ARAB ACADEMY FOR SCIENCE, TECHNOLOGY AND MARITIME TRANSPORT

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Multi-objective Optimization Analysis on Isolated Microgrid Systems

by

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A Thesis
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In (Electrical and Control Engineering)

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(MAY) 2015

DECLARATION

I certify that all the material in this thesis that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

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ABSTRACT

Energy is and will continue to be the backbone of the global economy in the foreseeable future. However, due to fast rising energy prices, climate change and technology advance, reshaping the energy industry has become an international priority, introducing the concept of smart grid. The future smart grid is expected to be an interconnected network of small-scale and self-contained microgrids, in addition to the large-scale electric power systems. By utilizing different types of small scale generations, microgrids can supply electrical and heat loads in local areas in an economic and environment friendly way. As a result, several countries are encouraging small scale contributions to the power generation using Distributed Generation (DG) and Distributed Energy Resources (DER). A great deal of effort has been made to pursue the optimal design and operation of a microgrid system, raising the need of accurate optimization techniques in order to improve and manage its performance.

In this thesis an isolated microgrid is modeled to accommodate different types of DERs, such as diesel generator, Photovaltic (PV), Wind Turbine (WT) and fuel cell utilized through a hydrogen storage system consisting of an electrolyzer and a hydrogen tank. Two different optimization techniques were used to investigate the performance of the microgrid under different case studies; Non-dominated sorting genetic algorithm II and a novel flower pollination optimization algorithm. The optimization objectives are to minimize fuel costs and line losses in the system under equality and inequality constraints (such as bus voltages, generation lower and upper limits and hydrogen storage capacity), using three main parameters; active power, reactive power and slack bus selection. Different case studies were simulated using Matlab® and results of the different techniques were compared to measure the microgrid´s performance and the impact of the addition of hydrogen storage system.

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LIST OF ACRONYMS/ABBREVIATIONS

DER	Distributed Energy Resources
DG	Distributed Generation
FC	Fuel Cell
FPA	Flower Pollination Algorithm
GA	Genetic Algorithm
MO	Multi-Objective
MPC	Model Predictive Control
NSGA-II	Non-dominant Sorting Genetic Algorithm II
PV	Photo-Voltaic
WT	Wind Turbine

LIST OF SYMBOLS

C_F	Diesel generation cost.
P_G	Diesel generation output [kW].
a_i, b_i, c_i	Coefficients of fuel consumption.
P_{mppt}	Power at maximum power point.
V_{mpp}, I_{mpp}	Voltage and current at maximum power point.
P_{wind}	Power obtained from the wind turbine.
ρ	Air density in kg/m^3.
A	Swept area in m^2.
v	Wind velocity in *m/s.*
C_p	Betz constant.
x_i^{t+1}	The solution vector at t+1.
x_i^t	The solution vector in iteration t.
L	The step size.
g_*	Current best solution among all solutions.
γ	Scaling factor.
Γ	Standard gamma function.
x_j^t, x_k^t	Pollens from local flowers
m	Number of objectives.
w_i	Non-negative weights.
f_i	Fitness functions.
N_G	Number of generation units.

C_G	Fuel cost of generation.
N_{line}	Number of lines.
I_{line}	Line current.
R	Line resistance.
N_G, N_{bus}, N_{line}	Number of generation units, buses, and lines respectively.
P_g, Q_g	Generated active/reactive power at bus *i*.
P_D, Q_D	Active/reactive power demand at bus *i*.
P_l, Q_l	Active/reactive losses at line *i*.
V_{min}, V_{max}	Minimum/maximum limits of bus voltage.
V_{bus}	Voltage at bus *i*.
$P_{g_{min}}$, $P_{g_{max}}$	Active power operation limits of generator *i*.
$Q_{g_{min}}$, $Q_{g_{max}}$	Reactive power operation limits of generator *i*.
P_g, Q_g	Active/reactive generated power at bus *i*.
$S_{PV_{min}}$, $S_{PV_{max}}$	Min/max apparent power obtained from PVs at time *t*.
$S_{wind_{min}}$, $S_{wind_{max}}$	Min/max apparent power obtained from WTs at time *t*.
$S_{FC_{min}}$, $S_{FC_{max}}$	Min/max apparent power obtained from Fuel cell at time *t*.
S_{PV}, S_{wind}, S_{FC}	Apparent power supplied by PVs, WTs, and fuel cell.
$P_{elyz_{min}}$, $P_{elyz_{max}}$	Min/max active power that can be supplied to the electrolyzer.
P_{elyz}	Active Power supplied to the electrolyzer to generate hydrogen.
$H_{tank_{min}}$, $H_{tank_{max}}$	Min/max capacity of the Hydrogen storage tank (kg).
H_{tank}	Current capacity of Hydrogen tank.
E_{H2}	Energy from stored Hydrogen.

η_{FC}	Efficiency of fuel cell.
E_{elyz}	Energy consumed by electrolyzer.
η_{elyz}	Efficiency of electrolyzer.
E_{night}	Energy supplied by storage device during night.
P_{peak}	Peak demand at a certain hour at night.
P_{base}	Base demand.
$P_{storage}$	Power required by the storage device.
PSH	Peak sun hours.
SF	Safety factor.

Chapter One

1 INTRODUCTION

1.1 MOTIVATION

In the last decades, the world has been facing great challenges, due to the depletion of energy resources. Although it survived long years on the abundant availability of fossil fuels, it has recently reached the time of “energy crisis”, where the reserves will not last for long and expected to decline significantly. The main reasons behind energy crisis are global warming, energy sustainability, energy security, and population growth. The use of fossil fuels led to the phenomenon of global warming. In which, the emissions from the combustion of fuels caused the greenhouse effect, which participated in raising the earth’s temperature. The fear of depletion of earth’s energy resources (when oil and gas reserves are used up) raised a question mark on what will provide us sustainable and everlasting energy. Wars have been waged in the name of energy security, while the reserves of energy resources are concentrated in parts of the world; other parts have the highest energy demands. The massive growth in earth’s population led to a proportional growth in energy requirement. All these problems, among others, promoted to the introduction of renewable energy, energy storage, energy management and various modern technologies that all built a concept known as the “smart grid”. Figures 1.1, 1.2 show a trend in the European Union towards the integration of renewable energy resources in electrical grids, the trend is expected to extend beyond this decade [1].

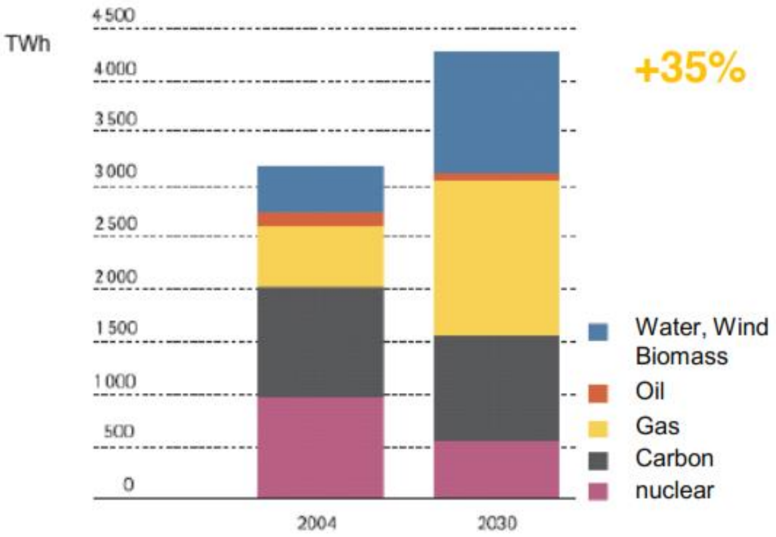
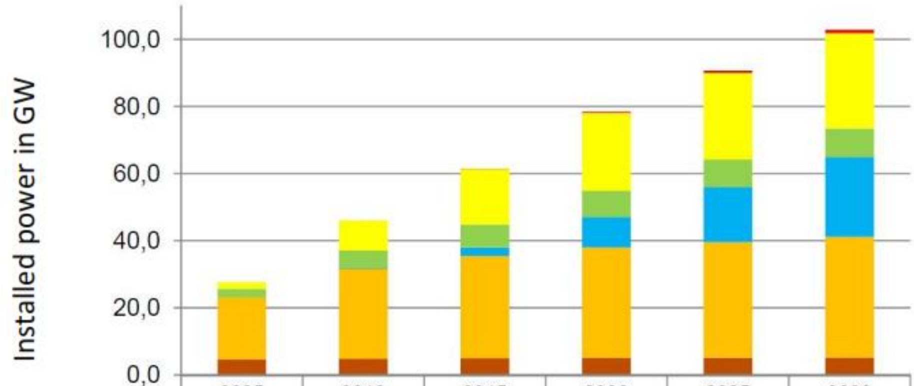


Figure 1.1-Generation Growth in EU



	2005	2010	2015	2020	2025	2030
Geothermal energy	0,0	0,0	0,1	0,3	0,65	1,0
Photovoltaic	1,9	8,9	16,6	23,2	25,8	28,4
Biomass	2,6	5,3	6,8	7,9	8,2	8,5
Wind offshore	0,0	0,2	2,5	9,0	16,4	23,8
Wind onshore	18,4	26,8	30,5	32,9	34,4	35,9
Hydro power ((w/o) pump)	4,7	4,8	5,0	5,1	5,15	5,2
SUM	**27,6**	**46,0**	**61,5**	**78,4**	**90,6**	**102,8**

Figure 1.2-Energy Development in Germany

Moreover, a decrease in the installed capacity of coal and nuclear power plants is also planned in most countries around the world. However, the planned increase in renewable resources does not secure enough energy to cover the growing demand. Thus, a conventional generation backup is vital to the operation of the modern electrical grid. Figure 1.3 shows a comparison between different energy resources according to secured power. The figure shows that fossil fuels have a power security as high as 93% compared to 7% in case of renewables. The integration of conventional and non-conventional energy resources and the technical requirements of such integration creates the modern smart grid.

	Availability	Secured power
Hard coal	91.2%	86.0%
Brown coal	95.3%	92.0%
Nuclear power	95.5%	93.0%
Combined gas and oil	91.4%	86.0%
Domestic gas	56.1%	42.0%
Running-water power station	40.0%	40.0%
Biomass	90.0%	88.0%
Wind power	95.0%	7.0%
Photovoltaic	N/A	1.0%
Geothermal energy	90.0%	90.0%
Pump storage	97.0%	90.0%
Combined heat and power	97.0%	86.0%
Mirco-combined heat and power	97.0%	78.0%

Figure 1.3-Secured Power of Energy Resources

A smart grid is composed of smaller units, microgrids, each is an independent unit capable of autonomously operating and managed locally and treated as a single entity. Research in this field concluded that new techniques and theories are needed to control such a grid. This is due to high penetration of renewable energy resources, smaller generation capacity provided by local distributed generation, coordination between different energy providers, deregulation of the electricity market and the emerging energy open market. One of the main issues addressed in the field of microgrids is the optimization of its operation, in order to preserve the energy resources and supply the energy requirements of the population.

1.2 MICROGRID DEPLOYMENT STATUS

More than 160 microgrid projects are currently active around the world with total capacity of 1.2GW [2]. 69% of these are in North America. Asia Pacific and Europe share 19%, 12% of the microgrid projects.

Some leading examples are:

- CERTS microgrid in Ohio, USA established in 1999. Focused on the dynamics of switching sensitive loads and pwer trading with the utility.

- BC Hydro and Hydro Quebec microgrid in Canada focused on the research of protection and control in cases of intentional and un-intentional islanding. The purpose is to achieve higher supply reliability.

- Microgrids Project was undertaken by a consortium led by National Technical University of Athens in Kythnos, Greece. Focused on Plug and play and universalization feature of a microgrid central controller.

- More Microgrids Project also undertaken by NTUA and implemented in Bronsbergen Holiday Park, Netherlands. The project focuses on lifetime optimization, energy management, and reliability of storage systems in islanded microgrids.

- Institut für Solare Energieversorgungstechnik implemented the DeMoTec microgrid in Germany to test monitoring and SCADA systems for microgrids with DERs.

Despite the great advancements in microgrids and the various research projects, progress in the field is expected to take faster pace as more countries join the race to reach practical microgrids.

1.3 OUTLINE

This thesis is outlined as the following:

Chapter 2: studies the concepts of microgrids and distributed generation, highlighting their benefits and drawbacks.

Chapter 3: is a literature review over microgrid optimization, emphasizing on previous work related to optimization objectives, techniques and obtained results.

Chapter 4: reviews different optimization techniques, proposing the most appropriate technique to achieve the microgrid system´s optimization objectives. Moreover, a novel technique is proposed and explained.

Chapter 5: the model is presented, along with the simulation and results of different case studies.

Chapter 6: presents conclusions, discussion and future work.

Chapter Two

2 MICROGRIDS & DISTRIBUTED GENERATION

2.1 INTRODUCTION

For a very long time, and all over the world, conventional energy resources were used to generate electrical power which has become the most important form of energy in the modern world. These conventional methods of generation, however, are facing many problems that threaten the future of energy. These problems are the reason behind what is known nowadays as the energy crisis. Some of these problems are the depletion of fossil fuels (Oil, natural gas, coal, etc.), the increased prices of energy due to the rise in prices of fossil fuels, the political tensions and sometimes war over energy resources, environmental pollution and the greenhouse effect, and the low efficiency of conventional generation methods.

These problems led to many trends and evolutions in the methods of electrical power generation, transmission and distribution. Renewable energy resources became very important and attracted research efforts. Moreover, the generation of electricity locally uses micro-sources based on renewable energy resources and micro-turbines, fuel cells or biogas and integrating them with the distribution network at low voltages. This type of generation is called distributed generation (DG) which is a type of distributed energy resources (DERs). These are small, locally controlled generation plants which are integrated into distribution networks. This may lead to many benefits such as reducing environmental impact of energy generation, co-generation of heat and power, achieving modularity and proximity of generation to consumption, which reduces transmission losses and costs dramatically and achieving better power quality and reliability [3].

Moreover, the integration of DG into utility networks, whether those DGs are using renewable energy resources or other types of generation, have recently developed the main aspect of microgrids; emerging active distribution networks.

2.2 MICROGRIDS

A microgrid - among many definitions- is a small scale supply network for loads of a small community and is essentially an active distribution network as it is composed of DERs at distribution level, these resources are usually non-conventional.

A microgrid requires the use of power electronics and modern controllers to maintain stability and power quality. Thus, it is seen by the upstream medium voltage network as a single entity (load). This makes it a suitable solution for remote areas and areas affected by any kind of energy disruptions. Uninterruptible power is possible and feeder losses are dramatically decreased. By utilizing renewable energy resources environmental impact of energy production is reduced. Figure 2.1 shows different scales of microgrids [4].

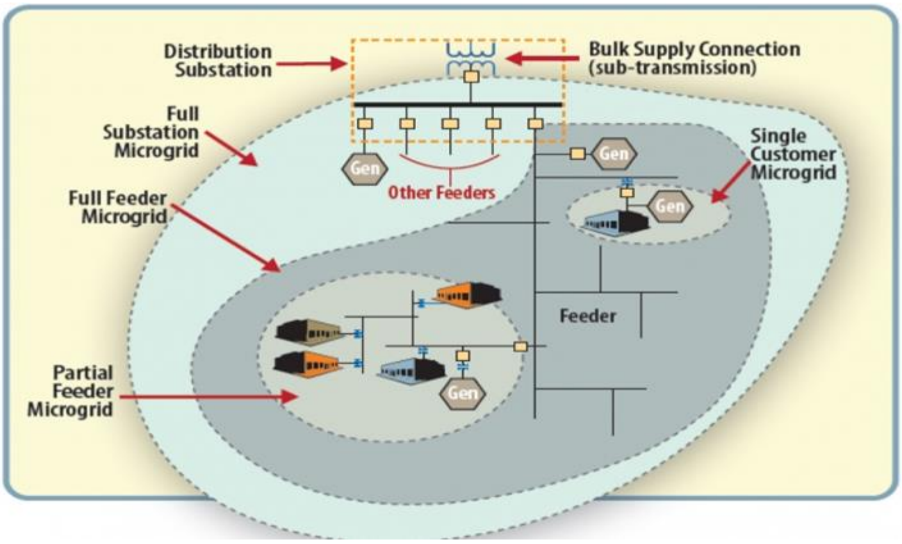


Figure 2.1- A Typical Microgrid

From operational point of view, a microgrid can operate in two modes; Grid-connected or Island.

