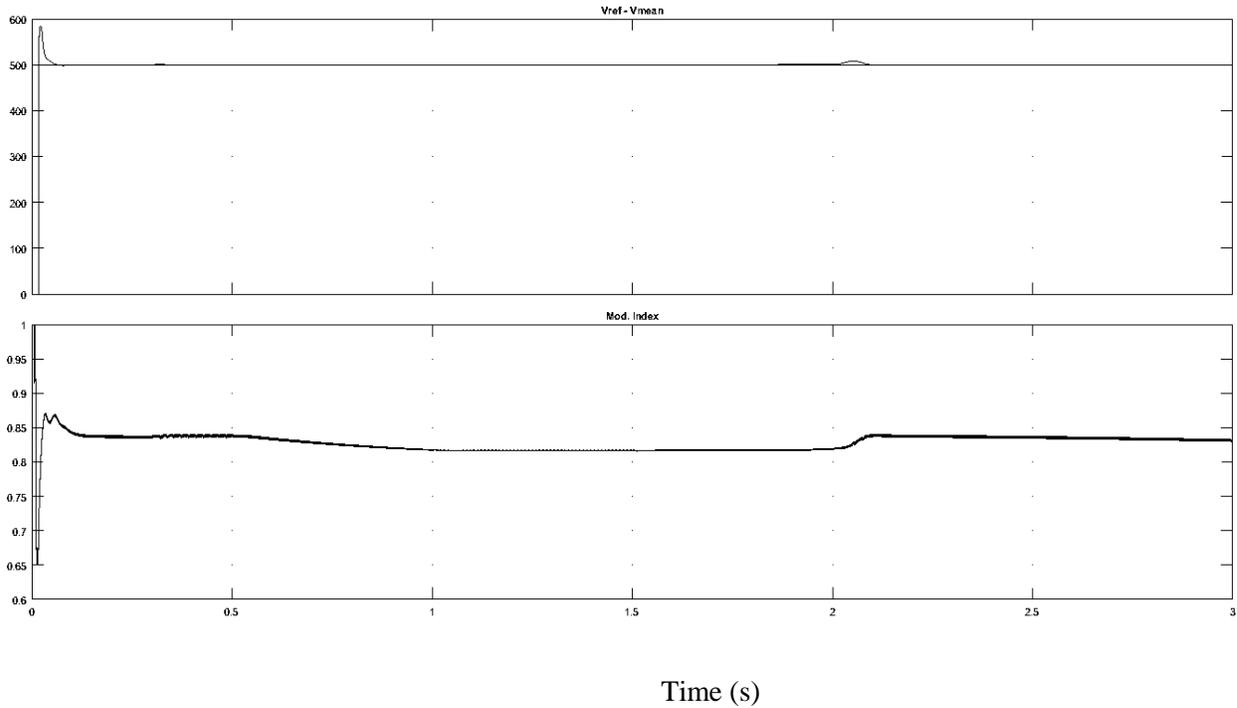


Figure 7-4: Reference voltage, mean voltage and modulation index in GC

Table 7-1: Power quality KPI in GC

Bus	THD_Voltage %	THD_Current %	Real Power (W)	Reactive Power (W)	Power Factor
PCC	4.021	4.453	$4.898 \times 10^6$	$1.835 \times 10^6$	0.9364
WT	3.187	2.391	$3.416 \times 10^6$	$1.583 \times 10^6$	0.9073
AC Load	4.156	2.185	$5.759 \times 10^6$	$2.371 \times 10^6$	0.9247
DC	-----	-----	$1.874 \times 10^5$	-----	-----

Table 7-1 shows the summary of the simulation of the microgrid in Grid- connected. The THD of the voltage at PCC is 4.021%. In addition, the THD of the current at PCC is 4.453%. The real and reactive power at PCC is  $4.898 \times 10^6$  W and  $1.835 \times 10^6$  W respectively. The power factor at PCC is 0.9364. The THD of the voltage at the bus that is connected to WT is 3.187%. In addition, the THD of the current at that bus is 2.391 %. The real and reactive power at this bus is  $3.416 \times 10^6$  W and  $1.583 \times 10^6$  W respectively. The power factor at that bus is 0.9073. The THD of the voltage at AC load is 4.156%. In

addition, the THD of the current at AC load is 2.185%. The real and reactive power at this bus is  $5.759 \times 10^6$  W and  $2.371 \times 10^6$  W respectively. The power factor at this bus is 0.9247. The real power of the DC side of the microgrid is  $1.874 \times 10^5$  W.

As it mentioned before, according to IEEE standards, that the percentage of the Total Harmonic Distortion (THD) in every node of the system and for every device which is connected to it should be less than 5 %. The simulation result shows that the THD for each node is less than 5% and the standards have been met. According to the Table 5-1, all the power factors are above 0.9 and that means as the power factor increases, the effectiveness of electric power being used increased.

## 7.1.2 Economic Analysis

*Table 7-2: Economic analysis in GC*

PV (kW)	#WT MW	Battery ( kW)	COE (\$)	NPC (\$)	Operating Cost (\$)	Initial Cost (\$)
100	1.5	3	0.135	3.15 M	677665	3.33 M

According to Table 7-2, the cost of the energy is \$0.135. The net present cost is 12.1 M. The operating cost is \$677665 and the initial cost is 3.33 M. The environmental indicator is measuring the emission of CO<sub>2</sub>. However, since the microgrid consists of the renewable energy resources, the environmental indicator for the microgrid shows that the emission is almost zero for both operation modes which are Grid-connected and islanding mode. These costs are very important when it comes to analyzing the microgrid according to the economic indicators.

## 7.2 Islanding Mode

When the microgrid is not connected to the Grid, it should have the ability to provide the power to the load. As it mentioned before, there are different cases when the microgrid is in islanding. This part of the thesis covers the different cases in details.

## 7.2.1 Case I: Output power of the PV and WT is more than the Load Power

In this case the output power of the PV and WT is more than the load power. The battery is charging and the fuel cell is off. Based on the optimization that was done with GA, the size of the WT and the size of the PV are 1.5 MW and 100 kW respectively. The load power is 1.2 MW.

### 7.2.1.1 Electrical Analysis

Figure 7-5 shows the graph of the three phase voltage at the bus that is connected to the wind turbine. In addition the three phase current at the same bus is measured. Furthermore, the real power and the reactive power of the wind turbine are evaluated. It is shown that the real power of the WT is 1.5 MW and the reactive power of the WT is almost zero. Figure 7-6 shows the load graphs in this case. The simulation time is 1 sec and it is shown in x-axis.

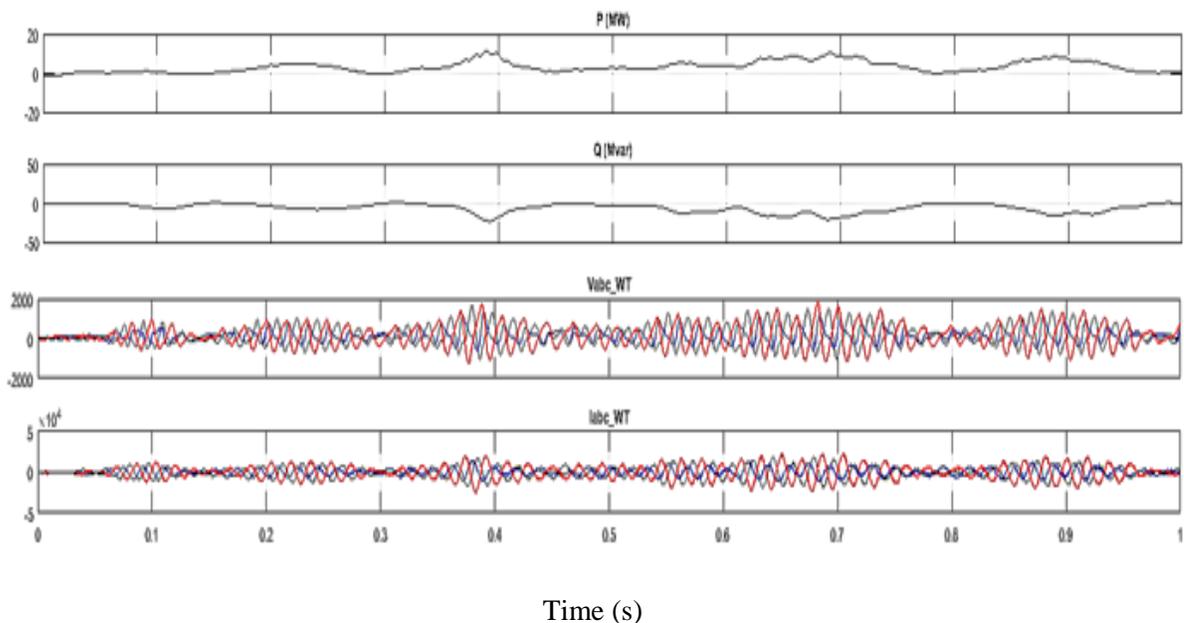


Figure 7-5: Voltage and current of PCC, WT; Real and reactive power of WT in load in Islanding 1

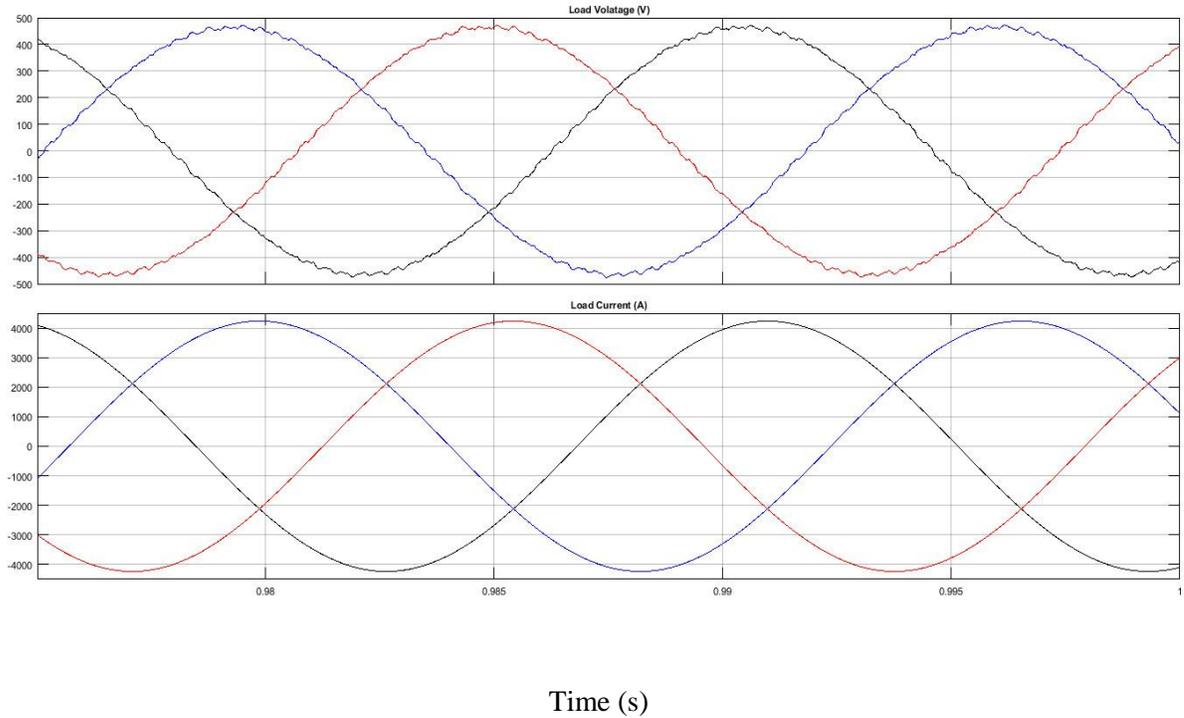


Figure 7-6: Voltage and current of the load in Islanding 1

The DC side of the microgrid consists of PV, fuel cell and battery. Figure 7-7 shows the irradiances ( $\text{W}/\text{m}^2$ ), duty cycle, and the power of the PV and the DC voltage of the PV. The irradiance is  $1000 \text{ (W}/\text{m}^2)$ , the duty cycle is 0.5, the power of the PV is 100 kW and the DC voltage of the PV is 300 V. The voltage of the inverter is 499.78 V. Figure 7-8 shows the reference voltage of the  $V_{\text{DC}}$  regulator which is 500V. In addition, the modulation index is shown. The modulation index is 0.848.