2.2.1 Grid-connected mode:

The microgrid is connected to the medium voltage grid at the point of common coupling (PCC), and imports/exports energy depending on local loads and local generation status. The microgrid is seen by the main grid as a single controlled entity. Figure 2.2 shows a typical grid-connected microgrid.

2.2.2 Islanded mode:

In this mode, the microgrid is required to supply priority loads, or all loads according to its purpose. Local DERs are used and controlled by local controllers, central controllers and co-ordination modules. Figure 2.3 shows a typical isolated microgrid

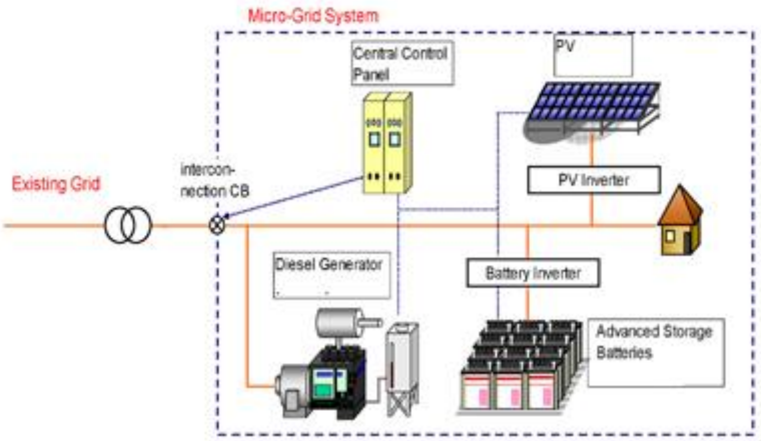


Figure 2.2-Grid Connected Microgrid

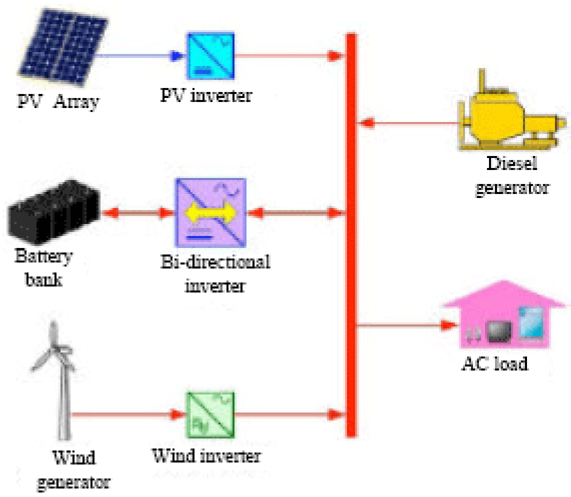


Figure 2.3- Isolated Microgrid

2.3 MICROGRID BENEFITS AND DRAWBACKS:

Microgrids have proved to be very promising, mainly due to its environmental benefits, as the use or renewable energy resources which are based on natural, non-polluting forms of energy will help dramatically decrease greenhouse emissions and toxic pollutants from fossil fuels. The proximity of generation to consumers will increase the awareness of energy issues and drive the whole community in the direction of better energy utilization. Moreover, microgrids offer technical benefits such as the physical proximity of generation to loads will reduce transmission losses and costs, voltage profiles will improve as better reactive power support will be available. Large scale outages will have smaller impact as each microgrid will be able to operate autonomously in islanded mode. From an economic point of view, costs of transmission of energy are almost eliminated; costs of large scale central generation plants are also reduced as the dependence on them decreases. Some networks will not require any expansion as microgrid resources are modular and able to expand to cover for the local load growth. The emerging markets of renewable resources and microsources will provide new employment and research opportunities. The availability of different resources in different areas will achieve variety and competitiveness in the energy market and end the long time monopoly of oil companies and large scale generation companies. The newly developed energy management techniques will reduce energy customer prices.

However, microgrids also have several drawbacks, one of which is its high initial investments, due to the high prices of microgrid components such as wind turbines, PVs, fuel cells and controllers required for the operation of a microgrid. This is partially solved by subsidies and loans, which are incentives to drive the market towards investing in the transformation to microgrids, which is taking place gradually. Technical difficulties due to the lack of technical experience in microgrids require extensive research on the management, control and protection of microgrids. In addition, communication infrastructure is not available to facilitate the use of local controllers and coordination between protection and control devices. In most countries there are no standards for operation, safety and protection of microgrids. Laws to regulate the use of green energy and local generations are available in only a few countries around the world. The problem of monopoly of private sector generation companies is a main concern when considering an open energy market. Islanded grids will be supplied by local generation which, if monopolized, will be provided with very high prices.

2.4 OPERATIONAL CONSIDERATIONS FOR ISLANDED MICROGRIDS

In islanded microgrids, certain aspects must be considered in the operation of the microgrid. For instance, generation and storage must be planned according to load demand and long term energy balance. However, short term scheduling must be done in order to provide higher reliability and energy quality. Economic operation must be achieved at all times through energy management and if required; demand side management. As well as issues such as reactive power compensation and power electronic interfacing between different components must be considered. Optimization of generation and optimal power flow is vital in case of islanded microgrids, and this is the scope of this thesis.

2.5 DISTRIBUTED ENERGY RESOURCES

Prior to the study of microgrid as a whole, each component of the microgrid is detailed. In this section, each DER used is studied and modeled to be later integrated into a microgrid.

2.5.1 Diesel Generators

A diesel generator consists of a diesel engine coupled with a synchronous generator and uses the direct combustion of diesel as a source of kinetic energy which is then transformed into electrical energy. A group of usually 3 generators are used in islanded systems to achieve redundancy, which means that 2 of the generators can supply the required load without shortage. Generators work in parallel by synchronizing phase voltages, phase shifts, frequency and phase sequence.

Diesel generators can be used as standby power supplies at times of failures of the main grid, Support to main grid in times of high stress where diesel generators can start up and synchronize in less than two minutes and without any effect of the main grid, or as separate supplies in islanded systems where a group of generators supply islanded loads in locations where utility grid is not available or not reliable.

The modularity of diesel generators makes them a suitable solution for small-scale microgrids, more generators can be added when loads grow. Moreover, installation of diesel generators is easy as it comes usually in an enclosed set with all required control, protection and fuel systems. Purchasing and installation costs are very low but the typical fuel is ether diesel or bio-diesel which makes running costs higher compared to renewable resources.

The Fuel cost function of a diesel generator can be expressed as in [5]:

$$C_F = a_i + b_i P_G + c_i P_G^2 \qquad (2.1)$$

Where,

C_F=Diesel generation cost.

P_G=Diesel generation output [kW].

a_i, b_i, c_i=coefficients of fuel consumption.

2.5.2 Photo-Voltaic cells

Photovoltaic (PV) technology uses semi-conductor wafers to convert sunlight directly into electricity. This is done by placing the wafers in a large p-n junction diode configuration. Numerous cells form a PV module. These are static sources of electricity that does not require complex installation, does not produce vibrations or noise.

The cost of energy from PVs is still higher than utility prices. This limits their use to remote areas. However, the decline in semi-conductor prices due to the advancements in the manufacturing process will eventually make PVs cheaper and with higher ratings.

PVs attract a great deal of investments and research as they have the following major advantages [6]:

- Short lead time to design, install, and start up a new plant.

- Highly modular, hence, the plant economy is not a strong function of size.
- Power output matches very well with peak load demands.
- Static structure, no moving parts, hence, no noise.
- High power capability per unit of weight.
- Longer life with little maintenance because of no moving parts.
- Highly mobile and portable because of light weight.

PV cells have many technologies which vary in efficiency and cost. A mono-crystalline cell is a cell cut from single silicon crystal, these cells are then arranged into a module. These have the highest efficiencies but the manufacturing process is very slow and costly. Poly-crystalline cells are easier and cheaper to manufacture but have lower efficiencies. Thin film cells are the cheapest and easiest to manufacture, using composites such as Galium Arsenide (GaAs). The material is formed into thin film rolls that are flexible compared to crystalline cells. This technology uses much less material per square-meter of cell [6], hence, is less expensive per watt of power generated

<u>Power from Photovoltaics</u>

It is the total yearly energy capture potential of the site which determines the economic viability of installing a PV power plant [6]. Solar energy is distributed in different amounts to different geographical locations. Egypt is very rich in solar energy as can be seen in Figure 2.4, where the white areas receive the highest yearly solar energy.

When such solar irradiation falls on the surface of a PV, The energy from photons is transferred to semi-conductor electrons which circulate under the effect of the junction electric field in the external circuit, as shown in Figure 2.5.

A solar cell is the smallest unit in a PV system, such cells are gathered to form a module, modules are then connected in series as a string, and these are connected in parallel to form a PV array which is the main unit of generation in power systems. The PV cell can be represented by an equivalent circuit as shown in Figure 2.6.

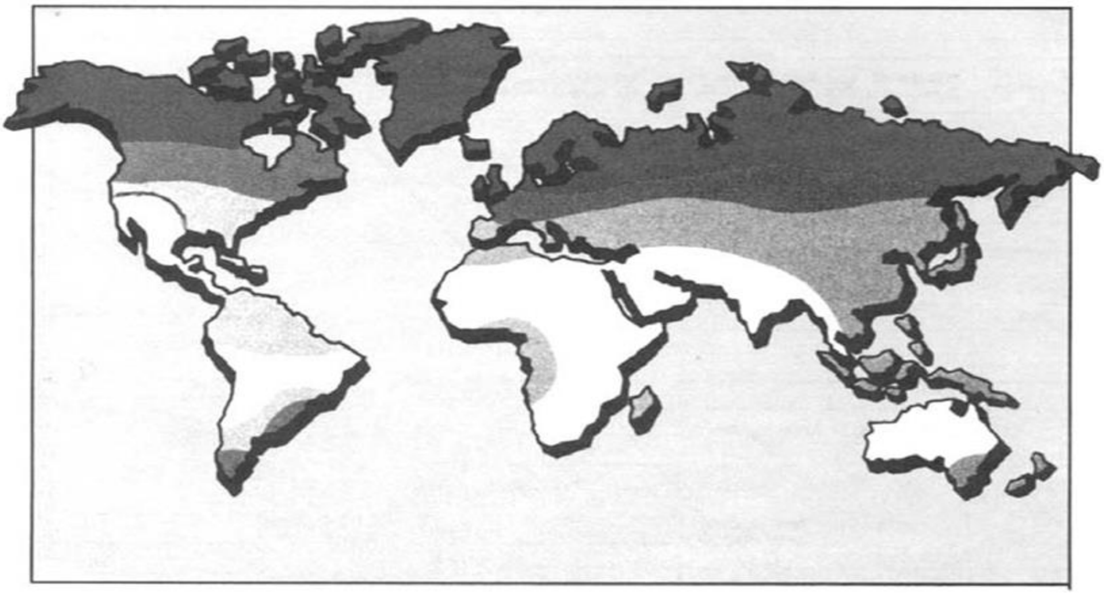


Figure 2.4- Global Solar Irradiation Distribution

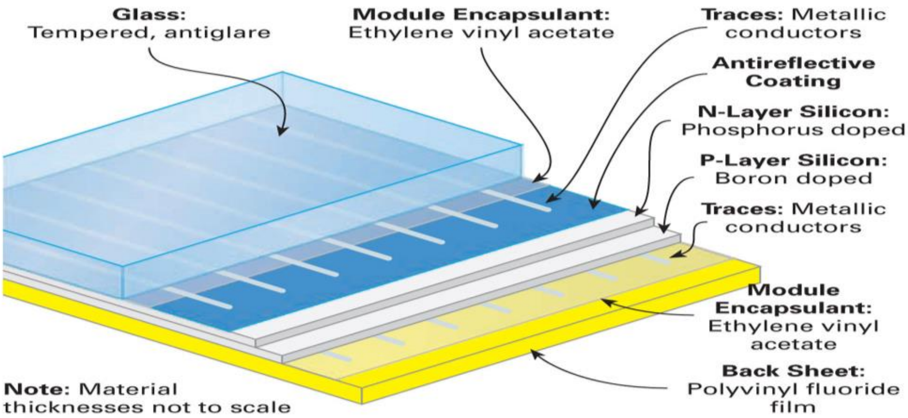


Figure 2.5- Construction of a PV Cell

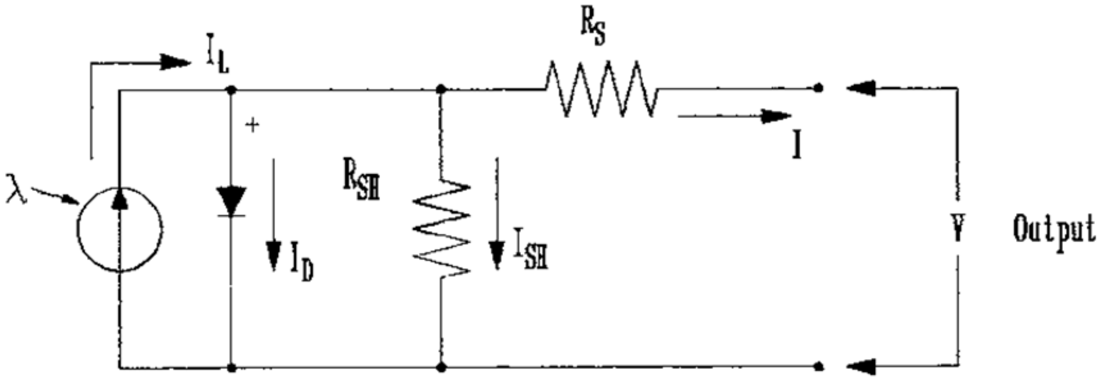


Figure 2.6- PV Cell Model

The model in [7], based on this equivalent circuit, provides the maximum power output from a PV module at any given irradiation and temperature. Such that:

$$P_{mppt} = V_{mpp} * I_{mpp} \tag{2.2}$$

Where,

P_{mppt}=Power at maximum power point.

V_{mpp}, I_{mpp} =Voltage and current at maximum power point.

By studying the modelled PV system it is observed that two curves can be produced to identify the operation of PV systems. The P-V and V-I characteristics of a PV cell are shown in Figure 2.7 and the maximum power point is shown.

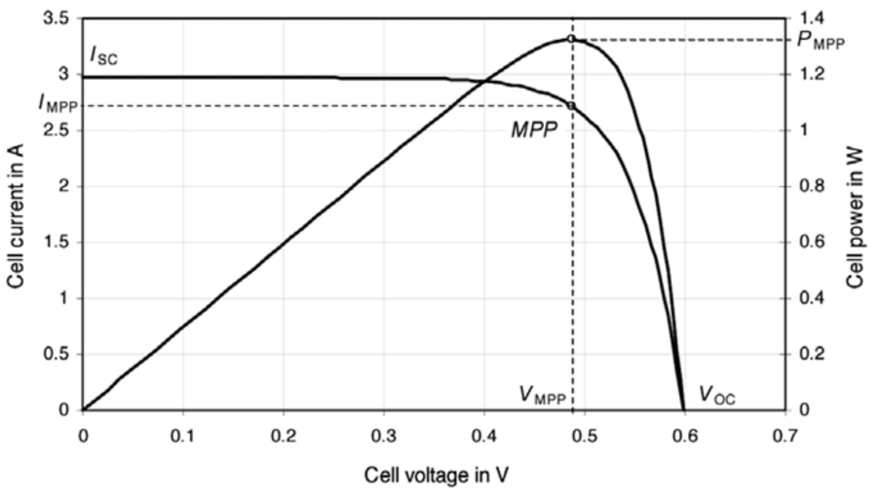


Figure 2.7-Output of a PV cell

It is also observed that the variation in both temperature and irradiation affects greatly the production of a PV cell. Such that a decrease in temperature would increase the maximum power at constant solar radiation and the open circuit voltage is inversely proportional to the variations in temperature, as shown in Figures 2.8, 2.9 [6].

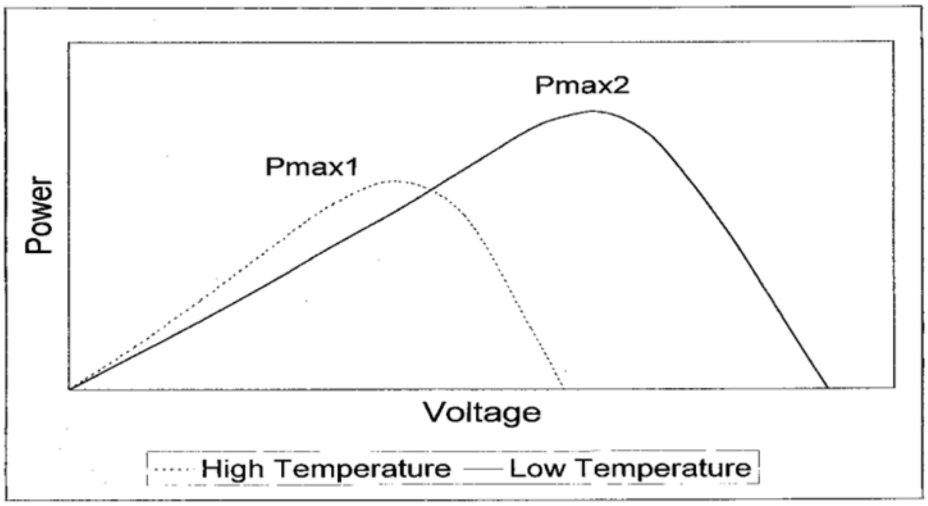


Figure 2.8- Effect of Temperature on PV Power Output

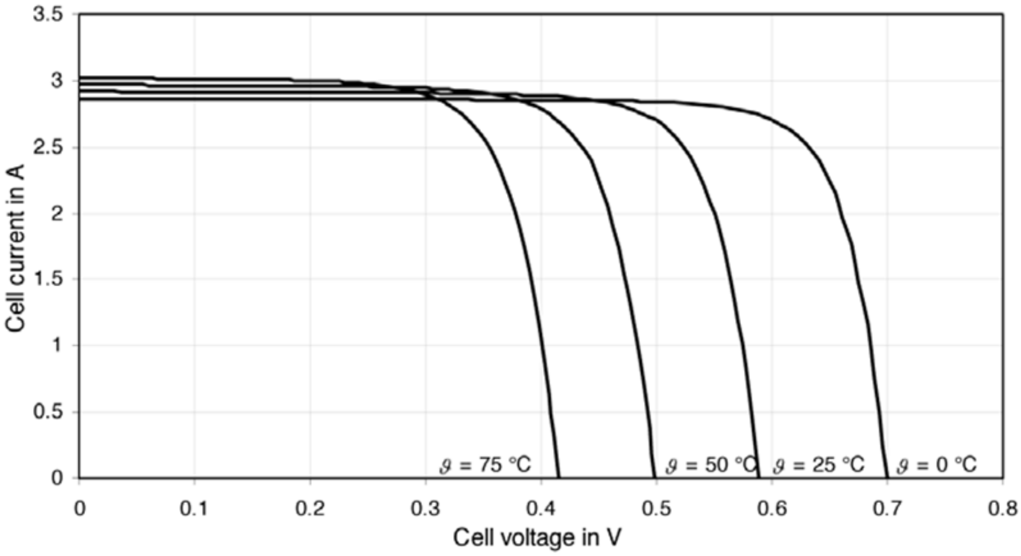


Figure 2.9- Effect of Temperature on PV Cell Voltage

On the other hand, the current generated by a PV cell is directly proportional to the solar irradiation intensity. Higher solar irradiation will result in higher power generated by the cell. This can be seen in Figure 2.10 where power output from a PV cell is compared for different solar irradiation.

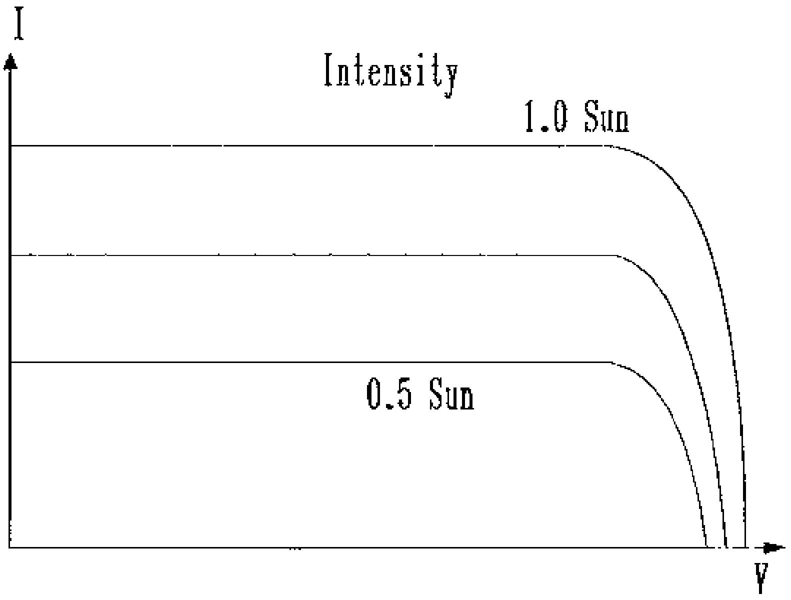


Figure 2.10-Effect of Irradiation on PV Cell Output

The nature of PV cells impose that the generation is done in DC waveform. Since most systems and loads use AC, a power electronic interface (inverter) must be used to transform DC generated from PV into AC for the microgrid, this inverter also guarantees synchronization with the grid and some basic types of protection.

2.5.3 Wind Power

Wind power has been used by humans for a very long time. Sail ships and windmills are examples of many applications for wind power throughout history. In 1890, the first electricity producing wind turbine was installed in USA [6]. Nowadays, wind Turbines (WT) are very advanced due to advancements in power electronics, high strength fibres, variable speed generators, and accumulated field experience.

Since wind turbines capture wind energy using blades that are coupled to the rotor of an electrical generator, sites with higher steady wind speeds are preferred. Wind turbines are divided into vertical axis and horizontal axis turbines as shown in Figure 2.11 [6].

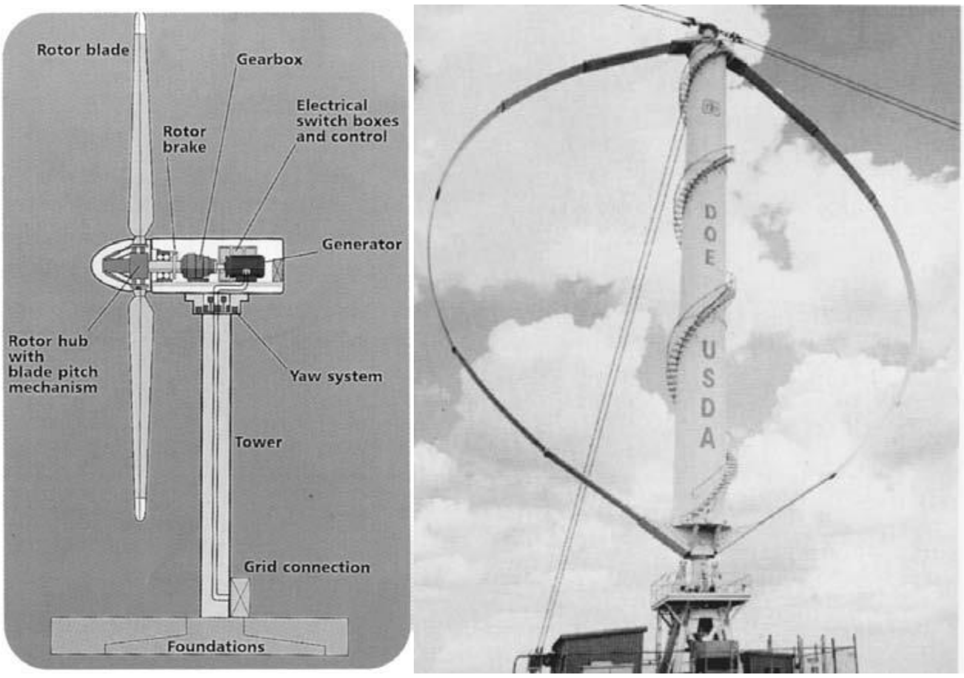


Figure 2.11- Horizontal and Vertical Wind Turbines

Horizontal axis WTs are preferred due to efficiency advantages. Figure 2.12 shows the distribution of average wind speeds across Egypt. It is observed that areas surrounding the Gulf of Suez have the highest wind speeds (8-10) m/s [8].

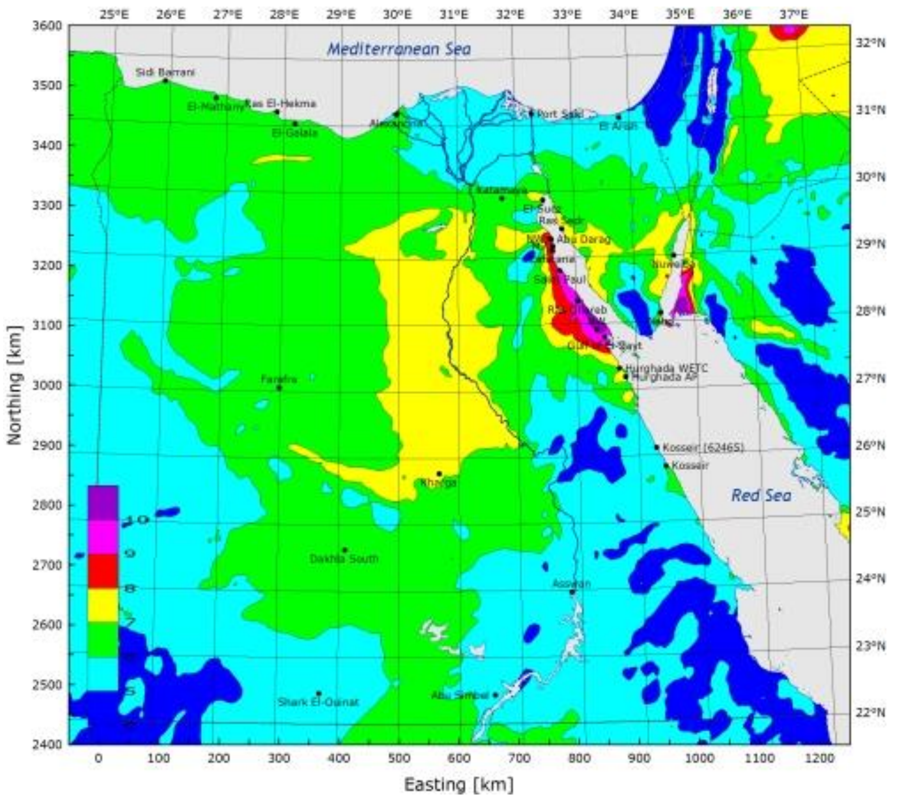


Figure 2.12- Wind Speed Map of Egypt

Fixed Speed Wind Power Systems:

These systems are usually used for small WTs as they are simple and have a low cost. Such systems either have no speed control at all or stall control. Which means that the turbine generates different power at different wind speeds as speed is only controlled by the wind. The WT reaches its maximum efficiency "tip speed ratio" at only one speed thus called "fixed speed".

Variable Speed Wind Power Systems:

Yaw, tilt and pitch controls are used to control the turbine in this case. The objective is to achieve maximum tip speed ratio, thus achieve maximum efficiency. The control requirements in this case are the cut in speed, the maximum efficiency region (constant CP), the constant power output region and the cut out speed. The output of a wind turbine will vary with wind speeds as given in Figure 2.13. Table 2.1 is a comparison between fixed speed and variable speed operation [6].

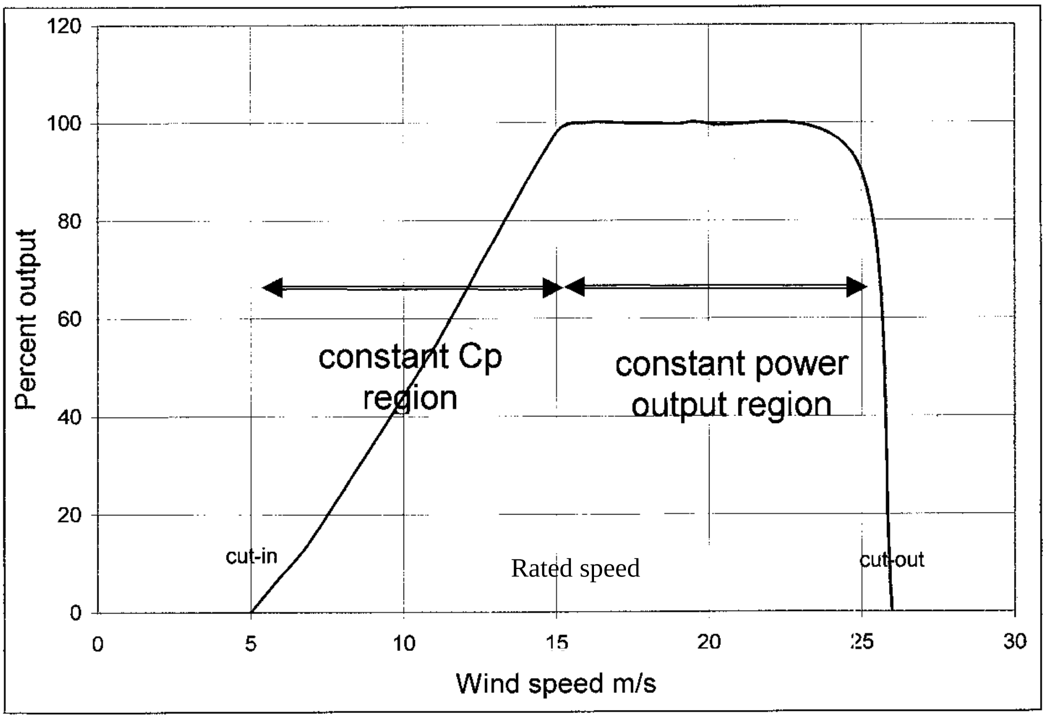


Figure 2.13-Output of a Typical Wind Turbine

Table 2.1- Comparison Between Wind Turbine Systems

Fixed-Speed System	Variable-Speed System
Simple and inexpensive electrical system	Higher rotor efficiency, hence, higher energy capture per year
Fewer parts, hence higher reliability	Low transient torque
Lower probability of excitation of mechanical resonance of the structure	Fewer gear steps, hence inexpensive gear box
No frequency conversion, hence, no current harmonics present in the electrical system	Mechanical damping system not needed, the electrical system could provide damping if required
Lower capital cost	No synchronization problems
	Stiff electrical controls can reduce system voltage sags

The power extracted from a wind turbine can be expressed by [9]:

$$P_{wind} = \frac{1}{2}\rho \times A \times v^3 \times C_p \qquad (2.3)$$

Where,

P_{wind}= Power obtained from the wind turbine.

ρ= Air density in kg/m^3.

A= Swept area in m^2.

v= Wind velocity in *m/s.*

C_p= Betz constant.

That is only when wind speed is between the cut in speed and the rated speed of the turbine. If wind speed is higher than rated but lower than cut out speed, the output remains constant at the rated power as observed from the characteristics in Figure 2.13. If wind speed are lower than cut in speed or higher than cut out speeds the turbine is either pitched out of wind or stalled to stop the blades.

2.6 ENERGY STORAGE

To ensure reliable and continuous operation to loads in a microgrid, an energy management system needs to control the operation of energy storage devices. These devices take advantage of the uncertainty of renewable devices. PVs and WTs produce intermittent power and solar power is only available during day, while loads are not following the same pattern. Thus, energy storage devices are used to capture the extra energy available and store them until they are required by loads.