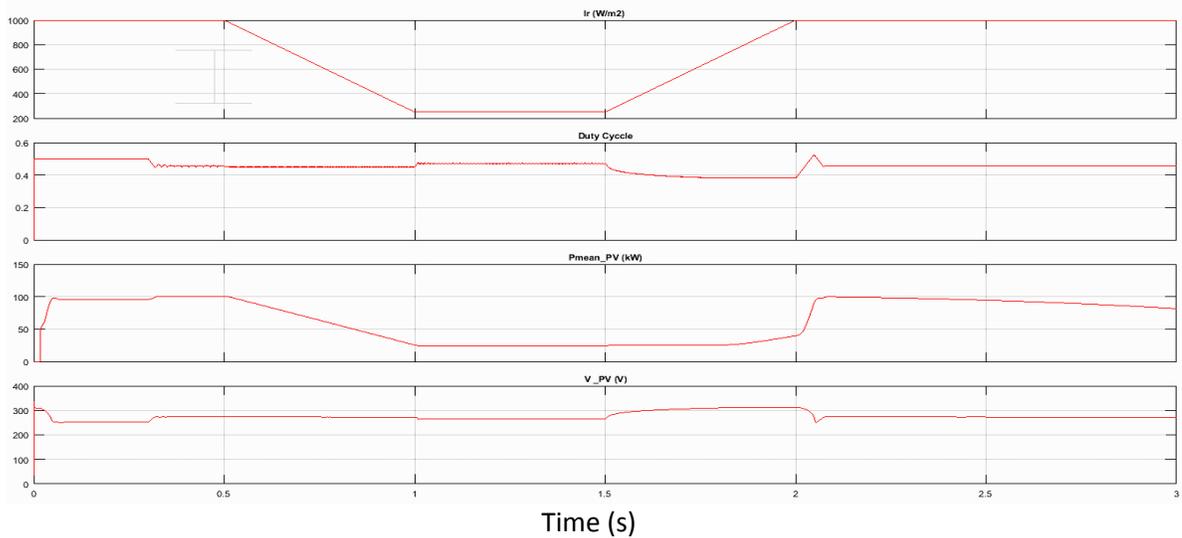


Figure 7-7:  $I_r$ , duty cycle, power and the voltage of PV in Islanding 1

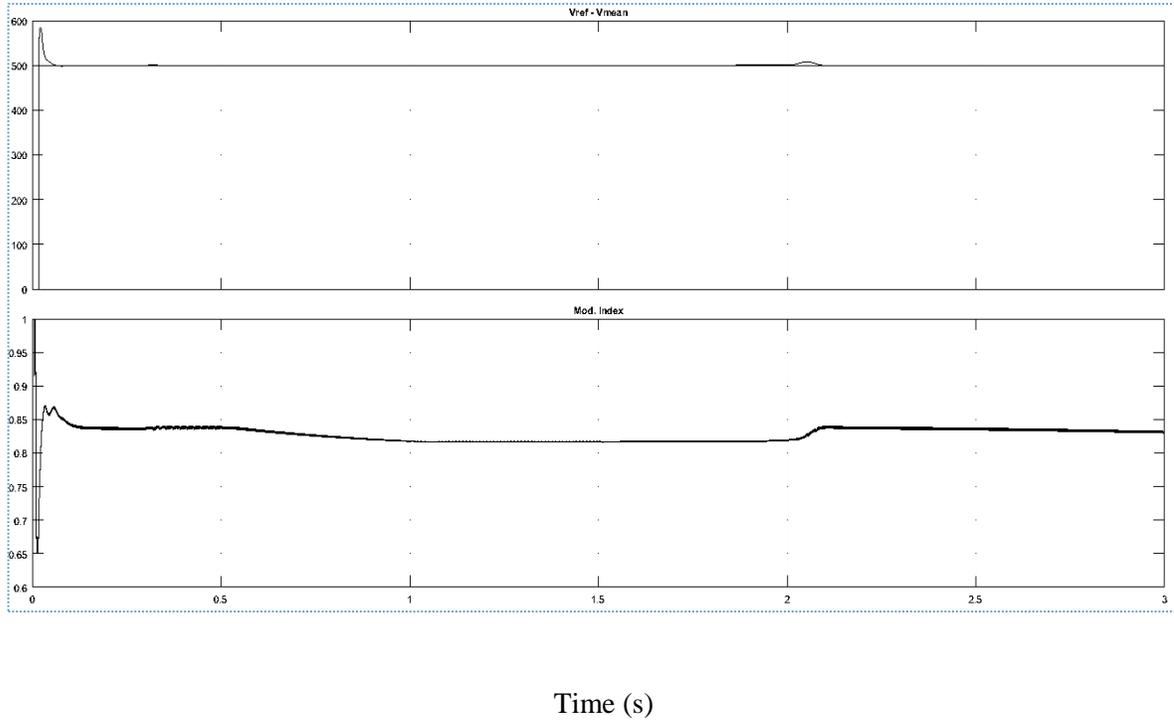


Figure 7-8: Reference voltage, mean voltage and modulation index in Islanding 1

Table 7-3: Power quality KPI Islanding\_case 1

Bus	THD_Voltage %	THD_Current %	Real Power	Reactive Power	Power Factor
WT	2.736	1.751	$5.159 \times 10^5$	$2.379 \times 10^5$	0.9081
Load	2.189	2.718	$4.181 \times 10^5$	$3.708 \times 10^5$	0.7481
DC	-----	-----	$5.042 \times 10^4$	-----	-----

According to Table 7-3, the THD of the voltage at the bus that is connected to WT is 2.736%. In addition, the THD of the current at that bus is 1.751 %. The real and reactive power at this bus is  $5.159 \times 10^5$  W and  $2.379 \times 10^5$  W respectively. The power factor at that bus is 0.9081. The THD of the voltage at AC load is 2.189%. In addition, the THD of the current at AC load is 2.718%. The real and reactive power at this bus is  $4.181 \times 10^5$  W and  $3.708 \times 10^5$  W respectively. The power factor at this bus is 0.7481. The real power of the DC side of the microgrid is  $5.042 \times 10^4$  W.

According to this simulation, the THD at every node is less than 5% and all the IEEE standards have met. The reactive power at the load is higher than the one in WT and that is the reason for less PF.

Table 7-4: Reliability analysis in islanding\_case 1

$MG_T$ (MW)	$MG_{TCL}$ (MW)	$MG_{GR}$ %	$MG_S$ %
1.6	1.2	1.33	No shortage

Table 7-4 shows the KPIs to measure the microgrid total generation ( $MG_T = 1.6 MW$ ), microgrid total connected loads ( $MG_{TCL} = 1.2 MW$ ), microgrid generation reliability ( $MG_{GR} = 1.33\%$ ). There would be no shortage in microgrid because the total generation would be much more than the load that is connected.

### 7.2.1.2 Economic Analysis

Table 7-5: Economic analysis in islanding case 1

PV (kW)	WT (MW)	COE (\$)	NPC (\$)	Operating Cost (\$)	Initial Cost (\$)
100	1.5	0.725	8.52M	381766	3.58M

According to Table 7-5, the cost of the energy is \$0.725. The net present cost is 8.52 M. The operating cost is \$381766 and the initial cost is 3.58 M.

### 7.2.2 Case II: Shortage in Power is less than the Power of the Fuel Cell

In this case the shortage in power is less than the power of the fuel cell. Therefore, the battery is discharging and the fuel cell is off. The size of the PV is 45 kW; the size of the WT is 1.15 MW. The power of the fuel cell is 6 kW. The load power is 1.2 MW. Therefore, the power of the battery is 5 kW.

### 7.2.2.1 Electrical Analysis

Figure 7-9 shows the graph of the three phase voltage (V) at the bus that is connected to the wind turbine. In addition the three phase current (A) at the same bus is measured. Furthermore, the real power and the reactive power of the wind turbine are evaluated. It is shown that the real power of the WT is 1.15 MW and the reactive power of the WT is almost zero. The x-axis is the time in Sec.

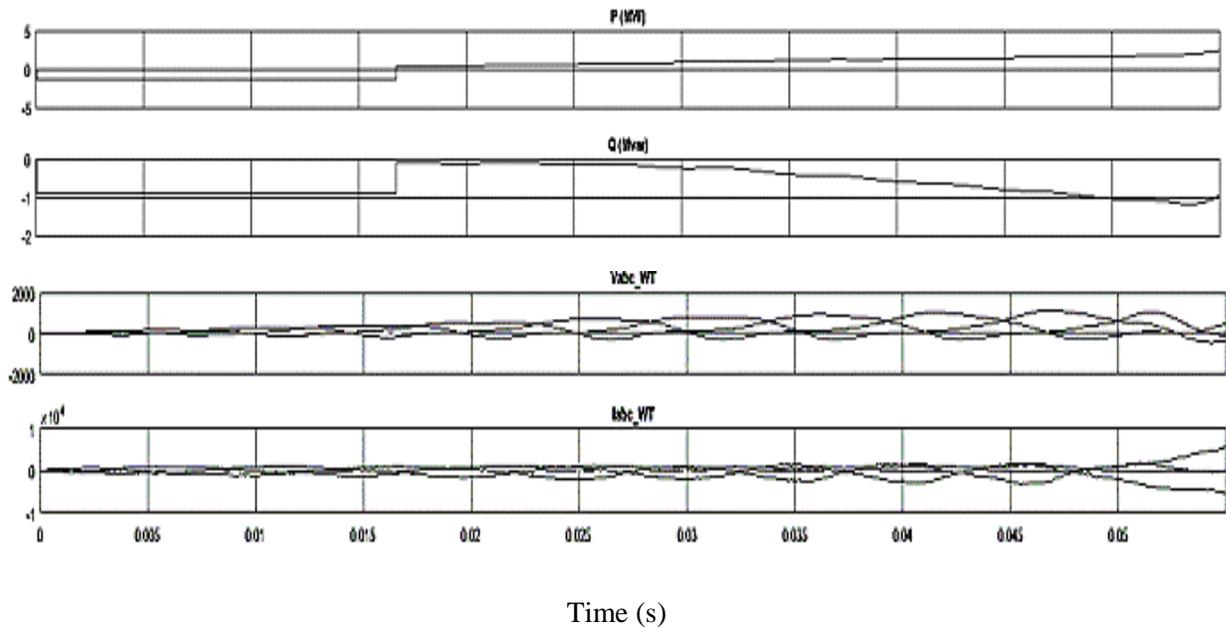


Figure 7-9: Voltage and current of WT; Real and reactive power of WT in Islanding 2

The DC side of the microgrid consists of PV, fuel cell and battery. Figure 7-10 shows the irradiances ( $\text{W}/\text{m}^2$ ), duty cycle, and the power of the PV and the DC voltage of the PV. The irradiance is  $1000 \text{ (W}/\text{m}^2)$ , the duty cycle is 0.5, the power of the PV is 45 kW and the DC voltage of the PV is 300 V. The voltage of the inverter is 500 V. Figure 7-11 shows the reference voltage of the  $V_{\text{DC}}$  regulator which is 500V. In addition, the modulation index is shown which is 0.825.

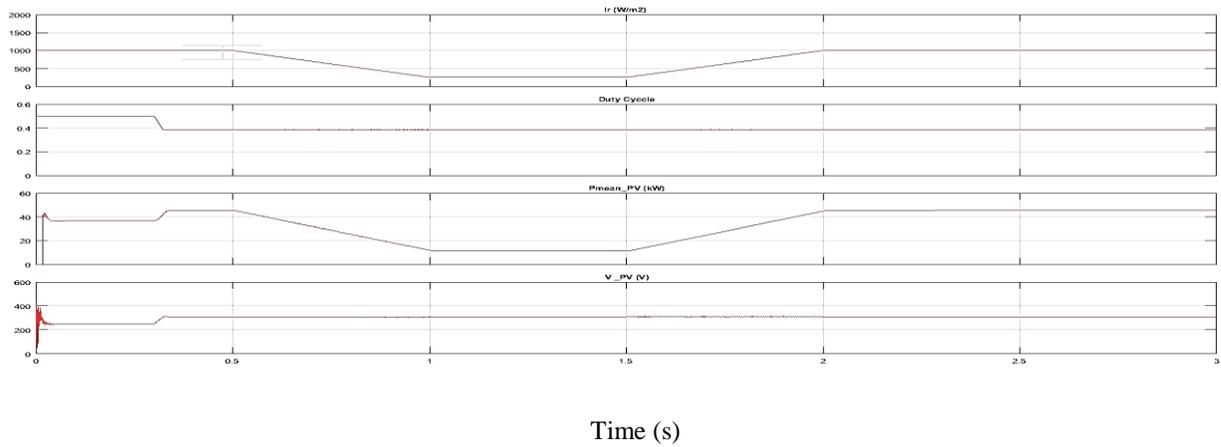


Figure 7-10:  $I_r$ , duty cycle, power and the voltage of PV in Islanding 2

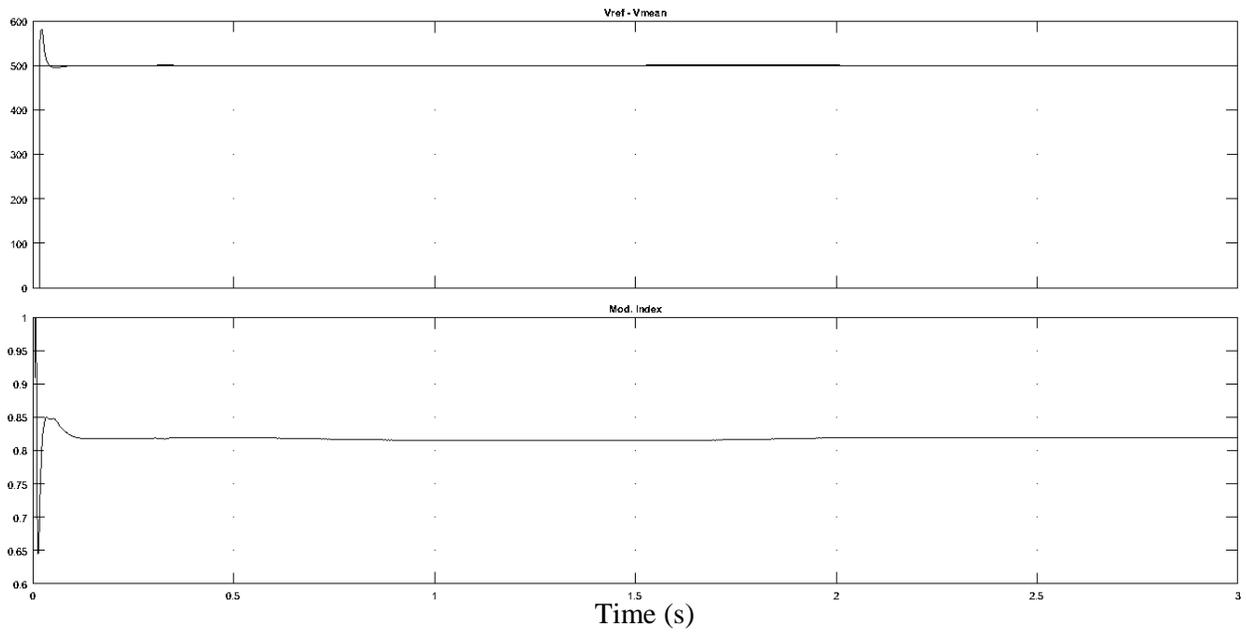


Figure 7-11: Reference voltage, mean voltage and modulation index in Islanding 2

Figure 7-12 shows the voltage (V) and the current (A) at the load bus. The simulation time is 1 sec which is shown on the x-axis.