A technique used recently in energy storage is the Hydrogen energy storage system. In such a system, Hydrogen is produced using electricity by the process of electrolysis, then stored and used to generate electricity again by Fuel cells. The overall system efficiency has been limited to 30% for experimental conditions and less in realistic conditions. Thus, other storage systems such as batteries are preferred over Hydrogen storage systems. However, Hydrogen storage provides higher storage capacity, and with latest developments it is expected that the current status may differ in the near future due to the decrease in the costs of fuel cells and electrolyzers [10] and efficiencies are expected to rise to 50%.

Currently, several companies offer integrated hydrogen solutions for small isolated sites. Some demonstration projects were made in Europe and USA. Three large scale systems exist in USA and three others in the UK.

2.6.1 Fuel cell

A fuel cell converts the chemical energy stored in a fuel (Hydrogen) directly into electrical energy [3]. It consists of an anode, cathode and an electrolyte. It is similar to battery except that the components of reaction, in this case Hydrogen and Oxygen are not stored in the cell, rather fed continuously to the cell. Basic construction of a fuel cell is shown in Figure 2.14.

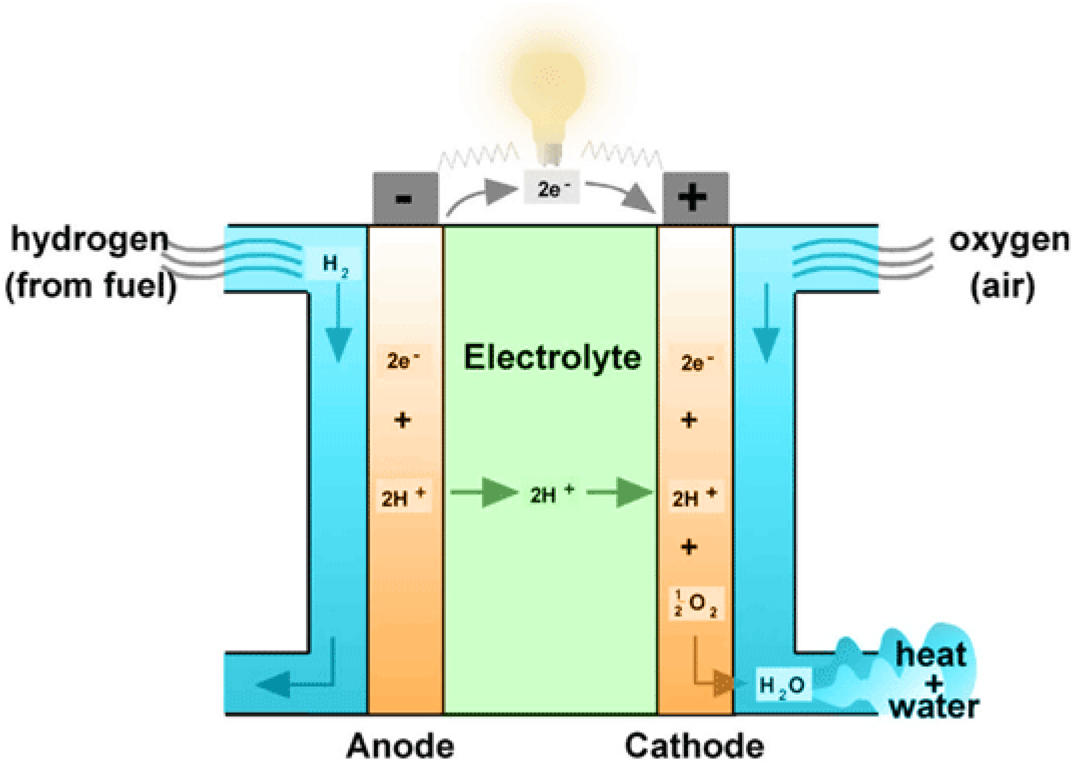


Figure 2.14- Construction of Fuel Cell

Fuel is fed into the anode and oxidant is fed into cathode and they are separated by electrodes and electrolyte between them. Oxidation takes place and produces electricity, heat and water. Fuel cells are environment friendly, free of noise, vibration, and require very low maintenance. They use a variety of fuels using reformers that can produce Hydrogen from natural gas, propane, diesel and methane. A stack of fuel cells is needed to produce higher voltages. The following equation shows the chemical reaction inside a FC.

$$2H_2 + O_2 \rightarrow 2H_2O + \text{elec.energy} + \text{heat} \tag{2.4}$$

The open circuit voltage of a fuel cell from the chemical reaction is expected to be 1.23v. However, internal losses due to resistive elements of the fuel cell (such as Activation losses, resistive losses and current density losses) are accompanied by voltage drop as depicted in Figure 2.15. These losses contribute to this voltage drop resulting in an output of nearly 1v of a single FC. Thus, a stack of series and parallel FCs are arranged to provide voltage and current suitable for the required application.

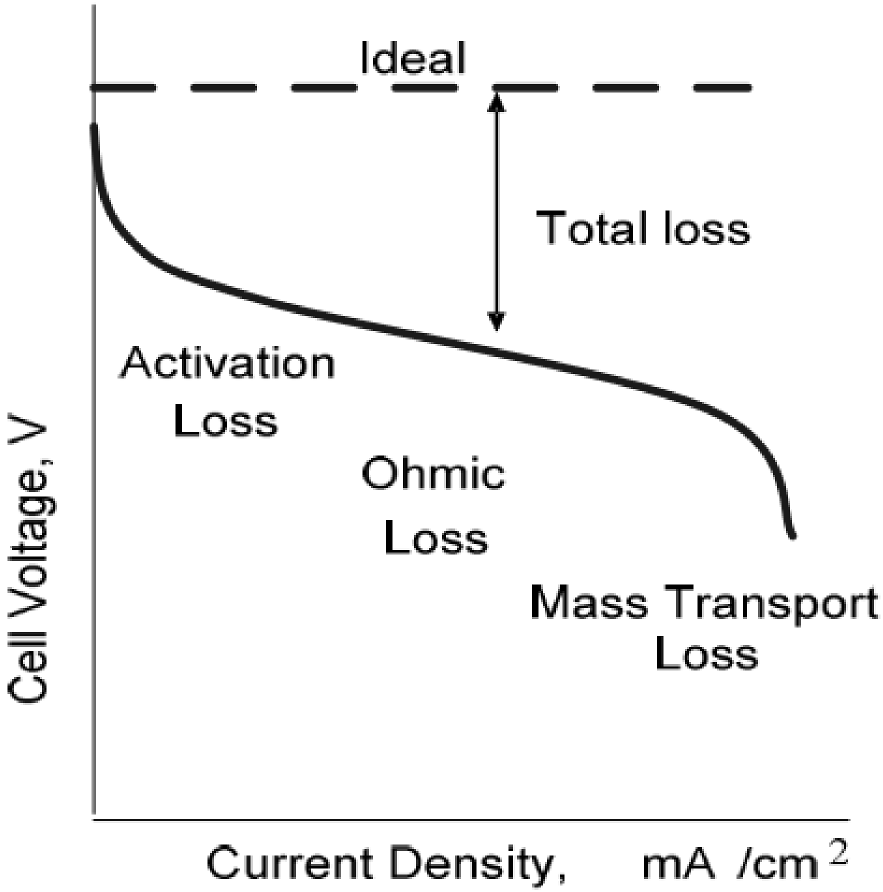


Figure 2.15-voltage output of a Fuel Cell

There are many types of fuel cells such as:

- Proton exchange membrane FC (PEMFC).
- Phosphoric acid FC.
- Molten carbonate FC.
- Solid Oxide FC.

The difference between each is the type of electrolyte and the operating temperature. Of these types, PEMFC has the lowest operating temperature at nearly 80°C which allows it to reach a steady state very fast (no need to warm up). Moreover, a PEMFC operates at a very wide range of reactants pressure, which makes it the most flexible and suitable for power applications.

Currently, PEMFCs are being developed for capacities below 500kW and used in residential applications and in electric vehicles.

2.6.2 Electrolyzer

An electrolyzer is a device where the reverse reaction of what occurs in a FC is used to produce Hydrogen from water by the process of electrolysis. Proton Exchange Membrane (PEM) electrolyzers are very flexible and can reach theoretical efficiencies of 60%. However, high temperature electrolyzers, currently developed in large scales, can provide hydrogen with efficienciesup to 90%. Figure 2.16 shows a simple process of electrolysis where the electrolyte solution (water) is decomposed into Hydrogen and Oxygen.

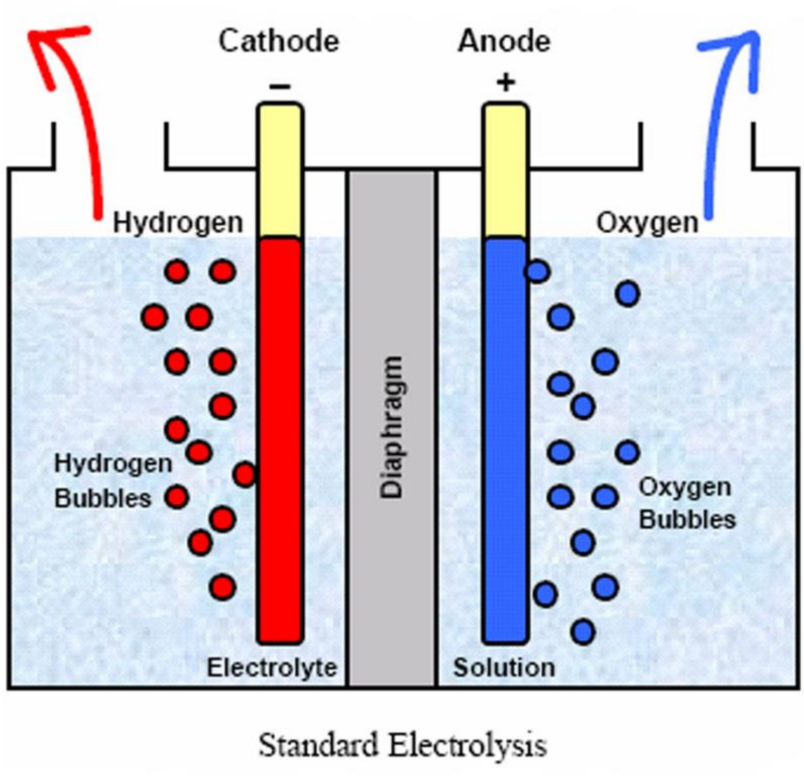


Figure 2.16-Electrolyzer

2.6.3 Hydrogen storage:

Small amounts of Hydrogen (up to a few MWh) can be stored in pressurized vessels or liquefied under high pressure. Large amounts can be stored in underground salt caverns. This allows the use of hydrogen for both short term storage and long term storage.

Hydrogen storage has very high efficiency compared to pumped hydroelectric storage (large scale) or batteries (small scale). However, the poor efficiencies of electrolyzers and fuel cells reduce the overall system efficiency to experimental values of 30%. Further research and developments in the manufacturing of FCs and electrolyzers make Hydrogen storage a promising solution to replace other storage techniques.

Chapter Three

3 LITERATURE REVIEW

3.1 INTRODUCTION

The newly developed concepts of microgrids, and microgrid optimization have attracted research efforts across the globe during the last decade. Literature survey shows that such concepts are promising and could prove useful to the current policy of deregulating the energy markets and applying latest technologies of smart grids and clean energy. Some deficiencies and technical difficulties are still present and require further research.

3.2 MICROGRIDS AND MULTI-OBJECTIVE OPTIMIZATION

As the focus on energy problems and latest developments in the concepts of smart grid and renewable energy, new concepts have emerged such as microgrids and microgrid optimization. A microgrid has different definitions proposed in different works [11, 12]. for instance it can be defined as a portion of the power system that has 1 or more DG units, expected to operate after islanding due to disturbances or pre-planned switching [11]. The effect of both pre-planned islanding and islanding due to disturbances is studied and it is concluded that an islanded microgrid with DGs interfaced through power electronic converters can increase power quality and reduce switching transients after both pre-planned and unintentional switching events. In [12], On the other hand the authors define a microgrid as a controllable component of Smart grid is a small scale low voltage supply network designed to supply electrical and heat load for a small community, a commercial area or an industrial site. The authors mentioned some of the trends and challenges in operating and optimizing the performance of microgrids. They conclude that due to the technical difficulties facing the control and operation of microgrids, Artificial Intelligence (AI) techniques are best used for optimization and power management of the microgrid. One of the areas of research in the field of microgrids is the optimization of operation of islanded microgrids, as in [13-18]. Numerous optimization algorithms can be applied to islanded microgrids; some of these have been tested by previous work. Other algorithms have not been tested thoroughly and need further research. In [13] Single objective economic optimization of a microgrid that consists of a wind turbine, micro turbine, diesel generator, PV array and a fuel cell is studied. Results are then compared with Multi-objective economic/environmental optimization. The paper stressed on off-line optimization and represents an inaccurate prediction. In [14] optimization of the energy cost was carried out while taking into consideration the maximization of lifetime of batteries using Multi-Objective optimization (MO). Model Predictive control (MPC) is used and results are compared to results obtained from static algorithms which does not consider future condition and changes to the system due to the control actions taken. The use of MPC proved better optimization and improvement in the microgrid’s performance. In [15] a generalized model for Microgrid (MG) energy management is developed and MO optimization is considered to optimize cost/environmental Impact of the microgrid depending on battery charge/discharge policy and DER forecasting and load demand. ANNs are used for load forecasting of the system while fuzzy logic control is used to schedule battery charging/discharging in order to maintain battery life and lower its maintenance costs. A hierarchical control system is proposed in [16] where the energy cost and CO2 emissions are minimized using self-adaptive low high evolution algorithm. Local, distributed and hierarchical control are compared. It is concluded that usage of hierarchical control is capable of finding better optimization results. Improved Fast Evolutionary Algorithm is adapted in [17] to minimize costs, emissions and maintenance of a microgrid with renewable energy and fuel cell the technique is compared to previously used methods (sequential quadratic programming and mesh adaptive direct search). The adopted method proved better convergence at reasonably good computation time and simple implementation. In [18] latest technologies in the field of microgrids are reviewed, advantages and disadvantages of microgrids are highlighted from both the utility and consumer point of view The latest control methods of microgrids are studied and compared.

3.3 SYSTEM MODELLING

A main step to study microgrid optimization is modelling the different components of the system in order to be able to identify the optimization parameters and objectives. Different models are adopted throughout previous works. Various models are available for each element of the microgrid depending on the factors taken into account and the purpose of the model [7, 19-22]. In [19], for example, power production of distributed generation in an islanded microgrid is controlled in order to minimize the cost and environmental impact of a microgrid, the optimization process is done using non dominated sorting genetic algorithm 2 (NSGA-II), based on the results of load flow analysis and only considers active power dispatch. In [20] a modified 15 bus radial distribution system is presented and load flow analysis of the system is studied. The system represents a typical distribution network and is considered suitable for use as a microgrid. In [21] a hybrid system is studied for stand-alone applications. The system is modeled using Matlab/Simulink and real load profile and weather data are used to simulate the performance of the system in different scenarios. A novel model of PV arrays is simulated in [7]. The model estimates the maximum power output of the PV modules according to ambient temperature and irradiation. The model is based on datasheet values. In [22] a microgrid is modelled and optimal power flow is carried out to minimize costs, total losses and voltage deviations using an interline power flow controller.

3.4 POWER FLOW ANALYSIS

In a typical power flow analysis there are generation buses, load buses and a single slack bus that is responsible for covering load mismatch and line losses and is considered as a reference to the system. However, in a microgrid such bus does not exist. Thus modifications to the conventional power flow analysis methods are required to compensate the absence of a slack bus [23-25]. The authors in [23] proposed a modified distributed slack bus method, where line losses are shared among generators according to participation factors. The proposed method achieved less line losses. In [24] power flow analysis were carried out using Newton Raphson method for a grid connected microgrid, the traditional NR method is applicable to grid connected microgrids only as the point of common coupling is usually considered the slack bus. However, in an islanded microgrid this is not the case. In [25] the authors proposed that traditional power flow analysis could be applied to an islanded microgrid only if there is a generation unit with a storage system and a suitable control strategy. Such generating unit can be controlled and used to substitute a traditional slack bus.