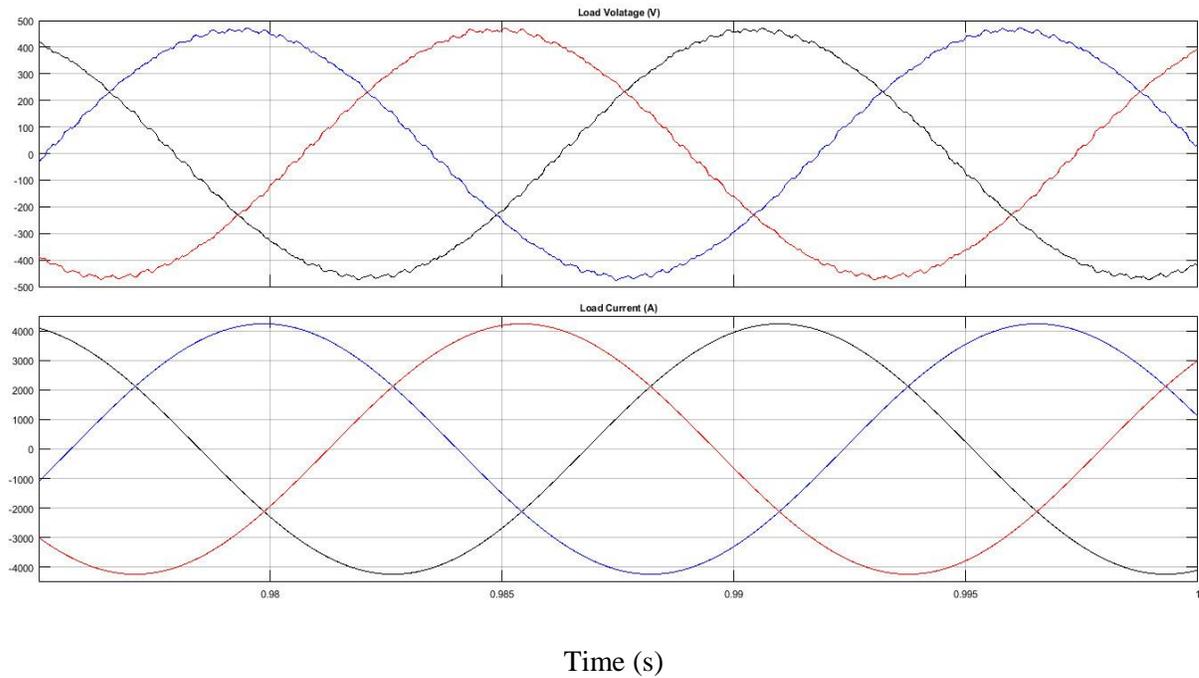


Figure 7-12: Voltage and current of the load in Islanding 2

Table 7-6: Power quality KPI Islanding\_case 2

Bus	THD_Voltage %	THD_Current %	Real Power	Reactive Power	Power Factor
WT	3.065	1.901	$7.072 \times 10^5$	$5.783 \times 10^5$	0.7741
Load	4.862	2.198	$5.169 \times 10^5$	$3.412 \times 10^5$	0.8346
DC	-----	-----	$3.808 \times 10^4$	-----	-----

According to Table 7-6, the THD of the voltage at the bus that is connected to WT is 3.065 %. In addition, the THD of the current at that bus is 1.901 %. The real and reactive power at this bus is  $7.072 \times 10^5$  W and  $5.783 \times 10^5$  W respectively. The power factor at that bus is 0.7741. The THD of the voltage at AC load is 4.862 %. In addition, the THD of the current at AC load is 2.198 %. The real and reactive power at this bus is  $5.169 \times 10^5$  W and  $3.412 \times 10^5$  W respectively. The power factor at this bus is 0.8346. The real power of the DC side of the microgrid is  $3.808 \times 10^4$  W.

The THD at all the buses is less than 5% and all the IEEE standards have been met. The power factor at the bus that is connected to WT is less than the load and the reason for that is the reactive power is much more than the reactive power at the bus that is connected to the load.

Table 7-7: Reliability analysis in islanding\_case 2

$MG_T$ (MW)	$MG_{TCL}$ (MW)	$MG_{GR}$ %	$MG_S$ %
1.195	1.2	99.58	0.42

Table 7-7 shows the KPIs to measure the microgrid total generation ( $MG_T = 1.195 MW$ ), microgrid total connected loads ( $MG_{TCL} = 1.2 MW$ ), microgrid generation reliability ( $MG_{GR} = 99.58\%$ ). In this case there would be a shortage since the total generation is less than the total connected load and microgrid generation shortage ( $MG_S$ ) would be 0.42 %

### 7.2.2.2 Economic Analysis

Table 7-8: Economic analysis in Islanding case 2

PV (kW)	WT (MW)	Fuel cell (kW)	Battery (kW)	COE (\$)	NPC (\$)	Operating Cost (\$)	Initial Cost (\$)
45	1.15	6	5	0.754	8.62M	399679	3.46 M

According to Table 7-8, the cost of the energy is \$0.754. The net present cost is 8.62 M. The operating cost is \$399679 and the initial cost is 3.46 M.

### 7.2.3 Case III: Shortage in power is bigger than the Power of the Battery

When the shortage in power is bigger than the power of the battery, in order to cover the shortage in power, the new value of the battery would be the difference of the shortage in power and the power of the fuel cell. Based on the GA optimization, the optimized value

of the fuel cell is 6 kW, the size of the PV is 40 kW and the size of the WT is 1.15 MW. The size of the load remains as 1.2 MW. The new value of the battery would be 4 kW.

### 7.2.3.1 Electrical Analysis

Figure 7-13 shows the graph of the three phase voltage at the bus that is connected to the wind turbine. In addition the three phase current at the same bus is measured. Furthermore, the real power and the reactive power of the wind turbine are evaluated. It is shown that the real power of the WT is 1.15 MW and the reactive power of the WT is almost zero.

Figure 7-14 shows the load graphs in this case.

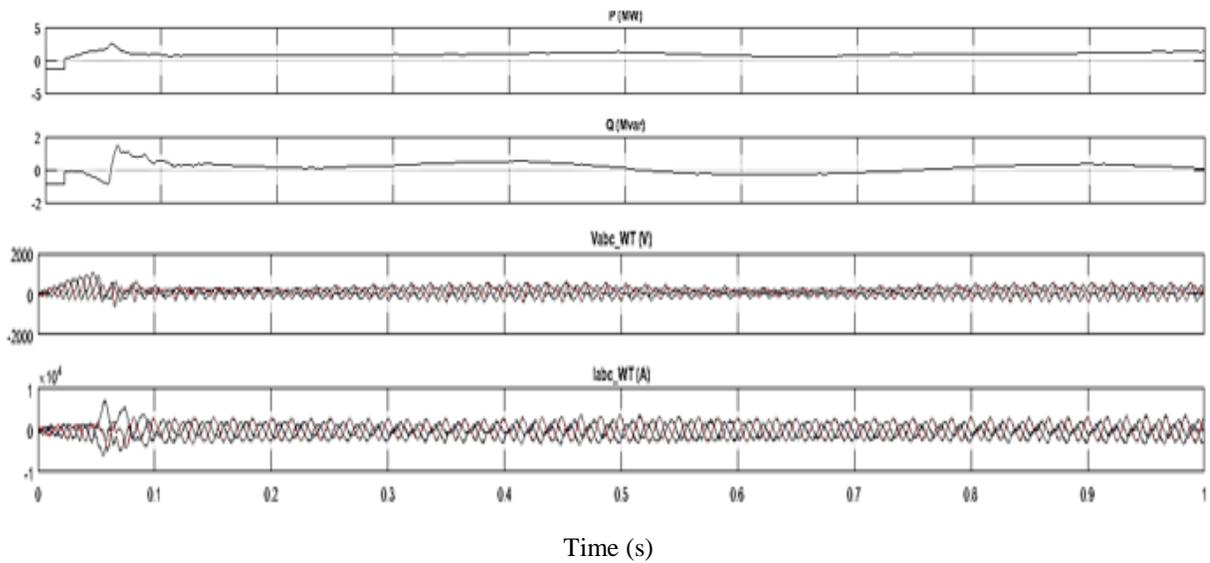


Figure 7-13: Voltage and current of WT; Real and reactive power of WT in Islanding 3

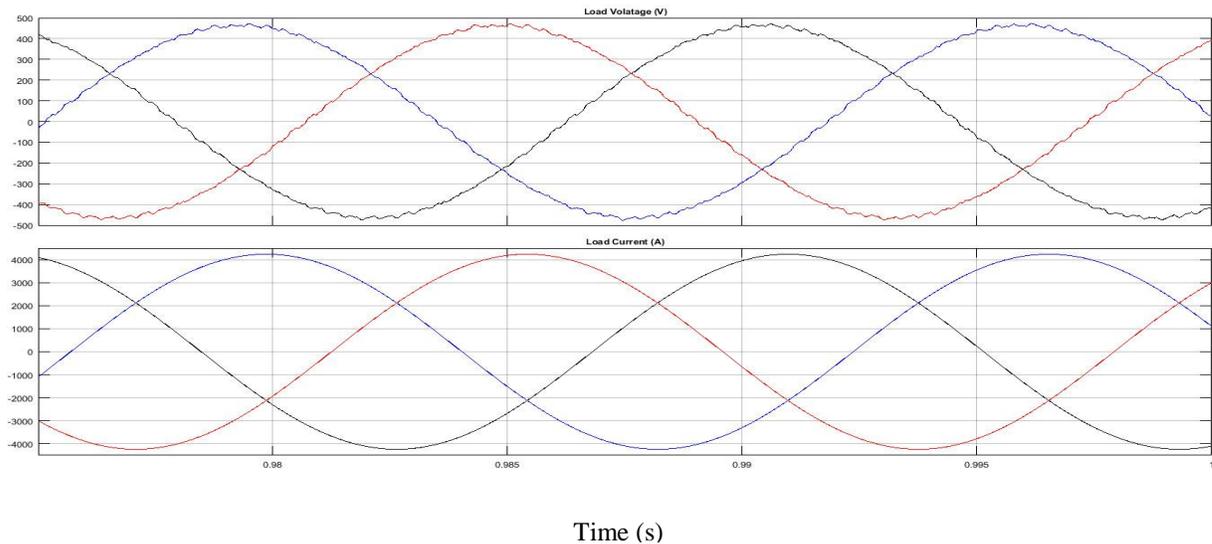


Figure 7-14: Voltage and current of the load in Islanding 3

The DC side of the microgrid consists of PV, fuel cell and battery. Figure 7-15 shows the irradiances ( $\text{W/m}^2$ ), duty cycle, and the power of the PV and the DC voltage of the PV. The irradiance is  $1000 \text{ (W/m}^2\text{)}$ , the duty cycle is 0.45, the power of the PV is 40 kW and the DC voltage of the PV is 280 V. The voltage of the inverter is 500 V. Figure 7-16 shows the reference voltage of the  $V_{\text{DC}}$  regulator which is 500V. In addition, the modulation index is shown which is 0.825.

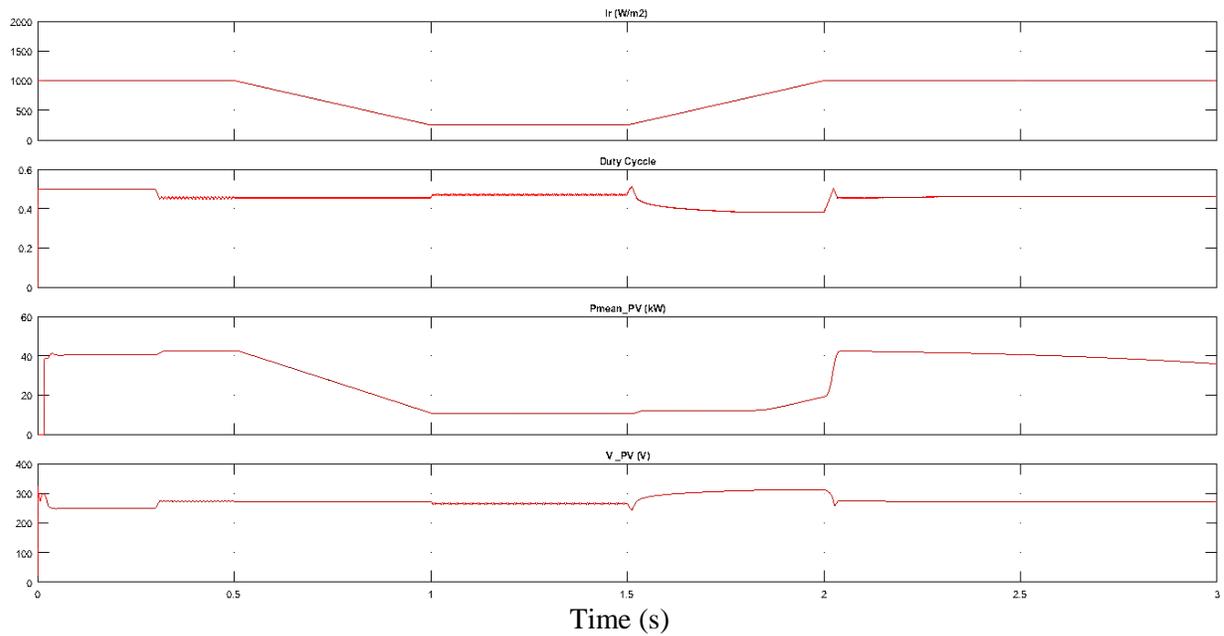


Figure 7-15: Ir, duty cycle, power and the voltage of PV in Islanding 3

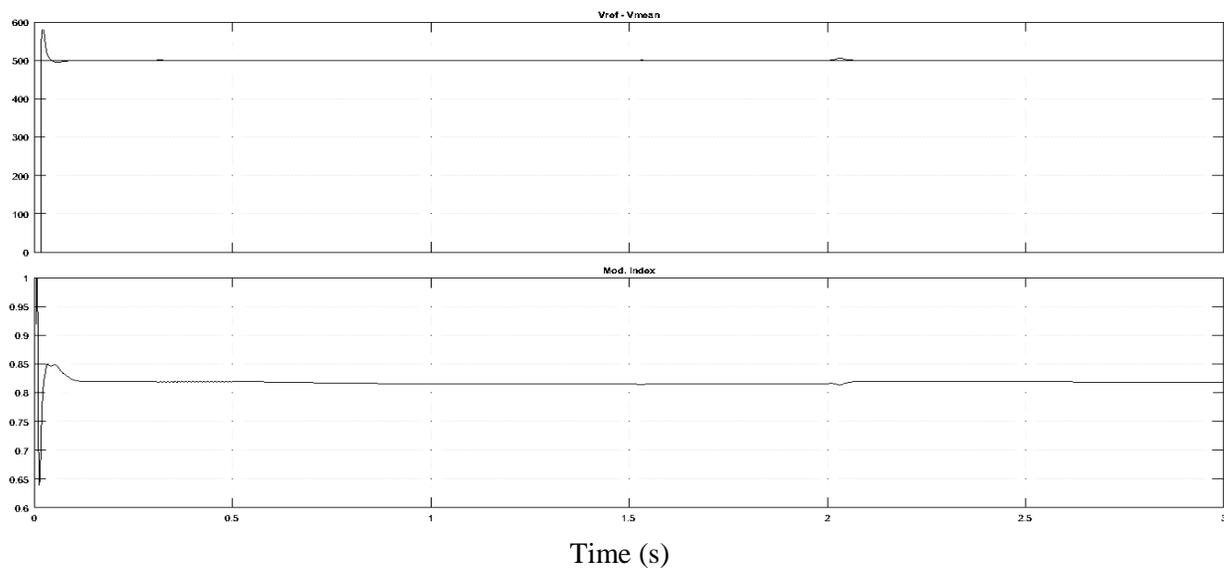


Figure 7-16: Reference voltage, mean voltage and modulation index in Islanding 3

Figure 7-17 shows the DC bus voltage and the DC bus current in fuel cell. The DC bus voltage is 100 V and the current is 58 A.

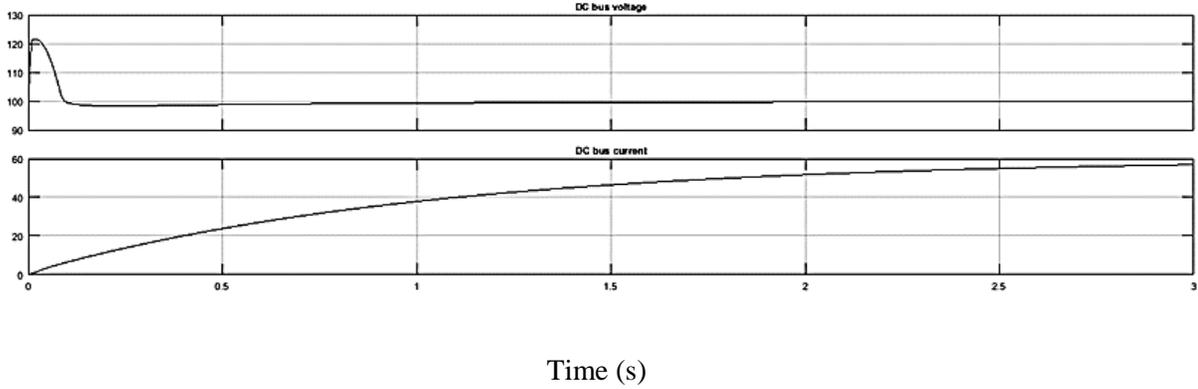


Figure 7-17: DC bus voltage and the DC bus current in fuel cell in Islanding 3

Table 7-9: Power quality KPI Islanding\_case 3

Bus	THD_Voltage %	THD_Current %	Real Power	Reactive Power	Power Factor
WT	2.929	1.949	$4.482 \times 10^5$	$1.722 \times 10^5$	0.9335
Load	2.836	2.921	$5.241 \times 10^5$	$3.454 \times 10^5$	0.8349
DC	-----	-----	$5.264 \times 10^4$	-----	-----

According to Table 7-9, the THD of the voltage at the bus that is connected to WT is 2.929 %. In addition, the THD of the current at that bus is 1.949 %. The real and reactive power at this bus is  $4.482 \times 10^5$  W and  $1.722 \times 10^5$  W respectively. The power factor at that bus is 0.9335. The THD of the voltage at AC load is 2.836 %. In addition, the THD of the current at AC load is 2.921 %. The real and reactive power at this bus is  $5.241 \times 10^5$  W and  $3.454 \times 10^5$  W respectively. The power factor at this bus is 0.8349. The real power of the DC side of the microgrid is  $5.264 \times 10^4$  W.

The THD at all the buses is less than 5% and all the IEEE standards have been met. The power factor at the load is less than the WT and that is due to higher reactive power.

Table 7-10: Reliability analysis in islanding\_case 3

$MG_T$ (MW)	$MG_{TCL}$ (MW)	$MG_{GR}$ %	$MG_S$ %
1.19	1.2	99.16	0.84

Table 7-10 shows the KPIs to measure the microgrid total generation ( $MG_T = 1.19 MW$ ), microgrid total connected loads ( $MG_{TCL} = 1.2 MW$ ), microgrid generation reliability ( $MG_{GR} = 99.16\%$ ) and microgrid generation shortage ( $MG_S = 0.84\%$ ). There would be a shortage in microgrid because the total generation is less than the total connected loads.

### 7.2.3.2 Economy Analysis

Table 7-11: Economic analysis in Islanding case 3

PV (kW)	WT (MW)	Fuel cell (kW)	Battery (kW)	COE (\$)	NPC (\$)	Operating Cost (\$)	Initial Cost (\$)
40	1.15	6	4	0.754	8.62 M	400533	3.44 M

According to Table 7-11, the cost of the energy is \$0.754. The net present cost is 8.62 M. The operating cost is \$400533 and the initial cost is 3.44 M.

### 7.2.4 Case IV: Shortage in Power is Bigger than the Power of the Fuel Cell and Less than or Equal to the Power of the Battery

In this case, the shortage in power is bigger than the power of the fuel cell. However, it is less than or equal to the power of the battery. The optimized values of the fuel cell, PV, WT and battery are 6 kW, 43 kW, 1.15 MW and 8 kW respectively. The size of the load is 1.2 MW.

### 7.2.4.1 Electrical Analysis

Figure 7-18 shows the graph of the three phase voltage (V) at the bus that is connected to the wind turbine. In addition the three phase current (A) at the same bus is measured. Furthermore, the real power and the reactive power of the wind turbine are evaluated. It is shown that the real power of the WT is 1.15 MW and the reactive power of the WT is almost zero. Figure 7-19 shows the load graphs in this case. The simulation time is 1 sec which is shown on the x-axis.

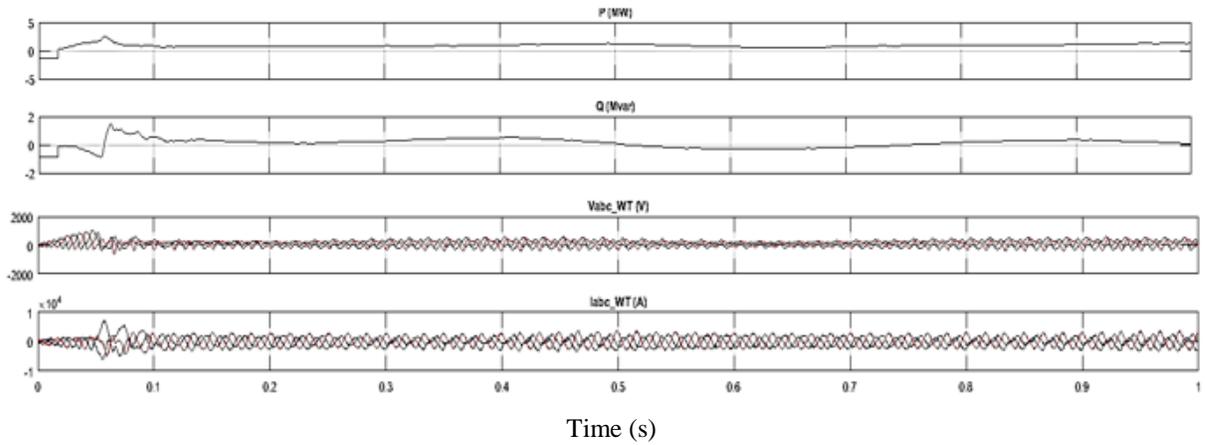


Figure 7-18: Voltage and current of WT; Real and reactive power of WT in Islanding 4

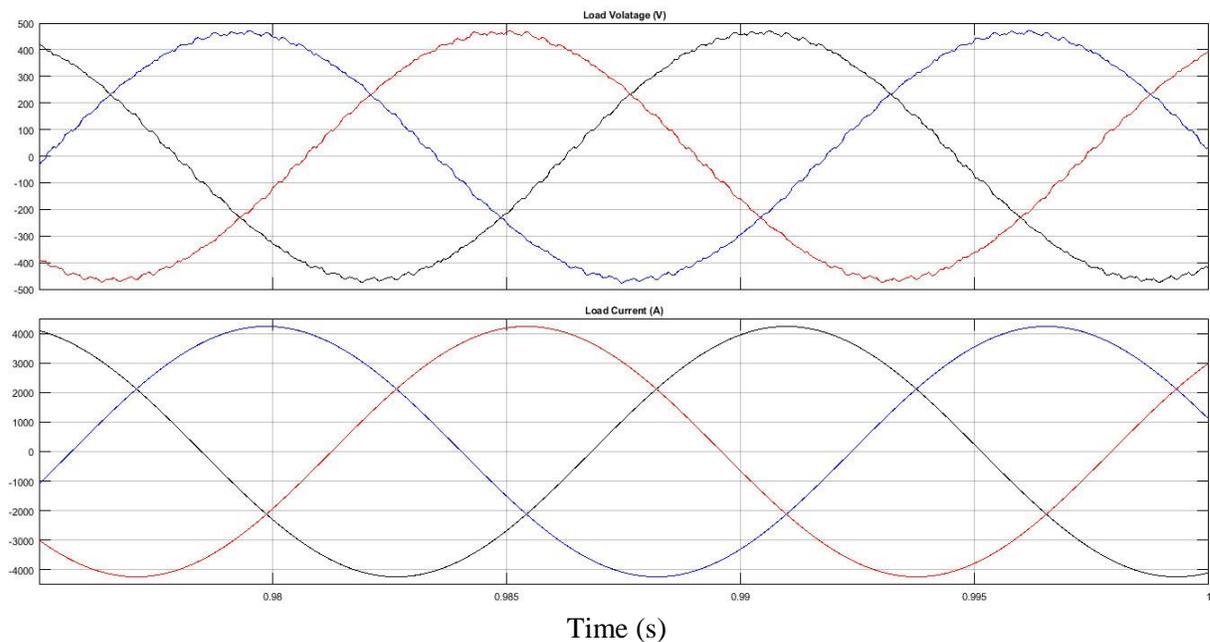


Figure 7-19: Voltage and current of the load in Islanding 4

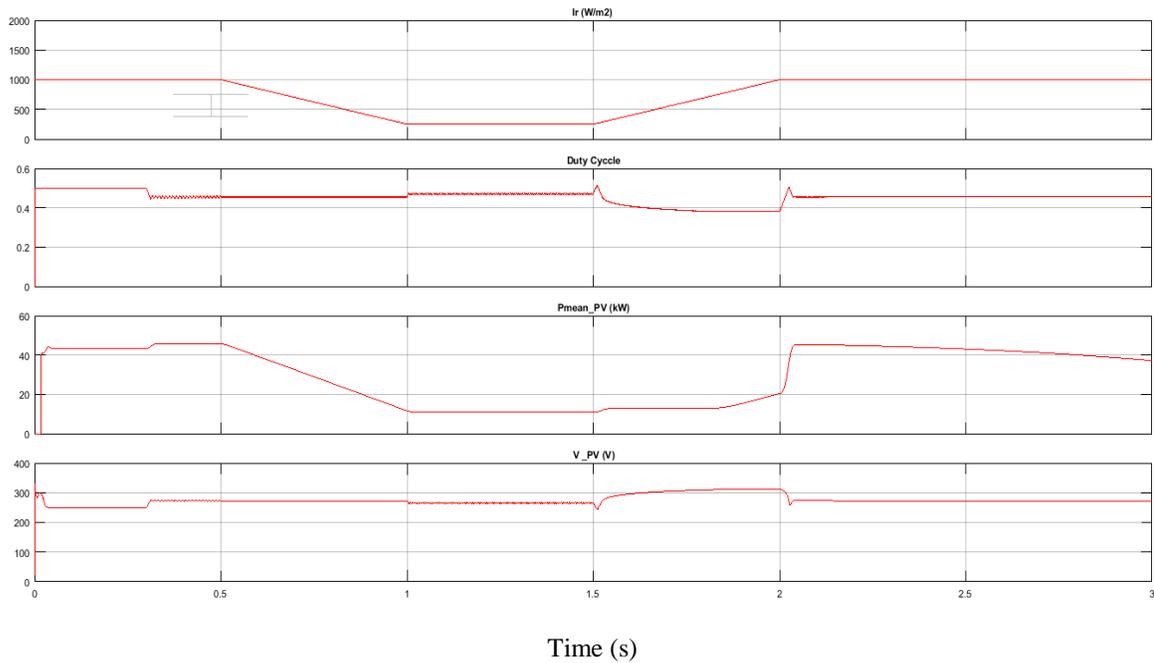


Figure 7-20: *Ir, duty cycle, power and the voltage of PV in Islanding 4*

The DC side of the microgrid consists of PV, fuel cell and battery. Figure 7-20 shows the irradiances ( $\text{W}/\text{m}^2$ ), duty cycle, and the power of the PV and the DC voltage of the PV. The irradiance is  $1000 \text{ (W}/\text{m}^2)$ , the duty cycle is 0.45, the power of the PV is 43 kW and the DC voltage of the PV is 280 V. The voltage of the inverter is 499.90 V. Figure 7-21 shows the reference voltage of the  $V_{\text{DC}}$  regulator which is 500V. In addition, the modulation index is shown which is 0.825.