3.5 OPTIMIZATION ALGORITHM

Multi-objective optimization can be done using a variety of AI techniques and algorithms. Many literature compare different techniques [26, 28, 30, 31 and 35].In [26] a comparison is made between Strength pareto evolutionary algorithm 2 (SPEA2) and non-dominated sorting genetic algorithm (NSGA-II) to optimize the operating costs and emissions of a microgrid. The comparison shows that NSGA-II have better convergence but with slightly higher computational time. Another algorithm is the self-adaptive genetic algorithm used in [28] and compared with traditional dispatch methods. In [30] the objective of the optimization process is to minimize frequency excursion of microgrids. Three techniques: particle swarm optimization (PSO), genetic algorithm (GA) and bacterial foraging are compared. Bacterial foraging is used as it has much faster convergence. However, GA and PSO prove more robust and simple to implement in complex problems. In [5] harmony search algorithm, PSO and GA are compared. The paper highlights the reduction in operating costs of a microgrid due to the introduction of distributed generation. GA appears to be superior in optimizing the cost of DG while, PSO shows superiority in optimizing the power trade with the main grid. Improved Fast Evolutionary Programming (EP) and GA are compared in [35], where GA is able to optimize large, complex microgrids. However, GA is proven to take much longer to produce optimal solutions compared to EP. Battery life loss cost has been considered in [27] where Economic optimization including battery life loss cost, maintenance, fuel and environmental cost is carried out using NSGA-II. Hybrid systems are also used in some cases, such as [28] where genetic algorithm is used to optimize the decisions taken by a fuzzy logic controller that controls the power flow to and from the main grid. Other techniques such as chaotic quantum GA, isolation niche immune GA are used in [31, 32]. In [33] multi-objective GA is used to optimize the performance of a Combined heat and power microgrid. In [34] it is concluded that GA enables easy handling of the optimization cost functions and system constraints. A grid connected microgrid is managed to achieve highest profit from energy trading with the main grid. In [36] it is concluded that GA is suitable for the optimization of large microgrids, but requires more computation time when more variables are considered. Voltage profile improvement of microgrids is studied in [37] where GA is used to optimize the operation of an islanded microgrids taking into consideration bus voltage profile. In [5, 26-31] it can be concluded that GA is preferred in applications related to optimization of microgrids. The robustness of the algorithm in handling complex problems compensates for the computation time required to produce optimal solutions. A variant of GA is the non-dominant sorting genetic algorithm 2 which is developed in [38]. Other EP and AI techniques were also tested and researched. Newly developed techniques still require further research such as flower pollination algorithm, a nature inspired algorithm developed in [39,40] and shows great promise compared to older optimization algorithms.

3.6 HYDROGEN ENERGY STORAGE

A major problem present in a microgrid is the high penetration of intermittent renewable energy resources. Such resources depend greatly on the variations in environmental conditions such as solar irradiation, temperature and wind speeds. This problem has attracted the attention toward energy storage solutions. While batteries are extensively used in small scale applications, they have many drawbacks in large systems. Using Fuel cell/electrolyzer systems to store energy in the form of Hydrogen is a promising solution. Economic modelling of fuel cell and electrolyzer systems for microgrid optimizations has been studied in literature [9, 41-43]. Moreover, issues like system sizing and optimization constraints were also presented. However, in [44, 10] it was concluded that Hydrogen storage systems are currently unfeasible. In the near future, however it is expected that the research in the area of Hydrogen energy will provide solutions for efficient and feasible energy storage.

3.7 REACTIVE POWER OPTIMIZATION

One of the issues that require research in islanded microgrids is the flow of reactive power and its effect on bus voltages and line losses. In [45] the active/reactive dispatch principle is studied. EP, PSO, and differential evolution techniques are used to optimize the flow of reactive power in an islanded microgrid. Different economic models for reactive power dispatch were proposed in [46-48]. It is easily noticed that the effect of reactive power on the operation of microgrids is rarely considered, or reactive power compensation devices are used to satisfy the requirements of the microgrid [47]. Such as [48] where the others studied the optimum loactions of SVC devices combined with generator support.

Chapter Four

4 MULTIOBJECTIVE OPTIMIZATION

4.1 INTRODUCTION

Microgrids require a wide range of controls. They are mainly needed for the overall energy management of the system, protection coordination, monitoring and controlling the power flow between buses, and controlling bus voltages. One of the primary roles of the microgrid central controller is the optimization of operation of the microgrid.

Many methods and techniques where proposed in previous literature [26, 28, 30, 5, 35]. In [26] it was concluded that genetic algorithms are superior when accuracy is the main concern. However, they require greater computation times. In [5] many techniques were reported, among these, PSO (Particle Swarm Optimization) is the simplest and fastest optimization technique. However, GA proves to be more robust in complex and large systems. In [30] GA is tested and compared with other techniques where it proves to be efficient regardless of the long computation time. Based on previous literature, genetic algorithm is a proven technique for microgrid optimization. In this chapter, genetic algorithms are explained and studied for application on the simulated microgrid. Moreover, a novel optimization algorithm is introduced based on the newly developed Flower Pollination Algorithm which was developed only for simple optimization problems. The algorithm is modified and developed to be able to handle microgrid optimization and has proven noticeably good results compared to traditional genetic algorithm.

4.2 GENETIC ALGORITHMS

In the 1960s, computer scientists studied the development of evolutionary programming, suggesting that evolution theories could be used for optimization in engineering problems. The main concept was to generate a population of candidate solutions and use nature inspired generators to reach other better solutions. GA was invented by an developed by John Holland In 1960s [49]. The idea was to study the theory of evolution using some form of natural selection, where fitter chromosomes will produce more offspring by crossover and mutation, thus reaching the most fit (optimum) chromosome. The concepts of natural selection according to fitness mimic the evolutionary theory “survival of the fittest”. Crossover mimics the mating process between two members of the population to produce an intermediate offspring. Mutation mimics the random mutants in living creatures where certain elements of a chromosome are randomly changed.

All living organisms are formed of cells; these contain chromosomes, strings of DNA that carry the detailed description of the organism. Each chromosome is formed of genes, which represent different traits of the organism. for example, a gene that represents eye color, another one for hair color, etc. each gene is located in a particular locus in the chromosome. The fitness of an organism represents the probability that this organism will live and reproduce.

In GA, the word chromosome refers to a possible solution; genes are the different elements of the solution (decision variables). A search space is the collection of possible solutions to the optimization problem. It is obvious that no clear definition for GA can be presented. However, it is agreed that GAs have the following elements [49]:

- Population of chromosomes.
- Selection according to fitness.
- Crossover and mutation.
- Fitness functions.

The three operators of GA are:

- Selection: selects chromosomes in the population for reproduction, the higher the fitness, the more likely the chromosome will be chosen for reproduction.
- Crossover: randomly chooses a locus and exchanges the genes before and after that locus. This roughly mimics mating between organisms. Figure 4.1 shows the process of crossover.

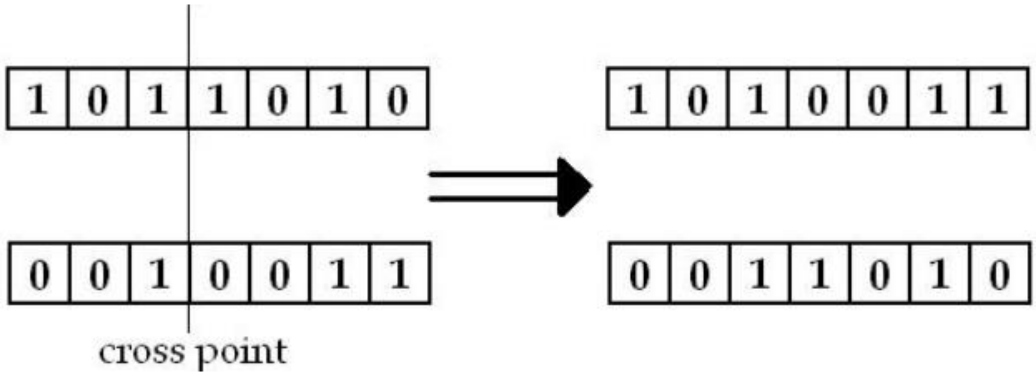


Figure 4.1 - Crossover

- Mutation: randomly flips some of the genes of the chromosome.

A simple genetic algorithm works as follows:

1- Start with randomly generated population of chromosome (possible solutions).

2- Calculate the fitness for each chromosome.

3- Select a pair of chromosomes for reproduction, the chromosome can be selected more than once and it is done according to fitness.

4- With selected probability, decision is made to either crossover or mutates the selected chromosomes, resulting in new population (offspring).

5- Repeat 3, 4 until a complete new population are formed.

6- Replace the current population with the new population.

7- Repeat from step 2 until a stopping criterion is reached.

Each iteration of the previous steps is called “generation”. The evolution process is highly random, thus scientists usually average the results from different runs of one optimization problem.

Generally, GAs are preferred when dealing with a problem that has a large, non-smooth search space where many other methods will find local optimum solutions or not search the space thoroughly. GAs accumulate fitness statistics across generations which make them suitable for such problems.

Some of the variants of GAs include elitism, adaptive GAs, Hybrid GAs and self-organization GAs, and many others [50]. Overall, GAs are promising in solving highly complex engineering problems and in the process of machine learning and evolutionary AI techniques.

4.3 NON-DOMINATING SORTING GENETIC ALGORITHM-II

One of the variants of GA mentioned and developed in [38] is NSGA-II. The variant addresses multi-objective optimization and tries to avoid known issues of previous MO methods of high complexity, nonelitism and constraint handling. The problem proves superior over archived techniques Pareto Archived Evolution Strategy and Strength Pareto Evolutionary Algorithm [38].

As the development of optimization techniques continued, many MO techniques were adopted and found. They mainly used a non-dominated sorting method to reach a Pareto optimal front of multiple solutions. However, the proximity of the solutions required that more operators are to be applied in order to produce more diverse Pareto fronts.

The naïve non-dominant sorting method states that in the first population of N chromosomes, each solution is compared to all other solutions, this requires M*N comparisons for each solution; Where M is the number of objectives. Then the solutions in the first front are discounted and the process is repeated to find the second front.

The fast sorting method stated in [38] assigns a domination count for each solution in the first non-dominated front. These counters are initially set to zero compared with each solution in its set and the solutions are divided into fronts. Each front is then ranked which reduces the complexity of the ranking process. The algorithm also features a non-crowding operator, that means that if two solutions have the same rank, the one in a lesser crowded area will be chosen. Figure 4.2 explains the ranking procedure in NSGA-II.

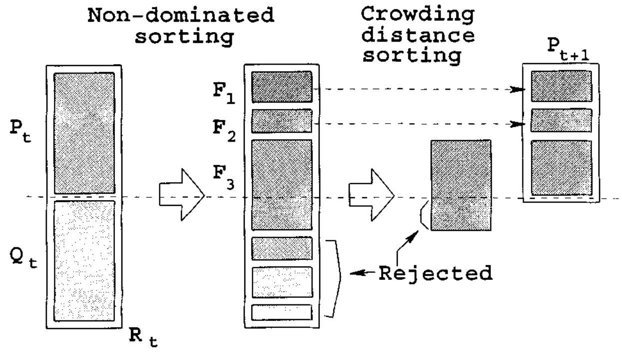


Figure 4.2-Elitism

4.3.1 Elitism

One of the features on NSGA-II is elitism. It forces the GA to retain the best individuals of each generation [49]. Such solutions can be lost or destroyed by crossover or mutation. Elitism is done by comparing current population with previously found best solutions. A combined population is formed between the previous (n-1) and current generations (n). The combined population of 2n is then sorted and by this way the best solutions in both generations are kept for reproduction. The best solutions are accumulated until a complete n population is formed, and the worst solutions are then discarded.

4.3.2 Constraint Handling

In [19] a method is proposed to handle the constraints imposed on the optimization algorithm. While evaluating the fitness of a chromosome, the solution is compared with the constraints of the optimization problem. If any constraint is violated, the chromosome is assigned a very high fitness value (very high cost, losses). Thus excluded by the selection operator and discarded from population.

A flowchart of NSGA-II is shown in Figure 4.3. Offspring is inserted into population to guarantee elitism [34].

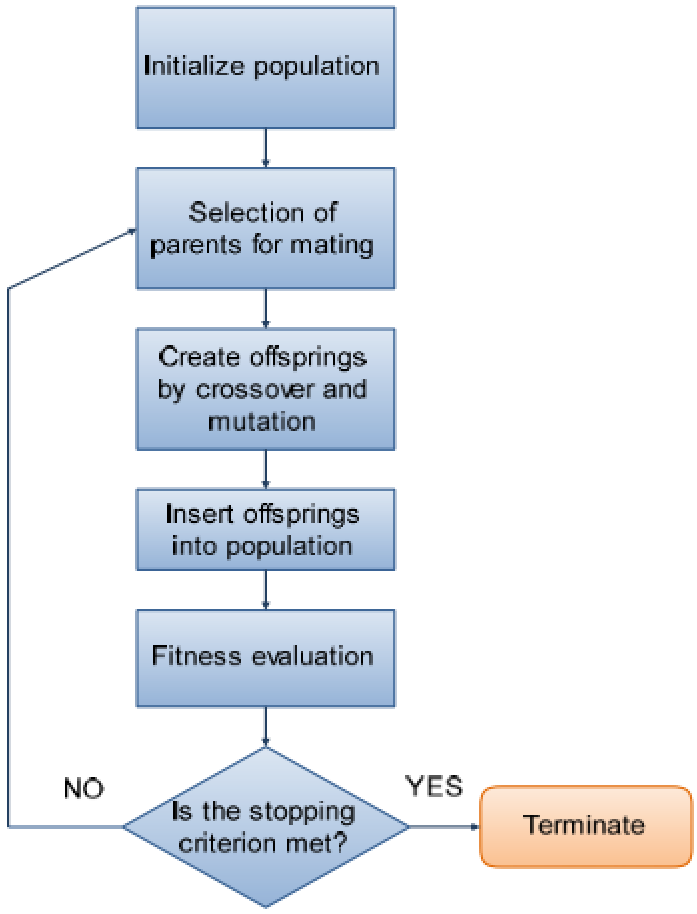


Figure 4.3- Flowchart of NSGA-II

4.4 FLOWER POLLINATION ALGORITHM

An innovative optimization algorithm was demonstrated in [39]. The new optimization algorithm is inspired by the process of flowering plants pollination. The results obtained by test functions shows that the new algorithm is more efficient than GA and PSO. From biological point of view, the purpose is to find the best reproduction of plants in both numbers and fitness. The pollination process is done locally and globally.

In optimization algorithms, the type of pollination is set by probability switch (resembles the crossover/ mutation probability in GA). The search method relies on a Levy flight distribution, such that:

$$x_i^{t+1} = x_i^t + \gamma L\left(x_i^t - g_*\right) \tag{4.1}$$

$$L = \frac{\lambda\Gamma(\lambda)\sin(\frac{\pi\lambda}{2})}{\pi} * \frac{1}{s^{1+\lambda}} \tag{4.2}$$

Where,

x_i^{t+1}=the solution vector at t+1.

x_i^t=the solution vector in iteration t.

L=the step size.

g_*=current best solution among all solutions.

γ=scaling factor.

Γ=standard gamma function.

Local pollination can be represented by:

$$x_i^{t+1} = x_i^t + \varepsilon(x_j^t - x_k^t) \tag{4.3}$$

Where,

x_j^t, x_k^t= pollens from local flowers

The proposed flower pollination algorithm was only tested for single objective non-constrained optimization problems. In later work [40] the method was developed to handle MO problems by using a weighted sum fitness function such as:

$$f = \sum_{i=1}^{m} w_i f_i \,, \sum_{i=1}^{m} w_i = 1 \,, w_i > 0 \tag{4.4}$$

Where,

m=number of objectives.

w_i= non-negative weights.

f_i =fitness functions.