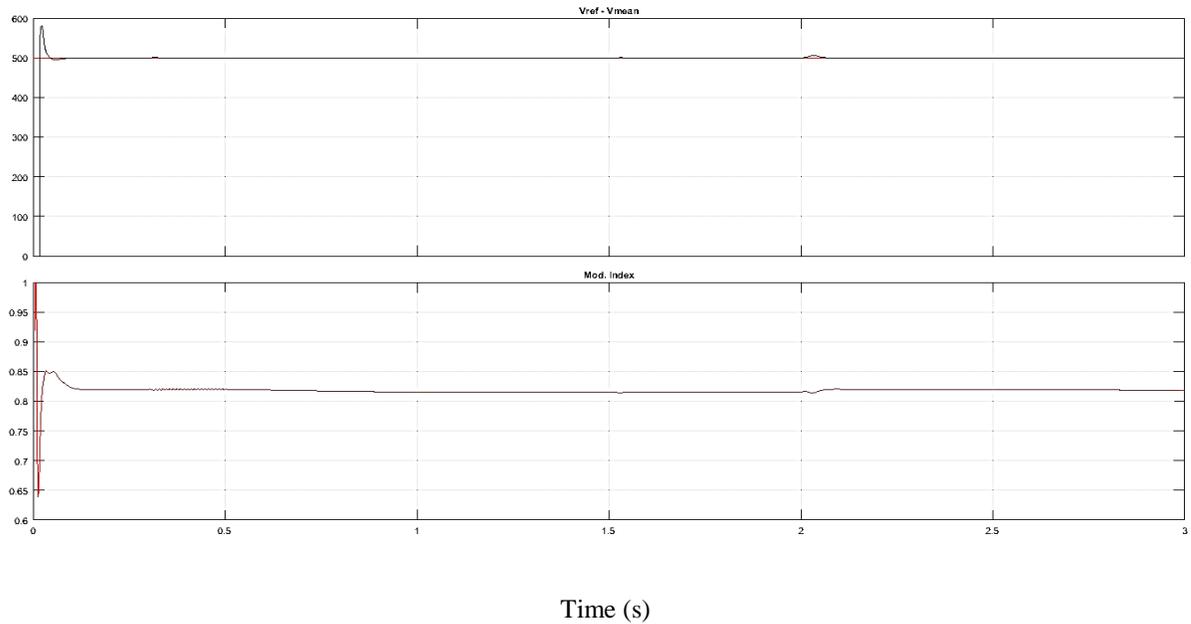


Figure 7-21: *Reference voltage, mean voltage and modulation index in Islanding 4*

Figure 7-22 shows the DC bus voltage and the DC bus current in fuel cell. The DC bus

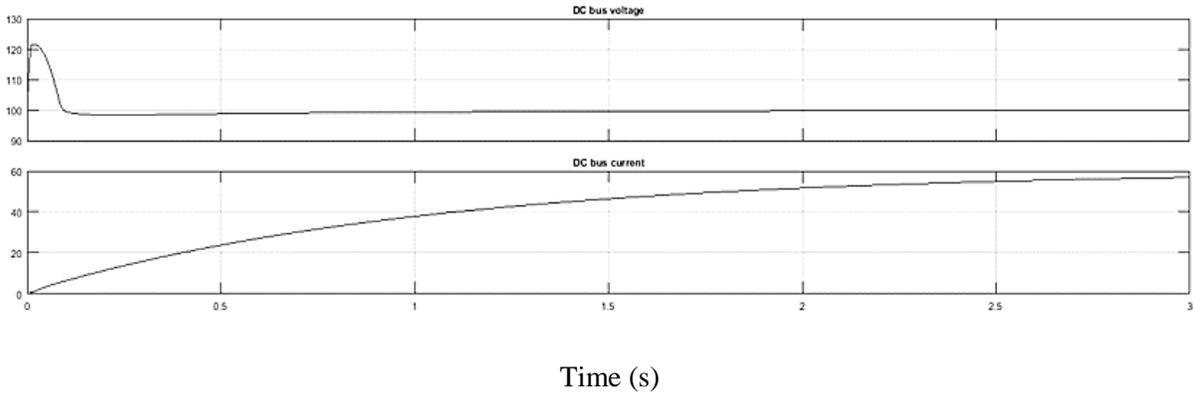


Figure 7-22: DC bus voltage and the DC bus current in fuel cell in Islanding 4

Table 7-12: Power quality KPI Islanding\_case 4

Bus	THD_Voltage %	THD_Current %	Real Power	Reactive Power	Power Factor
WT	4.768	1.366	$4.385 \times 10^5$	$2.546 \times 10^5$	0.8648
Load	3.718	2.218	$3.282 \times 10^5$	$2.679 \times 10^5$	0.7747
DC	-----	-----	$2.649 \times 10^4$	-----	-----

According to Table 7-12, the THD of the voltage at the bus that is connected to WT is 4.768%. In addition, the THD of the current at that bus is 1.366 %. The real and reactive power at this bus is  $4.385 \times 10^5$  W and  $2.546 \times 10^5$  W respectively. The power factor at that bus is 0.8648. The THD of the voltage at AC load is 3.718 %. In addition, the THD of the current at AC load is 2.218 %. The real and reactive power at this bus is  $3.282 \times 10^5$  W and  $2.679 \times 10^5$  W respectively. The power factor at this bus is 0.7747. The real power of the DC side of the microgrid is  $2.649 \times 10^4$  W.

The THD at all the buses is less than 5% and all the IEEE standards have been met. The power factor at the load is less than the WT and that is due to higher reactive power.

Table 7-13: Reliability analysis in islanding\_case 4

$MG_T$ (MW)	$MG_{TCL}$ (MW)	$MG_{GR}$ %	$MG_S$ %
1.193	1.2	99.42	0.58

Table 7-13 shows the KPIs to measure the microgrid total generation ( $MG_T = 1.193 MW$ ), microgrid total connected loads ( $MG_{TCL} = 1.2 MW$ ), microgrid generation reliability ( $MG_{GR} = 99.42\%$ ) and microgrid generation shortage ( $MG_S = 0.58\%$ ).

### 7.2.4.2 Economic Analysis

Table 7-14: Economic analysis in Islanding case 4

PV (kW)	WT (MW)	Fuel cell (kW)	Battery (kW)	COE (\$)	NPC (\$)	Operating Cost (\$)	Initial Cost (\$)
43	1.15	6	8	0.755	8.62 M	400366	3.45 M

Table 7-14 shows the economic analysis in case 4 in islanding mode. The cost of the energy is \$0.755. The net present cost is 8.62 M. The operating cost is \$400366 and the initial cost is 3.45M.

### 7.2.5 Case V: Shortage in Power is Bigger than the Power of the Fuel Cell and the Power of the Battery

In this case, the shortage in power is bigger than the power of the fuel cell and the power of the battery. Therefore, the power of the fuel cell needs to be adjusted in order to cover the shortage in power. The new value of the fuel cell would be found by the following formula:

$$P_{FC} = P_{diff} - (P_{FC(oid)} + P_{Bat}) \quad (7.1)$$

The optimized values of the WT, PV, fuel cell and battery are 1.1 MW, 80 kW, 2kW and 12 kW respectively. The size of the load is 1.2 MW. The new value of the FC would be 6 kW.

### 7.2.5.1 Electrical Analysis

Figure 7-23 shows the graph of the three phase voltage (V) at the bus that is connected to the wind turbine. In addition the three phase current (A) at the same bus is measured. Furthermore, the real power and the reactive power of the wind turbine are evaluated. It is shown that the real power of the WT is 1.1 MW and the reactive power of the WT is almost zero. Figure 7-24 shows the load graphs in this case. The simulation time is 1 sec and that is shown in x-axis.

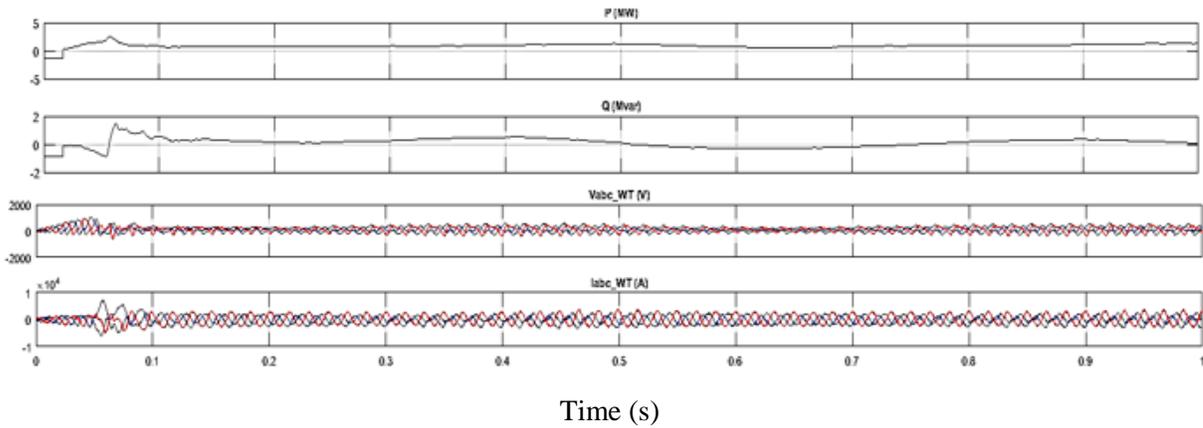


Figure 7-23: Voltage and current of WT; Real and reactive power of WT in Islanding 5

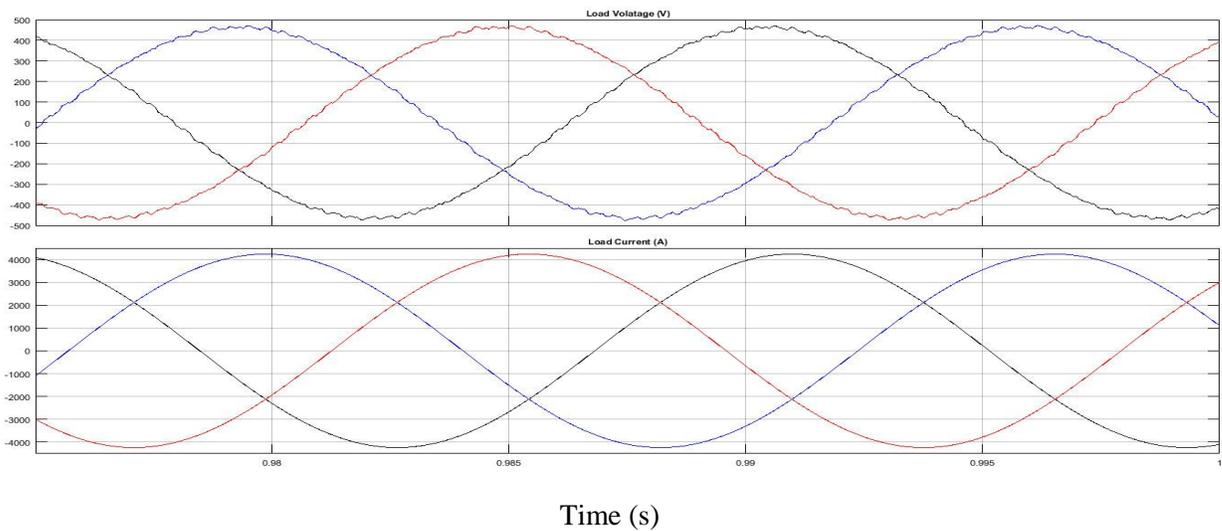


Figure 7-24: Voltage and current of the load in Islanding 5

The DC side of the microgrid consists of PV, fuel cell and battery. Figure 7-25 shows the irradiances ( $\text{W}/\text{m}^2$ ), duty cycle, and the power of the PV and the DC voltage of the PV. The irradiance is  $1000 \text{ (W}/\text{m}^2)$ , the duty cycle is 0.45, the power of the PV is 80 kW and the DC voltage of the PV is 300 V. The voltage of the inverter is 499.90 V. Figure 7-26 shows the reference voltage of the  $V_{\text{DC}}$  regulator which is 500V. In addition, the modulation index is shown which is 0.825 .

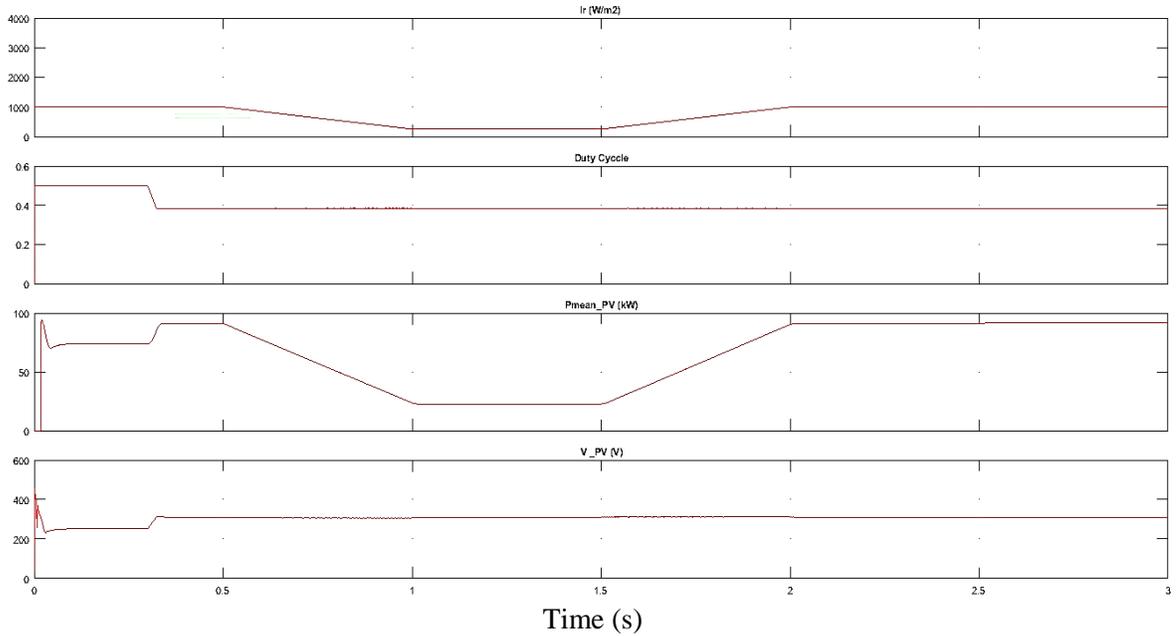


Figure 7-25:  $I_r$ , duty cycle, power and the voltage of PV in Islanding 5

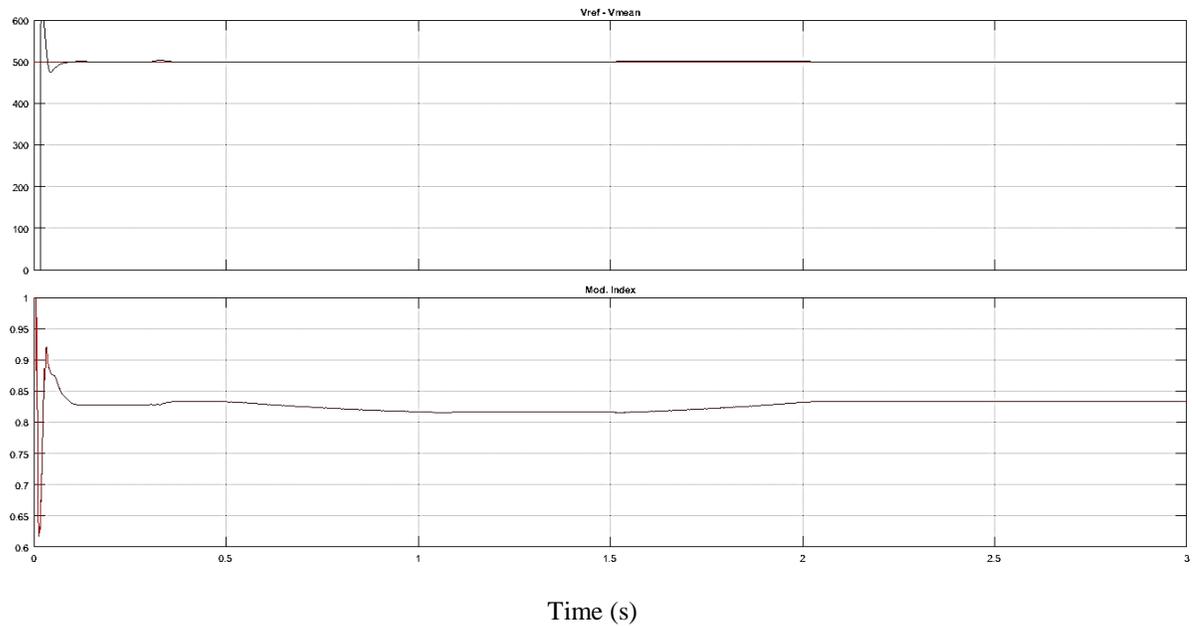


Figure 7-26: Reference voltage, mean voltage and modulation index in Islanding 5

Figure 7-27 shows the DC bus voltage and the DC bus current in fuel cell. The DC bus voltage is 100 V and the current is 58 A.

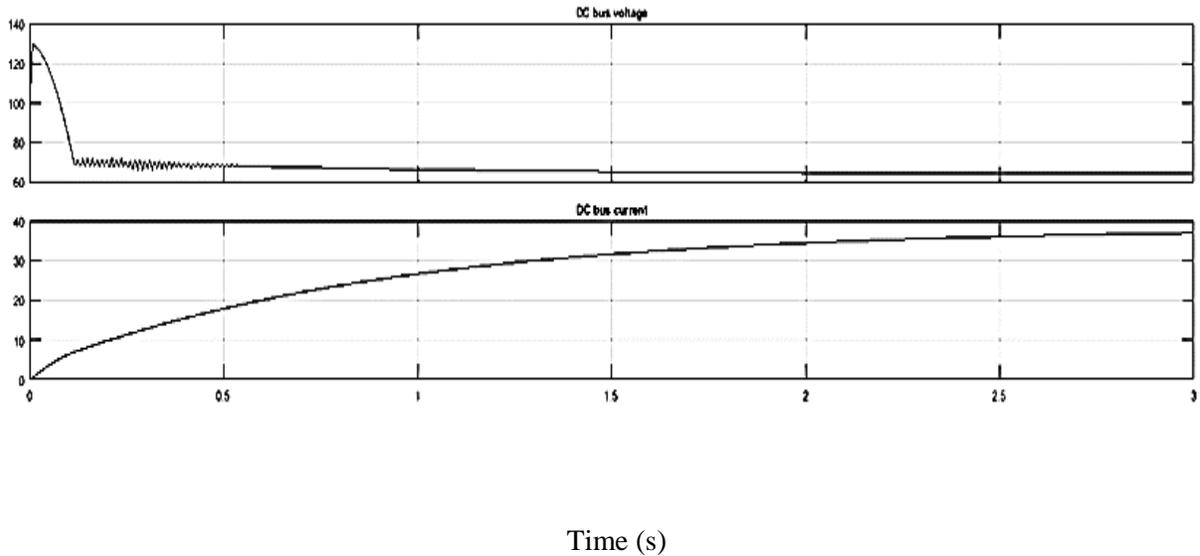


Figure 7-27: DC bus voltage and the DC bus current in fuel cell in Islanding 5

Table 7-15: Power quality KPI Islanding\_case 5

Bus	THD_Voltage %	THD_Current %	Real Power	Reactive Power	Power Factor
WT	3.941	1.201	$5.751 \times 10^5$	$3.952 \times 10^5$	0.8242
Load	4.842	2.091	$4.918 \times 10^5$	$3.496 \times 10^5$	0.8151
DC	-----	-----	$3.513 \times 10^4$	-----	-----

According to Table 7-15, the THD of the voltage at the bus that is connected to WT is 3.941%. In addition, the THD of the current at that bus is 1.201%. The real and reactive power at this bus is  $5.751 \times 10^5$  W and  $3.952 \times 10^5$  W respectively. The power factor at that bus is 0.8242. The THD of the voltage at AC load is 4.842%. In addition, the THD of the current at AC load is 2.091%. The real and reactive power at this bus is  $4.918 \times 10^5$  W and  $3.496 \times 10^5$  W respectively. The power factor at this bus is 0.8151. The real power of the DC side of the microgrid is  $3.513 \times 10^4$  W.

Table 7-16: Reliability analysis in islanding\_case 5

$MG_T$ (MW)	$MG_{TCL}$ (MW)	$MG_{GR}$ %	$MG_S$ %
1.18	1.2	98.33	1.67

Table 7-16 shows the KPIs to measure the microgrid total generation ( $MG_T = 1.18 MW$ ), microgrid total connected loads ( $MG_{TCL} = 1.2 MW$ ), microgrid generation reliability ( $MG_{GR} = 98.33\%$ ) and microgrid generation shortage ( $MG_S = 1.67\%$ ).

### 7.2.5.2 Economic Analysis

Table 7-17: Economic analysis in Islanding case 5

PV (kW)	WT (MW)	Fuel cell (kW)	Battery (kW)	COE (\$)	NPC (\$)	Operating Cost (\$)	Initial Cost (\$)
80	1.1	2	12	0.757	8.65 M	393967	3.56M

Table 7-17 shows the economic analysis is case 5 in islanding mode. The cost of the energy is \$0.757. The net present cost is 8.65 M. The operating cost is \$393967 and the initial cost is 3.56 M.

## 7.2.6 Case VI: Shortage is Bigger than the Power of the Battery and Less than or Equal to the Power of the Fuel Cell and the Power of the Battery

In this case the shortage in the power is bigger than the power of the battery. However, it is less than or equal to the power of the fuel cell and the power of the battery. Optimized values of the PV, WT, fuel cell and battery are 40 kW, 1.15 MW, 6 kW and 7 kW.

### 7.2.6.1 Electrical Analysis

Figure 7-28 shows the graph of the three phase voltage (V) at the bus that is connected to the wind turbine. In addition the three phase current (A) at the same bus is measured.

Furthermore, the real power and the reactive power of the wind turbine are evaluated. It is shown that the real power of the WT is 1.1 MW and the reactive power of the WT is almost zero. Figure 7-29 shows the load graphs in this case. The simulation time is 1 sec which is shown in x-axis.

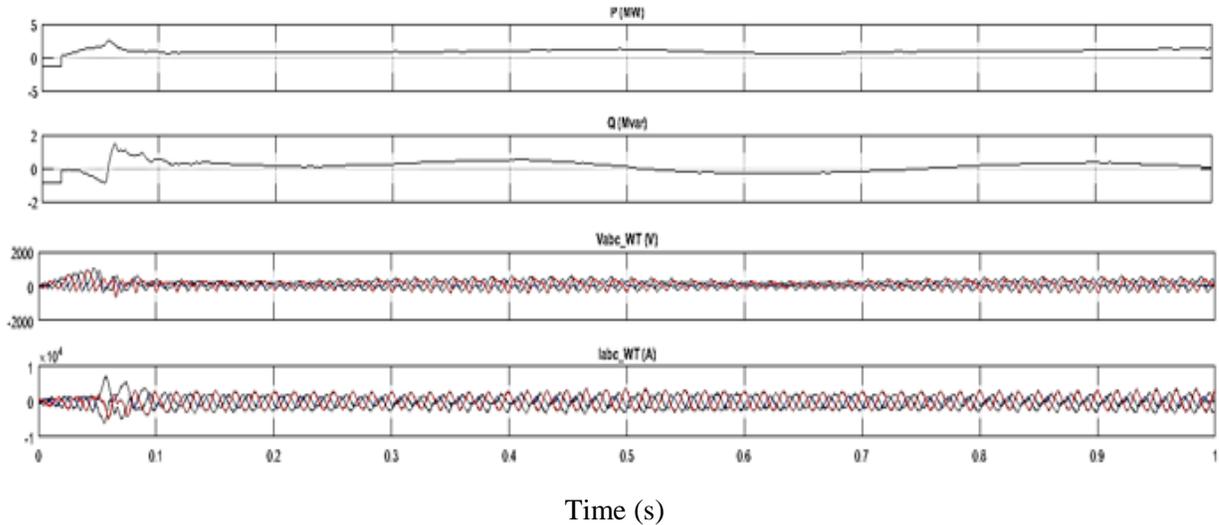


Figure 7-28: Voltage and current of WT; Real and reactive power of WT in Islanding 6

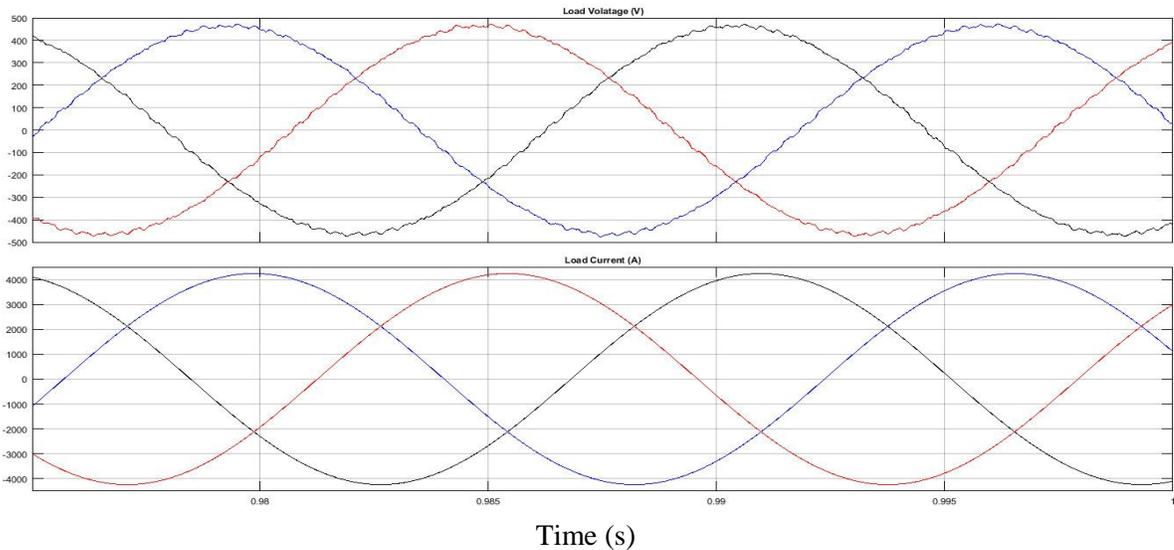


Figure 7-29: Voltage and current of the load in Islanding 6

The DC side of the microgrid consists of PV, fuel cell and battery. Figure 7-30 shows the irradiances ( $\text{W}/\text{m}^2$ ), duty cycle, and the power of the PV and the DC voltage of the PV. The irradiance is  $1000 \text{ (W}/\text{m}^2)$ , the duty cycle is 0.45, the power of the PV is 40 kW and the DC voltage of the PV is 300 V. The voltage of the inverter is 499.92 V. Figure 7-31

shows the reference voltage of the  $V_{DC}$  regulator which is 500V. In addition, the modulation index is shown which is 0.825.