The extended algorithm proved to be very efficient compared with other MO techniques. However, the algorithm require further testing and research as it is only applied to some simple example for demonstration by the original authors.

In this thesis, the concepts of non-dominated sorting (rather than weighted sum) and elitism are applied to the MOFPA proposed in [40]. The resulting algorithm merges the unique features of NSGA-II with the local and global pollination search techniques in MOFPA.

In [38], the flower pollination algorithm proposed in [39] is modified to be applicable on multi-objective optimization problems. The algorithm treats MO problems as single objective by weighted sum evaluation method. In this thesis the algorithm in modified to evaluate the objectives separately and using the non-dominating sorting method to select solutions. The unique features in NSGA-II are applied to the search technique of FPA to yield better results.

The algorithm starts with generating random population of flowers. This population is evaluated and sorted based on the non-dominated sorting method. Then, the search for better solutions is carried out by both local and global pollination. The resulting population of flowers is evaluated and merged with the original population. By doing this elitism can be achieved and the most optimum solutions are kept across generations. Finally, the resulting population is sorted and the least fit solutions are excluded.

The proposed algorithm is compared with the traditional NSGA-II in all case studies, as explained later; the proposed algorithm shows a noticeable improvement in optimization result. The results obtained from the simulation are explained thoroughly in the following chapter.

Chapter Five

5 SIMULATION & RESULTS

5.1 INTRODUCTION

In order to optimize the operation of an islanded microgrid it is required that optimization objectives and parameters are set. Then the whole system is modelled by modelling its components and an algorithm is designed to perform the optimization process.

The objective of the optimization process is to study the effect of minimizing both fuel consumption (f_1) –thus optimizing both fuel costs and emissions-and line losses (f_2), these can be represented as the following objective functions:

$$f1 = \sum_{i=1}^{N_G} C_G(i)\,, f2 = \sum_{i=1}^{N_{line}} I_{line}^2(i).R(i) \qquad (5.1)$$

Where,

N_G	Number of generation units.
C_G	Fuel cost of generation.
N_{line}	Number of lines.
I_{line}	Line current.
R	Line resistance.

The problem is treated as a multi-objective optimization problem with constraints, and solved using NSGA-II or non-dominated ranking based FPA. The decision variables are the active/reactive dispatch of each generating unit and the optimum slack bus. There are equality constraints such as load matching rules (both active and reactive power), these can be expressed as equations 5.2, 5.3.

$$\sum_{i=1}^{N_G} P_g(i) = \sum_{i=1}^{N_{bus}} P_D(i) + \sum_{i=1}^{N_{line}} P_l(i) \tag{5.2}$$

$$\sum_{i=1}^{N_G} Q_g(i) = \sum_{i=1}^{N_{bus}} Q_D(i) + \sum_{i=1}^{N_{line}} Q_l(i) \tag{5.3}$$

Where,

N_G, N_{bus}, N_{line} Number of generation units, buses, and lines respectively.

P_g, Q_g Generated active/reactive power at bus *i*.

P_D, Q_D Active/reactive power demand at bus *i*.

P_l, Q_l Active/reactive losses at line *i*.

Inequality constraints govern the lower and upper limits of generation units, the operation of Hydrogen storage system and the voltage profile of the system; such as in equations 5.4-5.11.

$$V_{min} < V_{bus}(i) < V_{max} \tag{5.4}$$

$$P_{g_{min}}(i) < P_g(i) < P_{g_{max}}(i) \tag{5.5}$$

$$Q_{g_{min}}(i) < Q_g(i) < Q_{g_{max}}(i) \tag{5.6}$$

$$S_{PV_{min}} < S_{PV} < S_{PV_{max}} \tag{5.7}$$

$$S_{wind_{min}} < S_{wind} < S_{wind_{max}} \tag{5.8}$$

$$S_{FC_{min}} < S_{FC} < S_{FC_{max}} \tag{5.9}$$

$$P_{elyz_{min}} < P_{elyz} < P_{elyz_{max}} \tag{5.10}$$

$$H_{tank_{min}} < H_{tank} < H_{tank_{max}} \tag{5.11}$$

Where,

V_{min}, V_{max}	Minimum/maximum limits of bus voltage.
V_{bus}	Voltage at bus *i*.
$P_{g_{min}}, P_{g_{max}}$	Active power operation limits of generator *i*.
$Q_{g_{min}}, Q_{g_{max}}$	Reactive power operation limits of generator *i*.
P_g, Q_g	Active/reactive generated power at bus *i*.
$S_{PV_{min}}, S_{PV_{max}}$	Min/max apparent power obtained from PVs at time *t*.
$S_{wind_{min}}, S_{wind_{max}}$	Min/max apparent power obtained from WTs at time *t*.
$S_{FC_{min}}, S_{FC_{max}}$	Min/max apparent power obtained from Fuel cell at time *t*.
S_{PV}, S_{wind}, S_{FC}	Apparent power supplied by PVs, WTs, and fuel cell.
$P_{elyz_{min}}, P_{elyz_{max}}$	Min/max active power that can be supplied to the electrolyzer.
P_{elyz}	Active Power supplied to the electrolyzer to generate hydrogen.

$H_{tank_{min}}, H_{tank_{max}}$ Min/max capacity of the Hydrogen storage tank (kg).

H_{tank} Current capacity of Hydrogen tank.

5.2 MODELLING OF SYSTEM COMPONENTS

5.2.1 System Description

To simulate the microgrid operation, each element must be modeled separately. Then outputs from all generating units, and load profile is fed into the optimization algorithm which then decides the operation parameters under the previously mentioned constraints.

The system used for simulation is a modified IEEE 15-bus radial distribution network [20]. Figure 5.1 shows a schematic of the system. The network is originally supplied by substation at bus 1, which is also the slack bus.

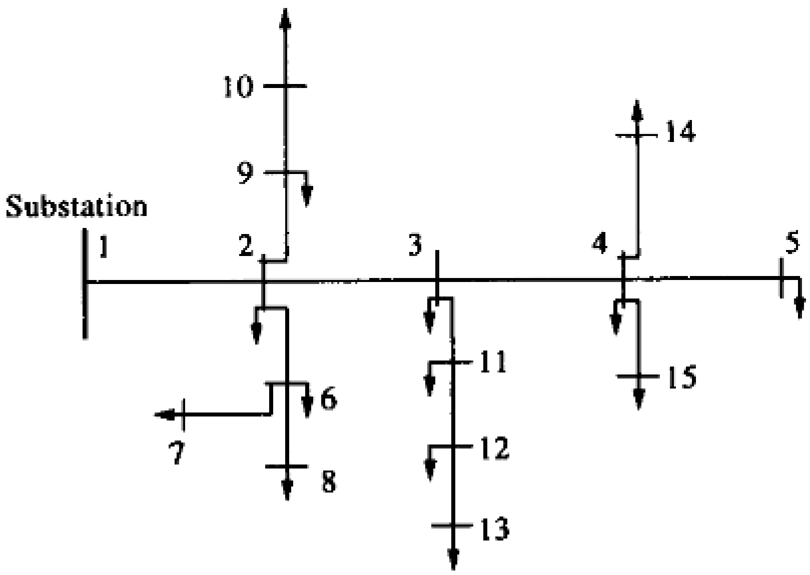


Figure 5.1-15 Bus Distribution Network

This distribution network can be converted into a microgrid by adding DERs at different locations. Choosing DERs´ location is crucial to the operation of a microgrid. DERs should be added at nodes that are connected to many branches, otherwise, losses will increase dramatically and in some occasions, power flow analysis will diverge, as in the case when DERs are added to buses 5, 13, 7 etc.

This suggests that buses 1, 2, 3, 4 are the best choices when adding DERs. Figure 5.2 shows the modified microgrid with all DERs added. Wind turbines are connected to bus1, Photovoltaic power plant is at bus 2 and buses 3, 4 are the diesel generator buses. The fuel cell/electrolyzer system is connected at the same bus with PVs as storage is preferred to be placed near renewable DERs in order to minimize energy lost during the storage process.

The microgrid has a peak load of 3.5 MWatts, distributed on 15 buses with power factor of 0.7. In order to simulate all possible cases of the microgrid, two daily load profiles shown in Figures 5.3, 5.4 are used in the simulation. Where Figure 5.3 represents a summer day and Figure 5.4 represents a winter day.

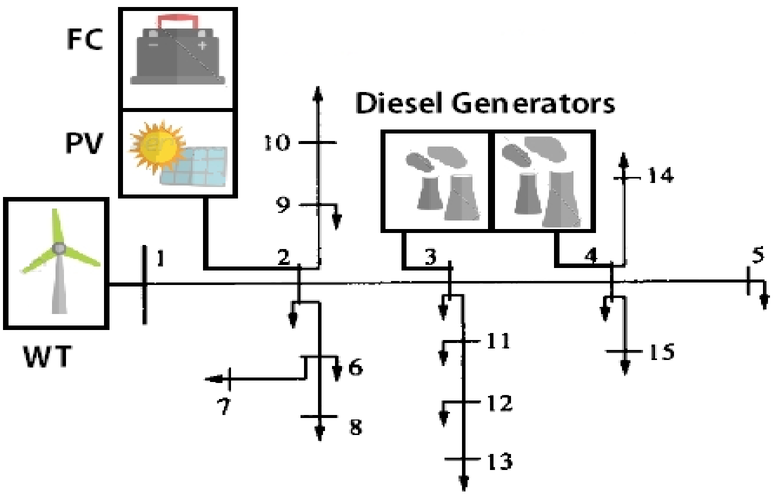


Figure 5.2- Modified Microgrid

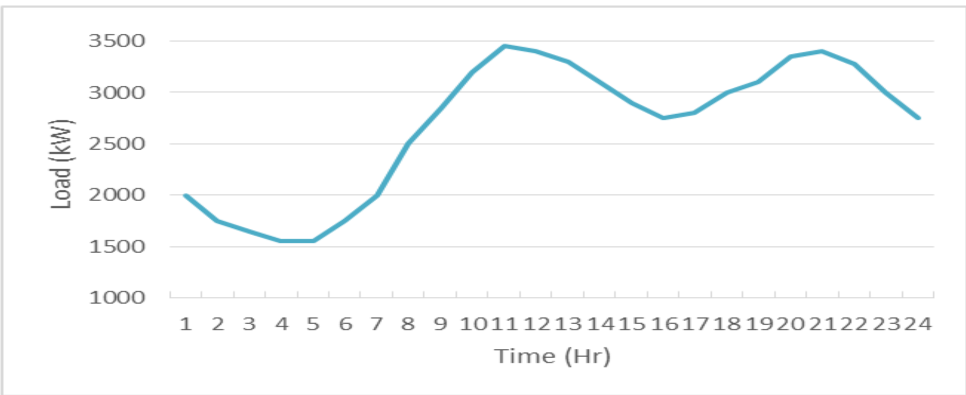


Figure 5.3-Summer Day Laod Profile

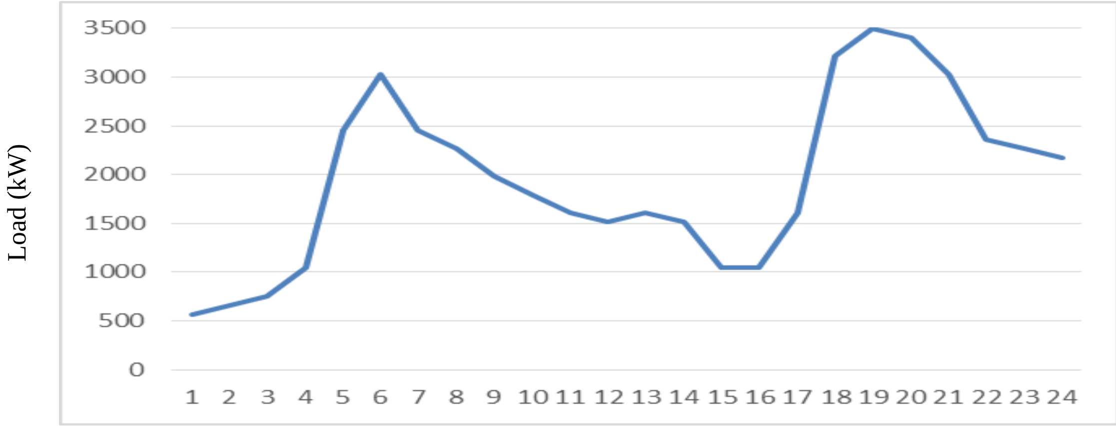


Figure 5.4-Winter Day Load Profile

5.2.2 DERs Modelling

The purposes of modelling DERs supplying the microgrids are:

- Determination of fuel cost at given power output (for diesel generators).
- Determination of available power according to environmental conditions (for photovoltaics and wind turbines).
- Determination of available power from fuel cell according to available Hydrogen storage.
- Determination of amount of Hydrogen produced by the electrolyzer.
- Representing the Hydrogen storage system and reacting to changes in the electrolyzer and fuel cell operation.

The economic model of a diesel generator is a function of the power generated by the diesel generator at a given hour. The model consists of three constants a_i, b_i, c_i which are the coefficients of fuel consumption as modelled in [5], where:

$$C_F = a_i + b_i P_G + c_i P_G^2 \tag{5.12}$$

Where a_i=0.4333, b_i=0.2333, c_i=0.0074.

The PV power plant model determines the maximum power output by the PV modules according to the current solar irradiation and ambient temperature. It can be modelled as:

$$P_{mppt} = V_{mpp} * I_{mpp} \tag{5.13}$$

The outputs of PV power plant for a summer day and a winter day are illustrated in Figures 5.5, 5.6. As PV produces DC current and the microgrid operates on AC, a power electronic inverter (assumed ideal) must be used as an interface, between the DC bus and the microgrid. Fuel cells and electrolyzer are also connected to the DC bus.