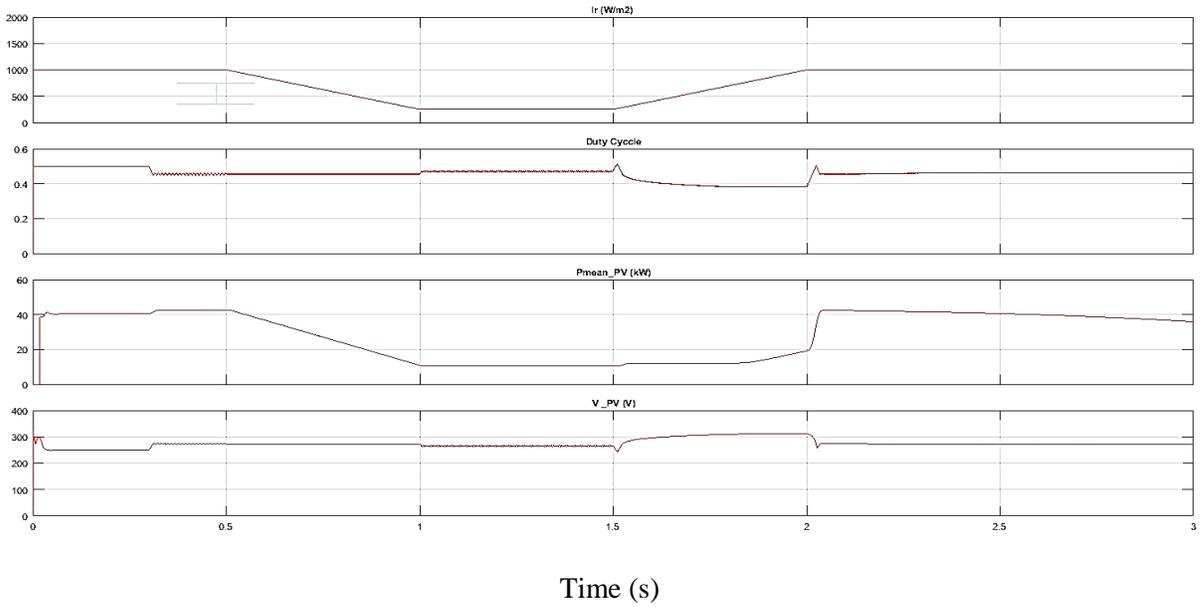


Figure 7-30: Voltage and current of the load in Islanding 6

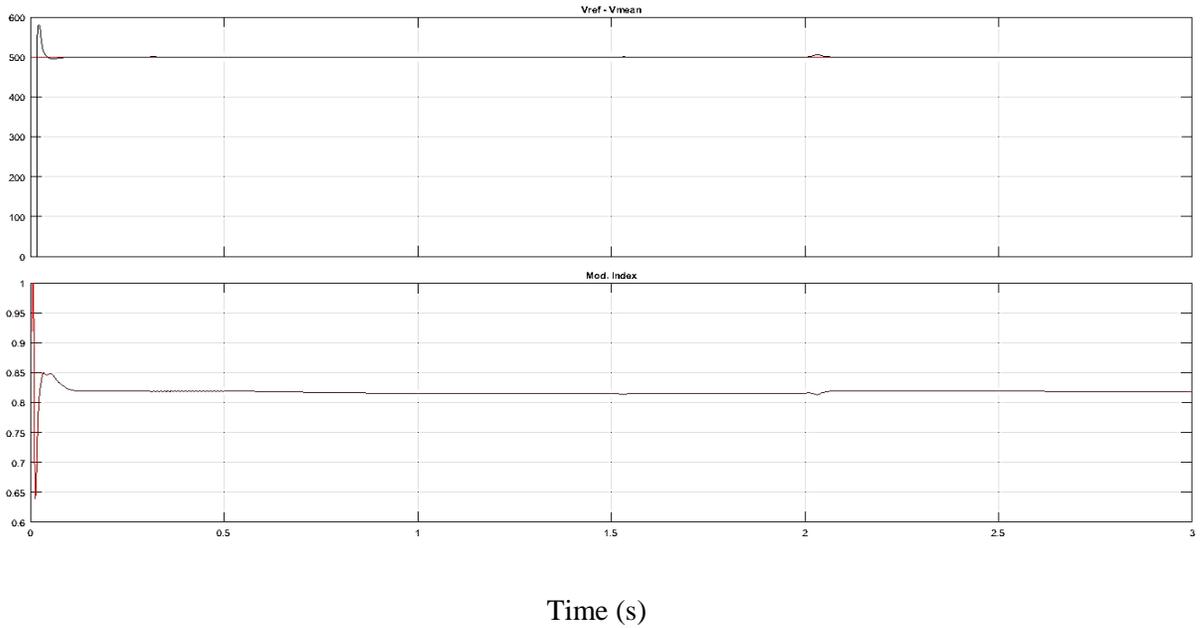


Figure 7-31: Reference voltage, mean voltage and modulation index in Islanding 6

Figure 7-32 shows the DC bus voltage and the DC bus current in fuel cell. The DC bus voltage is 70 V and the current is 35 A.

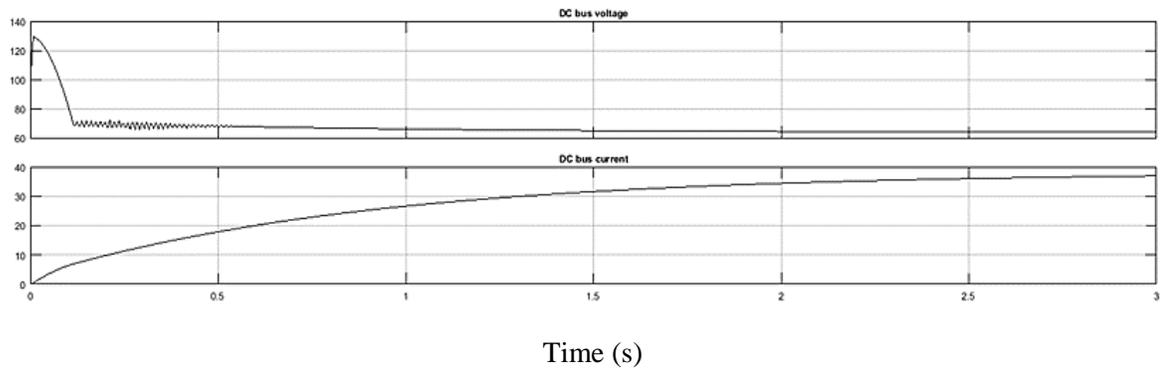


Figure 7-32: DC bus voltage and the DC bus current in fuel cell in Islanding 6

Table 7-18: Power quality KPI Islanding\_case 6

Bus	THD_Voltage %	THD_Current %	Real Power	Reactive Power	Power Factor
WT	3.632	1.471	$3.202 \times 10^5$	$2.361 \times 10^5$	0.8048
Load	3.591	2.607	$4.191 \times 10^5$	$3.848 \times 10^5$	0.7366
DC	-----	-----	$2.246 \times 10^4$	-----	-----

According to Table 7-18, the THD of the voltage at the bus that is connected to WT is 3.632 %. In addition, the THD of the current at that bus is 1.471 %. The real and reactive power at this bus is  $3.202 \times 10^5$  W and  $3.361 \times 10^5$  W respectively. The power factor at that bus is 0.8048. The THD of the voltage at AC load is 3.591 %. In addition, the THD of the current at AC load is 2.607 %. The real and reactive power at this bus is  $4.191 \times 10^5$  W and  $3.848 \times 10^5$  W respectively. The power factor at this bus is 0.7366. The real power of the DC side of the microgrid is  $2.246 \times 10^4$  W.

Table 7-19: Reliability analysis in islanding\_case 6

$MG_T$ (MW)	$MG_{TCL}$ (MW)	$MG_{GR}$ %	$MG_S$ %
1.19	1.2	99.167	0.833

Table 7-19 shows the KPIs to measure the microgrid total generation( $MG_T$ ) which is 1.19 MW, microgrid total connected loads ( $MG_{TCL}$ ) which is 1.2 MW, microgrid generation

reliability ( $MG_{GR}$ ) which is 99.167 % and microgrid generation shortage ( $MG_S$ ) which is 0.833%.

### 7.2.6.2 Economic Analysis

Table 7-20: Economic analysis in Islanding case 6

PV (kW)	WT (MW)	Fuel cell (kW)	Battery (kW)	COE (\$)	NPC (\$)	Operating Cost (\$)	Initial Cost (\$)
40	1.15	6	7	0.753	8.61M	399781	3.44M

Table 7-20 summarizes the economic analysis in case 6 in islanding mode. The cost of the energy is \$0.753. The net present cost is 8.61 M. The operating cost is \$399781 and the initial cost is 3.44 M.

## 7.3 AHP Results

The pairwise comparison of the following criteria which are power quality (C1), costs (C2), customer satisfaction (C3), and environmental impact reduction (C4) is shown in Table 7-21.

Table 7-21: Pairwise comparison of KPIs

	C1	C2	C3	C4	Weights
C1	1	5	5	0.25	0.34657
C2	0.2	1	6	2	0.24744
C3	0.2	1/6	1	2	0.12236
C4	4	0.5	0.5	1	0.28363
Consistency Index =0.846539					

The pairwise comparison of the following sub-criteria of power quality which are power grid voltage stability (C11), THD (C15), loss of power supply probability (C16), microgrid

total generation (C12), microgrid total connected loads (C17), microgrid generation reliability (C13) and microgrid generation shortage (C14) is shown in Table 7-22.

Table 7-22: Pairwise comparison of power quality sub-criteria

	C11	C12	C13	C14	C15	C16	C17	Weights
C11	1	1/4	1/2	6	5	9	1/5	0.11117
C12	4	1	7	9	6	3	1/9	0.23557
C13	2	1/7	1	5	2	3	1/7	0.08286
C14	1/6	1/9	1/5	1	3	3	1/7	0.04282
C15	1/5	1/6	1/2	1/3	1	8	1/3	0.05525
C16	1/9	1/3	1/3	1/3	1/8	1	1/5	0.02647
C17	5	9	7	7	3	5	1	0.44584
Consistency Index =0.440672								

The pairwise comparison of the following sub-criteria of cost which are capital cost (C21), maintenance cost (C22), generation cost (C23) and replacement cost (C24) is shown in Table 7-23.

Table 7:23: Pairwise comparison of cost sub-criteria

	C21	C22	C23	C24	Weights
C21	1	1/6	1/4	1/8	0.04024
C22	6	1	1/2	5	0.42005
C23	4	2	1	1/3	0.25928
C24	8	1/5	3	1	0.28042
Consistency Index =0.407149					

According to Table 7-21 power quality is the most important factor in evaluating the microgrid. Based on Table 7-22 microgrid total connected loads are the most factor in power quality category. Table 7-23 shows that maintenance cost is the most important factor in the cost category.

## 7.4 KPI Analysis

According to KPIs analysis, the overall demand has been reduced. That is one of the main advantages of using microgrid since the load is not depending on the main Grid to receive power. Technical losses have been reduced according to the power factors that have been evaluated in different cases (Grid-connected and Islanded). The power factor is really high in different buses in different cases. Since the microgrid uses DERs, therefore, the CO<sub>2</sub> has been reduced. Since the power factor is high in all the buses and the THD (%) is less than 5 % in all the cases, it is concluded that the power efficiency, power quality, efficiency of power delivery system and efficiency of power consumption have been improved according to KPIs analysis. The voltage and the current THD (%) is less than 5% and the power factor is really high in all the cases. AHP is used to evaluate the most important KPIs which are (the power quality - microgrid total connected loads) In addition, in the cost category, the maintenance cost is the most important KPI.

Summary: The proposed microgrid was examined under different scenarios. The microgrid was examined in Grid-connected and the simulation results were captured. Power quality indicators were examined. In addition, the economic indicators and the environment indicators were examined as well. The proposed microgrid examined in different scenarios in islanding mode. For each scenario, the power quality indicators, the economic indicators, the reliability indicators and the environment indicators were examined. In the end, these KPIs were analyzed by using AHP.

# Chapter 8-Conclusion and Future Work

The general conclusion of the thesis and the future scope of the work will be presented in this chapter. The conclusion is based on the work that has been done in the thesis through different chapters.

## 8.1 Conclusion

The summarized conclusions of the thesis are the following:

- The microgrid with PV, WT, FC and battery storage have been modeled in MATLAB. Each block in the MATLAB has been explained in details.
- The control system for each mode (Grid-connected and Islanding mode) has been modeled in MATLAB.
- Optimal sizing of the microgrid in islanding mode was found by using GA. The optimal configurations not only satisfy technical conditions but also minimize the costs.
- Different energy management strategies have been developed in both Grid-connected and Islanding mode. In the islanding mode, the objective function is to find the optimal sizing in order to minimize the annual cost by scheduling of DERs. The main purpose of energy management in Grid-connected is to minimize the net power exchange with the main grid by using the maximum energy out of PV, WT and the battery system.
- The proposed microgrid was examined under two different modes. The microgrid was examined in Grid-connected and the islanding mode and the simulation results were captured.
- KPIs modeling has been developed in order to evaluate the performance of the microgrid in different scenarios. The KPIs are in four different categories. These KPIs are, reliability indicators, environmental indicators, economic indicators, power quality factors.

- AHP is used to evaluate the KPIs and determine which ones are the most important ones when it comes to evaluating the performance of the microgrid. The most important KPI was the power quality. Furthermore, within the power quality indicators, microgrid total connected loads is the most important KPI. In addition, in the cost category, the maintenance cost is the most important KPI.
- Based on the KPI analysis in chapter 7, the overall demand has been reduced.
- Technical losses have been reduced according to the power factors that have been evaluated in different cases (Grid-connected and Islanded).
- The CO<sub>2</sub> emission has been reduced because the microgrid uses DERs.
- Since the power factor is high in all the buses and the THD (%) is less than 5 % in all the cases, it is concluded that the power efficiency, power quality, efficiency of power delivery system and efficiency of power consumption have been improved according to KPIs analysis.
- The voltage and the current THD (%) is less than 5% and the power factor is really high in all the cases.

## 8.2 Future work

This thesis presented a KPI modeling for an optimized microgrid. However, this thesis focused on the operational KPIs. As it mentioned before, the microgrid can be in Grid-connected or islanding mode. The KPIs that are used in the thesis are economic, environmental, power quality and reliability indicators. These KPIs are used in order to evaluate the performance of the microgrid.

The future work of this thesis would be focusing on different KPIs such as control and protection. There is still a long way to have a more stable system and use microgrid as an alternative source of power generation. One of the main problems is the MG protection system. Even though there has been a lot of research on this area, there is not a perfect solution for this problem. A microgrid can face a disturbance and the response time should be enough to detect the fault and restore the power. Some of the protection systems that

are used in MG are voltage based protection, distance protection, differential protection and OC protection.

As it mentioned earlier, protection indicators are very important to evaluate the MG performance and to ensure the safety and reliability of the system. Finding a solution to make the protection system better and more responsive in order to have a reliable MG that can be used as an alternative power generation could be one of the tasks of the future work.

In addition to protection indicators, control indicators are important in order to have a better and more resilient microgrid. These KPIs can be implemented on the operation and design. Furthermore, some KPIs can be developed for the microgrid components such as load, PV, wind turbine, fuel cell storage and power electronics devices.

Summary: This chapter presented a summary of the thesis and what have achieved in this study. In addition, the future work of this study was presented in this chapter as well.

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# Appendices

## A.GA MATLAB Codes [78]

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% Genetic Algorithm (GA)

clear % Initialize momery
rand('state',0) % Reset the random number generator so each time you re-run
                % the program with no changes you will get the same results.

load ElecHeatWindSolarProfile %Load the data
Ts=0.1;

NUM_TRAITS=4; % Number of traits in each individual
HIGHTRAIT=[15 15 50 3]; % Upper limit of a trait
LOWTRAIT=[0 0 0 0]; % Lower limit of a trait
SIG_FIGS=[2 2 2 2]; % Number of genes in each trait
DECIMAL=[2 2 2 2]; % Order of magnitude the trait
MUTAT_PROB=0.05; % Probability of mutation (typically <.1)
CROSS_PROB=0.8; % Probability of crossover (typically near 1)
SELF_ENTERED=0; % "0": a random initial population.
                % "1": a specified initial population
                % If you choose "1", enter it in the program.
POP_SIZE=20; % Number of individuals in the population
ELITISM=0; % Elitism ON/OFF, 1/0
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DELTA=10;          % Number of generations to be counted
                  % for the termination criteria.
EPSILON = 0.01;   % Range that the fitness must change
                  % in the termination criteria.
MAX_GENERATION=10; % Number of times the loop will run before
                  % giving up on the EPSILON-DELTA termination cond.

popcount=1;       % Initialize the generation count,
                  % set it to one, the first population

if SELF_ENTERED == 0      % Make a random initial population for
                          % base-10 operation by specifying the
                          % matrix of initial traits
for pop_member = 1:POP_SIZE
    for current_trait = 1:NUM_TRAITS,
        trait(current_trait,pop_member,popcount)=...
            (rand-(1/2))*(HIGHTRAIT(current_trait)-LOWTRAIT(current_trait))+...
            (1/2)*(HIGHTRAIT(current_trait)+LOWTRAIT(current_trait));
        % This starts the population off with numbers chosen randomly
        % on the allowed range of variation, for this example.
    end
end

else

for pop_member = 1:POP_SIZE
    for current_trait = 1:NUM_TRAITS,
        trait(current_trait,pop_member,popcount)=0;
        % To start with a guess where all the population members are zero
    end
end
end

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end

CHROM_LENGTH=sum(SIG_FIGS)+NUM_TRAITS; % Length of the chromosome
is
    % the number of sig. figs. plus
    % the number of sign positions
TRAIT_START(1)=1; % Initialize: the first trait
    % starts at the first digit
    % (this is the sign digit)

for current_trait=1:NUM_TRAITS, % Determine the start point of the
    % other traits - it is the start of
    % the last trait plus the no. of sig.
    % figs. plus one for sign
TRAIT_START(current_trait+1)=...
    TRAIT_START(current_trait)+SIG_FIGS(current_trait)+1;
    % Yes, we compute the TRAIT_START for one extra trait - this
    % is used for convenience in the code below.
end

while popcount <= MAX_GENERATION

% First, fix bad traits (i.e., ones that are out of the range
% specified by HIGHTRAIT and LOWTRAIT) by saturation at the extremes

for pop_member = 1:POP_SIZE

for current_trait = 1:NUM_TRAITS,

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if trait(current_trait,pop_member,popcount)>HIGHTRAIT(current_trait)

    % The trait has went higher than the upper
    % bound so let the trait equal to the
    % HIGHTRAIT bound.

trait(current_trait,pop_member,popcount)=HIGHTRAIT(current_trait);

% Now consider the other case:

elseif trait(current_trait,pop_member,popcount)<LOWTRAIT(current_trait)

    % The trait has went lower than the lower
    % bound so let the trait equal to the
    % LOWTRAIT bound

trait(current_trait,pop_member,popcount)=LOWTRAIT(current_trait);

    end

% Now that we have reset the traits to be in range, we must
% convert them to the chromosome form for use with the genetic operators.
% First, we transfer the sign of the trait into the chromosome

    if trait(current_trait,pop_member,popcount) < 0
        pop(TRAIT_START(current_trait),pop_member)=0;
    else
        pop(TRAIT_START(current_trait),pop_member)=9;
    end

% Next, strip off the sign and store the resulting value in a

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% temporary variable that is used in the construction of pop

temp_trait(current_trait,pop_member)=...
    abs(trait(current_trait,pop_member,popcount));
    % temp_trait is trait without the sign of trait

% Next, we store the numbers of the trait in the chromosome:
% First, set up a temporary trait with at most
% one nonzero digit to the left of the decimal point.
% This is used to strip off the numbers to put
% them into a chromosome.

    for counter=1:DECIMAL(current_trait)-1,

temp_trait(current_trait,pop_member)=...
    temp_trait(current_trait,pop_member)/10;

    end

% Encode the new trait into chromosome form

for make_gene = TRAIT_START(current_trait)+1:TRAIT_START(current_trait+1)-1,

% For each gene on the trait make the gene the corresponding digit on
% temp_trait (note that rem(x,y)=x-roundtowardszero(x/y)*y or
% rem(x,1)=x-roundtowardszero(x) so that rem(x,1) is the fraction part
% and x-rem(x,1) is the integer part so the next line makes the location in
% pop the same as the digit to the left of the decimal point of temp_trait

pop(make_gene,pop_member)=temp_trait(current_trait,pop_member)-...
    rem(temp_trait(current_trait,pop_member),1);

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% Next, we take temp_trait and rotate the next digit to the left so that
% next time around the loop it will pull that digit into the
% chromosome. To do this we strip off the leading digit then shift
% in the next one.

temp_trait(current_trait,pop_member)=...
    (temp_trait(current_trait,pop_member)-pop(make_gene,pop_member))*10;

end

    end % Ends "for current_trait=..." loop

end % Ends "for pop_member=..." loop

sumfitness = 0; % Re-initialize for each generation

% First, determine the values of the function to be minimized for
% each chromosome.
for chrom_number = 1:POP_SIZE, % Reset fitness
    fitness_bar(chrom_number)=0;
end
for chrom_number = 1:POP_SIZE, % Test fitness

    PVsize=trait(1,chrom_number,popcount)
    PWsize=trait(2,chrom_number,popcount)
    Ah=trait(3,chrom_number,popcount)
    FCsize=trait(4,chrom_number,popcount)

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end

% Next, compute the fitness function (this loop is only kept
% separate from the next one in case you need to implement
% some of the options discussed in the comments).

for chrom_number = 1:POP_SIZE,    % Test fitness

% The fitness function must be chosen so that it is always positive.
% To ensure this for our example we assume that we know that the value
% of f will never be below -5; so we simply add 5 to every fitness_bar value.
% Another approach would be to simply find the minimum value
% of the fitness_bar function for every element in the population
% and then add on its absolute value so that all the resulting
% values will be positive
fitness(chrom_number)=1/(fitness_bar(chrom_number)+0.1);

% Notice that when we turn a minimization problem into a maximization
% problem we often use
% fitness(chrom_number)=(1/(fitness_bar(chrom_number) + .1));
% The 1/fitness_bar function switches it to a maximization problem.
% The +.1 is to make sure that there is no divide by zero. Note that you can
% tune the GA in this case by changing the 1 in the numerator to another
% constant and the .1 to a different value.

sumfitness = sumfitness + fitness(chrom_number); % Store this for
% use below

end

% Next, determine the most fit and least fit chromosome and

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% the chrom_numbers (which we call bestmember and worstmember).

[bestfitness(popcount),bestmember]=max(fitness);
[worstfitness(popcount),worstmember]=min(fitness);
    C=[trait(1,bestmember,popcount) trait(2,bestmember,popcount)
trait(2,bestmember,popcount)]

    PowerDefBest(popcount)=PowerDef(bestmember);
    EmmissionBest(popcount)=Emmission(bestmember);
    LossBest(popcount)=Loss(bestmember);
    RunCostBest(popcount)=RunCost(bestmember);
    TotalCostBest(popcount)=TotalCost(bestmember);
    THDBest(popcount)= THDChrom(bestmember);
    PFBest(popcount)=PFChrom(bestmember);
    TotalEnergyBest(popcount)=TotalEnergy(bestmember);
    TotalWindEnergyBest(popcount)=TotalWindEnergy(bestmember);
    TotalGGBestPercent(popcount)=(TotalEnergyBest(popcount)-
TotalWindEnergyBest(popcount))/TotalEnergyBest(popcount);

TotalWindEnergyBestPercent(popcount)=TotalGGBestPercent(popcount)/TotalEnergyBest(popcount);

% Next, save these (if want to save worstindividual can too)

bestindividual(:,popcount)=trait(:,bestmember,popcount);
% worstindividual(:,popcount)=trait(:,worstmember,popcount);

% Compute the average fitness in case you want to plot it.

avefitness(popcount) = sumfitness / POP_SIZE;

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[n,m]=max(fitness);
trait(1,m,popcount);
trait(2,m,popcount);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Create the next generation
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%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

for pop_member = 1:POP_SIZE,
    if ELITISM ==1 & pop_member==bestmember % If elitism on, and have
        % the elite member
        parent_chrom(:,pop_member)=pop(:,pop_member); % Makes sure that
            % the elite member gets into the next
            % generation.
    else
        pointer=rand*sumfitness; % This makes the pointer for the roulette
            % wheel.
        member_count=1; % Initialization
        total=fitness(1);

        while total < pointer, % This spins the wheel to the
            % pointer and finds the
            % chromosome there - which is
            % identified by member_count
            member_count=member_count+1;
            total=total+fitness(member_count);
        end

% Next, make the parent chromosome

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parent_chrom(:,pop_member)=pop(:,member_count);
end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
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% Reproduce section
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for parent_number1 = 1:POP_SIZE, % Crossover (parent_number1 is the
    % individual who gets to mate
    if ELITISM ==1 & parent_number1==bestmember % If elitism on, and
        % have the elite member
        child(:,parent_number1)=parent_chrom(:,parent_number1);
    else
        parent_number2=parent_number1; % Initialize who the mate is
        while parent_number2 == parent_number1 % Iterate until find
            % a mate other than
            % yourself
            parent_number2 = rand*POP_SIZE; % Choose parent number 2
            % randomly (a random mate)
            parent_number2 = parent_number2-rem(parent_number2,1)+1;
        end
        if CROSS_PROB > rand % If true then crossover occurs

            site = rand*CHROM_LENGTH; % Choose site for crossover
            site = site-rem(site,1)+1; % and make it a valid integer
            % number for a site

% The next two lines form the child by the swapping of genetic

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% material between the parents

child(1:site,parent_number1)=parent_chrom(1:site,parent_number1);

child(site+1:CHROM_LENGTH,parent_number1)=...
    parent_chrom(site+1:CHROM_LENGTH,parent_number2);

    else                % No crossover occurs

% Copy non-crossovered chromosomes into next generation
% In this case we simply take one parent and make them
% the child.

child(:,parent_number1)=parent_chrom(:,parent_number1);

    end
    end % End the "if ELITISM..." statement
end % End "for parent_number1=..." loop

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Mutate children.
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%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for pop_member= 1:POP_SIZE,

    if ELITISM ==1 & pop_member==bestmember % If elitism on, and
        % have the elite member
        child(:,pop_member)=child(:,pop_member); % Do not mutate
        % the elite member
    else

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for site = 1:CHROM_LENGTH,

    if MUTAT_PROB > rand    % If true then mutate
        rand_gene=rand*10;    % Creat a random gene

        % If it is the same as the one already there then
        % generate another random allele in the alphabet

        while child(site,pop_member) == rand_gene-rem(rand_gene,1),
            rand_gene=rand*10;
        end;

        % If it is not the same one, then mutate

        child(site,pop_member)=rand_gene-rem(rand_gene,1);

        % If takes a value of 10 (which it cannot
        % mutate to) then try again (this is a very low probability
        % event (most random number generators generate numbers
        % on the *closed* interval [0,1] and this is why this line
        % is included).

        if rand_gene == 10
            site=site-1;
        end
    end % End "if MUTAT_PROB > rand ..."
end % End for site... loop
end % End "if ELITISM..."
end % End for pop_member loop

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%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
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% Create the next generation (this completes the main part of the GA)
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    pop=child;          % Create next generation (children
                        % become parents)

    popcount=popcount+1; % Increment to the next generation

for pop_member = 1:POP_SIZE

    for current_trait = 1:NUM_TRAITS,

        trait(current_trait,pop_member,popcount)=0; % Initialize variables
        place_pointer=1;

        % Change each of the coded traits on the chromosomes into base-10 traits:
        % For each gene on the current_trait past the sign digit but before the
        % next trait find its real number amount and hence after finishing
        % the next loop trait(current_trait,pop_member,popcount) will be the base-10
        % number representing the trait

        for gene=TRAIT_START(current_trait)+1:TRAIT_START(current_trait+1)-1,
            place=DECIMAL(current_trait)-place_pointer;
            trait(current_trait,pop_member,popcount)=...
            trait(current_trait,pop_member,popcount)+...
            (pop(gene,pop_member))*10^place;
            place_pointer=place_pointer+1;
        end
    end
end

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end

% Determine sign of the traits and fix
% trait(current_trait,pop_member,popcount) so that it has the right sign:

if pop(TRAIT_START(current_trait),pop_member) < 5
    trait(current_trait,pop_member,popcount)=...
        -trait(current_trait,pop_member,popcount);
end

    end % Ends "for current_trait=..." loop

end % Ends "for pop_member=..." loop

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Terminate the program when the best fitness has not changed
% more than EPSILON over the last DELTA generations. It would also
% make sense to use avefitness rather than bestfitness in this test.
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if popcount > DELTA+1 & ...
    max(abs(bestfitness(popcount-DELTA:popcount-1)-...
        bestfitness(popcount-DELTA-1:popcount-2)))<=EPSILON
    break;
end

end % End "for pop_count=..." loop - the main loop.

```

## B. Related Publications

- J1. Ahmed Othman, Hossam A.Gabbar, Negar Honarmand, (2015) Performance Analysis of Grid Connected and Islanded Modes of AC/DC Microgrid for Residential Home Cluster. *Intelligent Control and Automation*, 6, 249-270.
- J2. Hossam A.Gabbar, Ahmed M.Othman, Aboelsood Zidan, Jason Runge, Owais Munteer, Manir U Isham, Negar Honarmand, Mayn Tomal, Design and Demonstration of integrated Micro Energy Grid (MEG), (submitted)
- J3. Hossam A.Gabbar, Negar Honarmand, Abdelazeem A. Abdelsalam, Resilient Microgrids for Continuous Production in Oil & Gas Facilities, *Journal of Advances in Robotics and Automation*, November 28, 2014, 3:3.
- J4. Hossam A.Gabbar, Ming Xiaoli, Abdelazeem Abdelsalam, Negar Honarmand, Key Performance Indicator Modeling for Micro Grid Design and Operation Evaluation, *International Journal of Distributed Energy Resources and Smart Grids*, Volume 10, Number 4, October – December 2014, ISSN 1614-7138, pp 219-242.