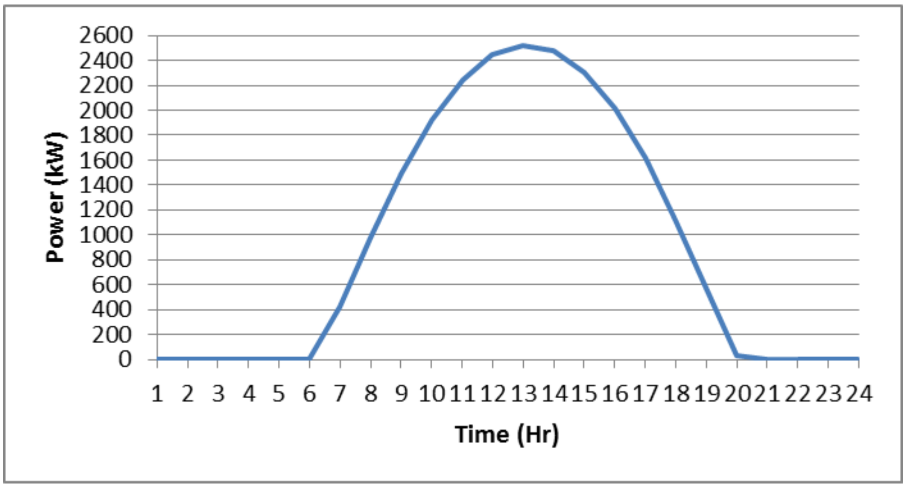


Figure 5.5-PV Plant Otput During Summer Day

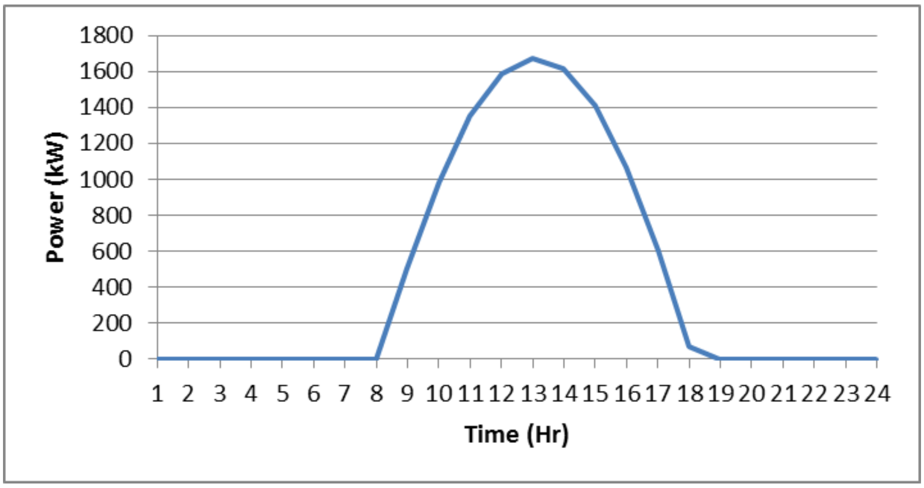


Figure 5.6-PV Plant Output During Winter Day

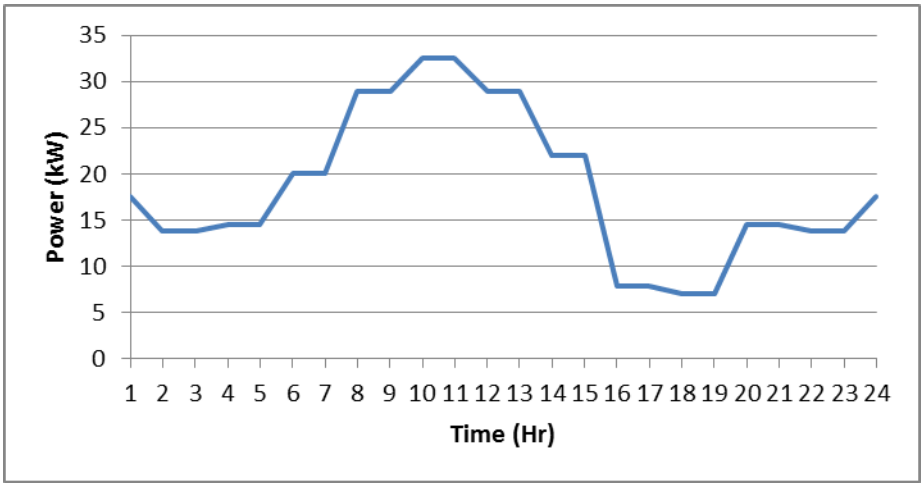


Figure 5.7- WT Output During Winter Day

Wind turbine produce power according to wind speed. The variation of WT output during a winter day is illustrated in Figure 5.7 and it can be modelled as:

$$P_{wind} = \frac{1}{2}\rho \times A \times v^3 \times C_p \tag{5.14}$$

The model is verified according to datasheet values from the datasheet of a polaris p21-100 100kW wind turbine [51]. Obtained from the datasheet, the output characteristics of the wind turbine against wind speed are shown in Figure 5.8. And the output of the wind turbine model is shown in Figure 5.9.

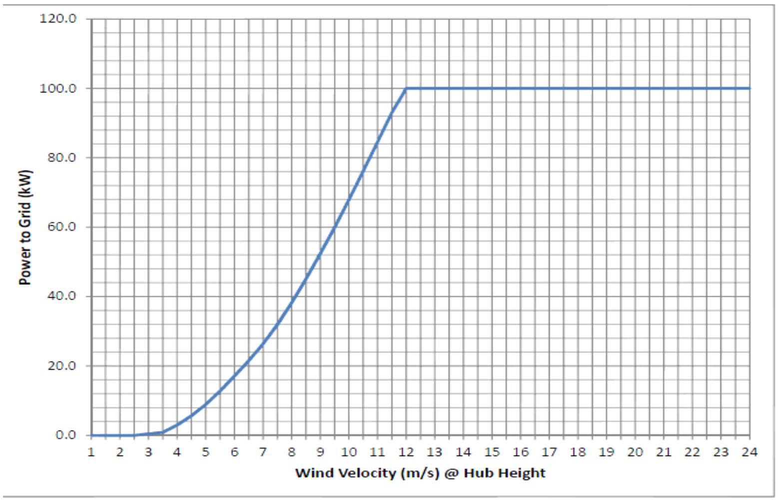


Figure 5.8-Datasheet Output Characterstics of P21-100 WT

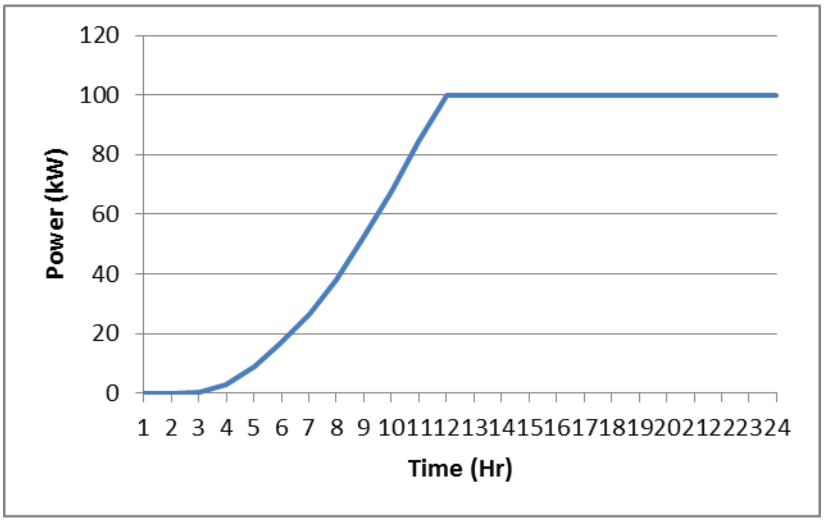


Figure 5.9-WT Model Output

The fuel cell is considered an energy conversion device where Hydrogen energy stored is converted to electrical energy with certain efficiency [44]. The output energy obtained from a FC is obtained by a simplified model in [44] where:

$$;E_{FC} = E_{H2} * \eta_{FC} \tag{5.15}$$

Where,

E_{H2} Energy from stored Hydrogen.

η_{FC} Efficiency of fuel cell.

As the electrolyzer is the reverse process of the fuel cell, it produces Hydrogen according to the same simplified model [44] where:

$$E_{H2} = E_{elyz} * \eta_{elyz} \tag{5.16}$$

Where,

E_{elyz} Energy consumed by electrolyzer.

η_{elyz} Efficiency of electrolyzer.

After the models are used to determine the operating parameters of DERs, power flow analysis are conducted using the data from the different models and the 15-bus network data.

5.3 POWER FLOW ANALYSIS

The objective of power flow analysis is to obtain bus voltages, line currents and active/reactive generation of dispatch-able DERs. Usually, conducted using the conventional Newton-Raphson method where all buses fall under three categories; slack bus, generator bus and load bus.

Since in microgrid, active/reactive power output of generators are controlled as the system requires, all generation buses are considered load buses with negative loads. However, one issue arises when using the conventional method for power flow analysis in an islanded microgrid; that is the absence of a slack bus.

A slack bus is a physical node with theoretically infinite generation capability. In reality it is a bus that has very high generation capacity, and is used to achieve load matching by covering the losses which cannot be predicted. In a microgrid with small scale DERs, such bus is not present, which makes power flow analysis more complicated.

In previous literature [14, 15, and 16] methods to solve this problem are proposed, where a single bus with surplus in generation is considered the slack bus. Or the distributed slack bus method where load mismatch is distributed among different generators according to participation factors.

However, since the objective of the optimization process is to minimize line losses and fuel costs, the optimization outcome is affected greatly by the selection of the slack bus [19], for this purpose, slack bus selection is done by the optimization algorithm itself. This can be done by adding a variable slack bus ID (SBID) to the optimization string (chromosome) where for each solution, the slack bus ID is included in the solution and power flow analysis are updated to consider the selected SBID. for another solution, power flow analysis is updated again to consider the different SBID and assess the output based on a different slack bus selection.

<u>Mixed Encoding GA:</u>

Encoding in GA means the representation of decision variables as chromosomes. Some applications require binary encoding where chromosomes are a series of bits. In case of microgrid optimization, real encoding is usually used as the dispatch of generation units will usually have real values.

However in this proposed algorithm, one bit of the chromosome (gene) is the slack bus ID, which is an integer that represents the number of the bus selected as slack. Thus mixed encoding is used and the solution vector (chromosome) is such as in equation 5.17. As it includes the active/reactive dispatch of each dispatch-able DER (real values) and the SBID (integer).

$$x = [P_1 \quad P_2 \ldots\ldots Q_1 \quad Q_2 \ldots\ldots SBID] \tag{5.17}$$

5.4 REACTIVE POWER OPTIMIZATION

The issue of reactive power in islanded microgrids has rarely been studied [45-48]. The effect of reactive power on microgrid economic operation is rarely considered, or the reactive power compensation devices are only used to meet the reactive demands of microgrid, without considering optimizing both active and reactive power of microsources, and the constraint conditions considered are too simplistic [20].

Reactive power dispatch minimizes active power transmission losses [45] as active power losses depend mainly on the bus voltages. In order to optimize reactive power dispatch while preserving system stability, voltage magnitude deviation from a reference has to be considered as a constraint [45] as in equation 5.4. Also the reactive power generation limits in equation 5.6 must be considered.

5.5 WORK FLOW OF THE PROPOSED ALGORITHM

The proposed optimization algorithm consists of parts:

- Data preparation.
- Renewable DERs modeling.

- Determination of operating mode (charge, discharge, etc.)
- Optimization of parameters according to mode of operation.
- Final result presentation.

The complete algorithm is shown in Figure 5.10, 5.11. Figure 5.11 explains the work flow of the optimization algorithm using GA and FPA.

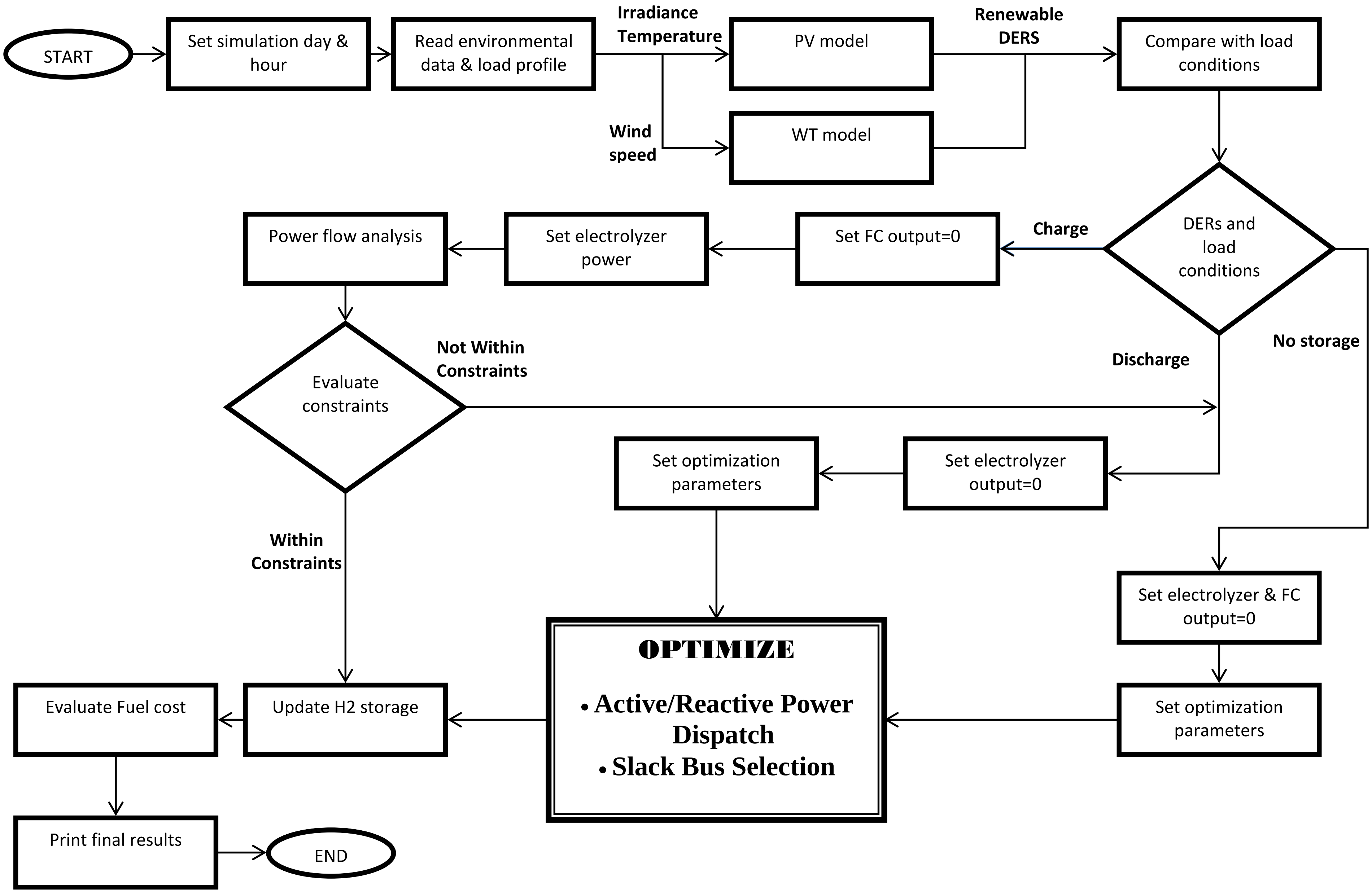


Figure 5.10- Simulation work flow

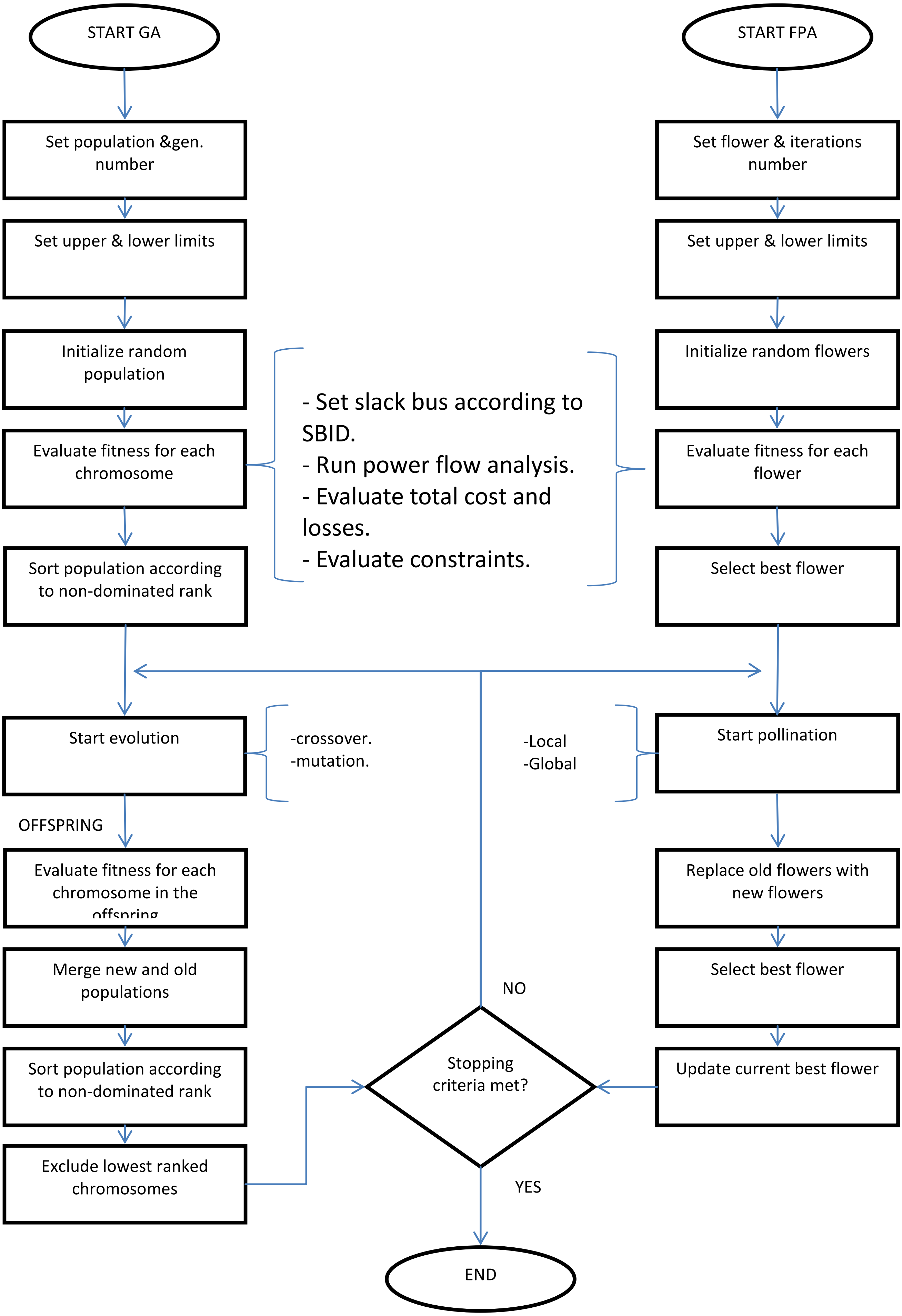


Figure 5.11- work flow of the Optimization Algorithm

As explained by the flow charts in Figures 5.10 and 5.11, the optimization algorithm starts by reading the load profile data and environmental data at a specific time interval (hour). This data consists of:

- Solar irradiation.
- Ambient temperature.
- Wind speed.
- System bus data including loads.
- System branch data (resistance, inductance, etc.).

DER models are then used to determine the power output from renewable (non-dispatch-able DERs). The resulting information is the power output from the wind turbines and the PVs. Moreover, total load demand is calculated.

DERs are often used to supply pure active power since it does not require any fuel consumption, or emissions. In this case, bus data is updated to include the power available from non-dispatch-able DERS.

These steps provide the input necessary to the optimization algorithm which also includes:

- Bus data and line data.
- Power output from non-dispatch-able DERs.
- Buses that are connected to dispatch-able DERs (for slack bus selection).
- Maximum and minimum operating limits of DERs.
- Number of chromosomes.
- Stopping condition (number of generations or a threshold).
- Number of objective functions and decision variables.

The optimization algorithm then generates initial population in the form of solution vectors (chromosomes/ flower pollens). These include the active/reactive dispatch of each dispatch-able DER, and a slack bus ID; see equation 5.17.

To evaluate the fitness of each solution, the slack bus is updated according to SBID, active/reactive dispatch is applied to each DER, the power flow analysis are conducted to assess the total line losses and the power supplied by slack bus to achieve load matching. Subsequently, total line losses and total fuel costs are calculated as previously illustrated in equation 5.1.

To satisfy the constraints (equations 5.2-5.11), the solution is then evaluated according to each constraint. A solution that violated any constraint is given a very high objective value (very low fitness) thus excluded later on by the ranking process.

The evolution process begins by producing offspring, evaluating this offspring, ranking the population, and finally excluding the least fit solutions. This is repeated until a stopping condition is reached (maximum number of generations/iterations, or a stopping threshold).

An optimal dispatch is then obtained, the results are saved and analysed.

Peak shaving by energy storage:

The concept of peak shaving is present when hybrid systems with energy storage are studied. This implies that diesel generators are kept at almost constant output and in times of high demand, either renewable DERs, or energy storage devices are used to supply the extra demand; thus, reducing the energy cost that is generally higher at times of high demand.

In case of using storage devices, the algorithm starts by dividing the day into day hours and night hours. The demand peaks at night hours are identified and accumulated to find the total energy storage required. Such that:

$$E_{night} = \sum_{i=1}^{Hr_{night}} P_{peak} - P_{base} \tag{5.18}$$

Where,

E_{night} Energy supplied by storage device during night.

P_{peak} Peak demand at a certain hour at night.

P_{base} Base demand.

This energy is then divided by the number of peak sun hours and storage system efficiency and multiplied by a safety factor to find the energy to be stored during day hours. This can be expressed as [52]:

$$P_{storage} = \frac{E\_night}{PSH * \eta_{fc} * \eta_{elyz}} * SF \tag{5.19}$$

Where,

$P_{storage}$	Power required by the storage device.
PSH	Peak sun hours.
SF	Safety factor.

During day hours, the energy required by the storage device (electrolyzer) is supplied only by renewable DERs. The surplus power from DERs is used to supply the main loads and assist non-renewable DERs. Reactive power is supplied from diesel generators and the active/reactive dispatch of each generator and the slack bus are determined by the optimization algorithm. In times of high demand no energy will be stored and all power from renewable DERs will be supplied to the loads in order to perform the peak shaving operation. Active power from renewable DERs will supply the peak demand and the rest will be supplied by diesel generators. During night hours, when load is below base, diesel generators will be used to supply the microgrid. However, in times of high demand, the energy stored will be used to shave the peak.

Power from renewable DERs and the Hydrogen storage system is used in the form of active power only as it is considered cheap energy and requires no fuel. However, it is noted that Hydrogen energy storage systems are economically infeasible due to current limitations in the manufacturing of efficient large scale electrolyzers/ fuel cells. It is expected that with further advancements in the area of Hydrogen energy, such systems will reach higher efficiencies at large scales and become feasible.

5.6 CASE STUDIES AND RESULTS

In order to assess and evaluate the benefits of the proposed algorithm, several case studies have been carried out. These case studies showed the benefits of adding DERs to a microgrid, and the advantage of using energy storage for the purpose of peak shaving. NSGA-II and modified FPA are evaluated and compared. The optimization of reactive power dispatch to reduce line losses and improve voltage profiles was also studied. Slack bus selection also proved to affect line losses and was included in the optimization algorithm.

Each case study had different circumstances and load conditions. Each case study was simulated during a summer day and a winter day, and each of them was applied to NSGA-II and to modified FPA.

5.6.1 Case study 1: Diesel generators only

In order to evaluate the total energy requirements and the total losses of the system, the option of supplying the full load demand with diesel generators is very important. In case study 1, the system is supplied solely by diesel generators at buses 3, 4. Since there is no other source of energy, diesel generators must be able to supply the peak load plus losses.

In this case study the algorithm will evaluate the hourly load demand depending on the daily load profiles shown in Figures 5.3, 5.4. Then, the optimization algorithm will find the optimal active/reactive dispatch for each of the diesel generators according to the optimization objectives and constraints.

Moreover, the algorithm will select the optimum slack bus among the two buses 3, 4. This will have direct effect on line losses and subsequently, on generation costs.

The generation data for this case is shown in table 5.1. It can be observed that at each generator bus, a set of five 400kW generators is connected.

Table 5.1- DERs Data for Case Study 1

Bus number	DER type	Minimum operating limits	Maximum operating limits
3	5*Diesel Generators (Pac1)	Pmin=0 Qmin=0	Pmax=400kW Qmax=500kVAR
4	5*Diesel Generators (Pac2)	Pmin=0 Qmin=0	Pmax=400kW Qmax=500kVAR

It can be observed from table 5.1 that the total installed capacity in this case will be 4000kW which provide 500kW spinning reserve to cover line losses.

The case study is divided into two scenarios, the first scenario represents a summer day. This is characterized by high load demand, possibly due to cooling applications. The second scenario represents a winter day which has noticeable lower consumption.

Each scenario is simulated using NSGA-II and modified FPA. The following optimization parameters were used in order to obtain comparable results.

Table 5.2- Optimization Parameters

Algorithm	**Population size**	**Stopping condition**
NSGA-II	40	500
MOFPA	40	500

Scenario 1: Summer day-Diesel only-Genetic Algorithm:

In this case, the load profile shown in Figure 5.3 is applied to the system. The load has a power factor of 0.7. Figures 5.12, 5.13 show the active/reactive dispatch of the two generator sets. It is noted that generator set 1 (Bus 3) is preferred and usually provides higher output. This is due to its proximity to load buses which reduces line losses. In times of high demand such as 9:00-15:00, generator set 1 reaches its peak output.

The load matching by the generation can be seen in Figures 5.14, 5.15. While Figures 5.16 shows the share of each generator set in the total active power supply.

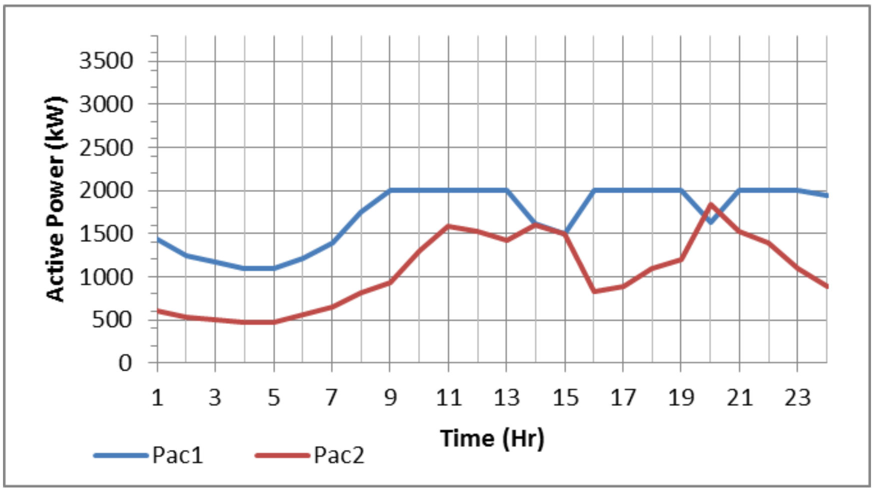


Figure 5.12- Active Dispatch of Generator Sets

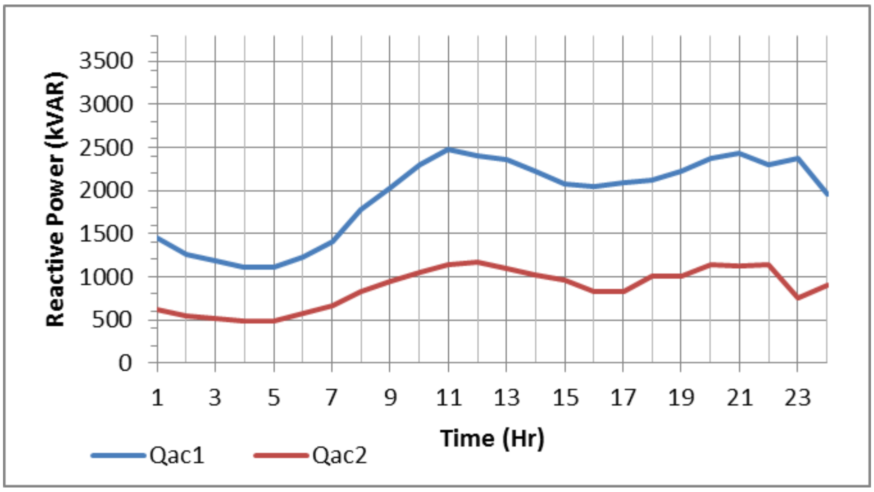


Figure 5.13- Reactive Dispatch of Generator Sets

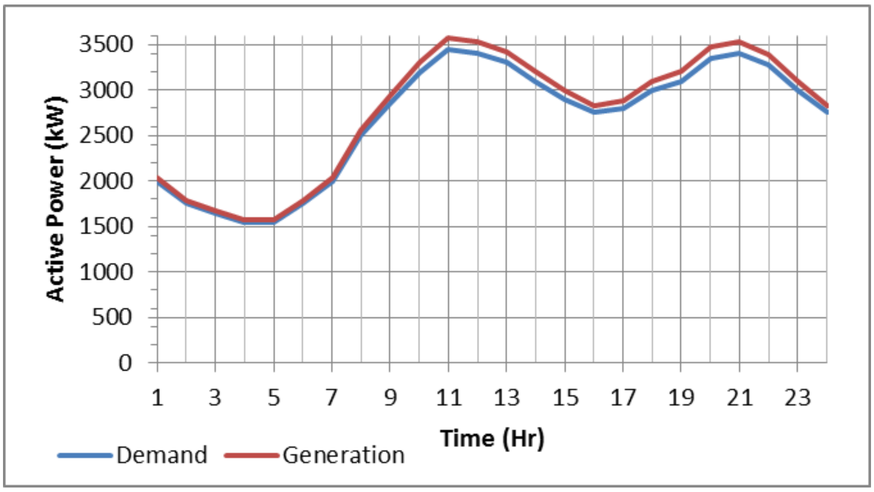


Figure 5.14-Active Power Demand vs. Generation

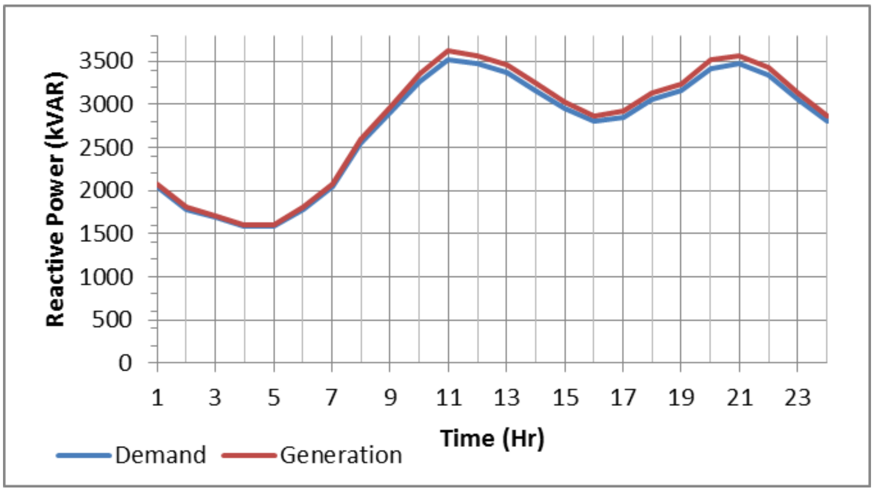


Figure 5.15- Reactive Power Demand vs. Generation

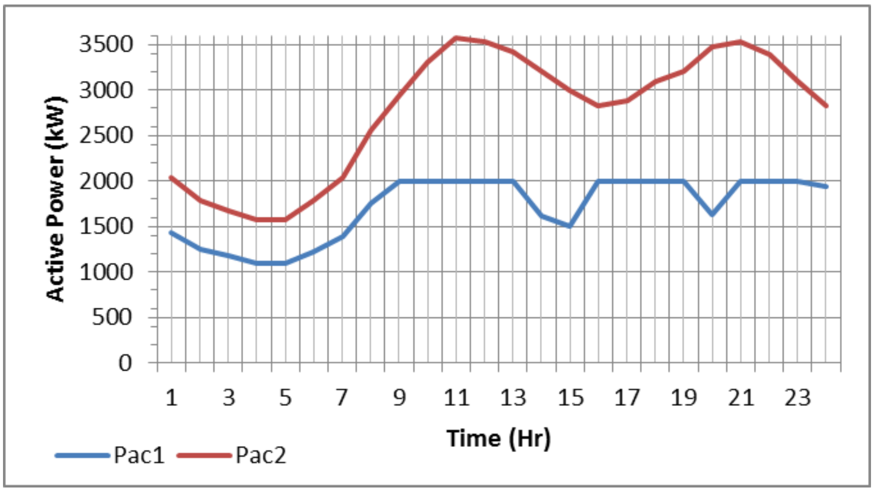


Figure 5.16- Load Sharing Among Generators

The system shows a daily fuel cost of 784,723$ and total line losses of 1960.9kWh. The voltage profile of the system has an average voltage of 0.9775Pu the average voltage deviation of the system buses are shown in Figure 5.17. Bus 4 was selected as a slack bus 8 hours; the remaining 16 hours bus 3 was selected.

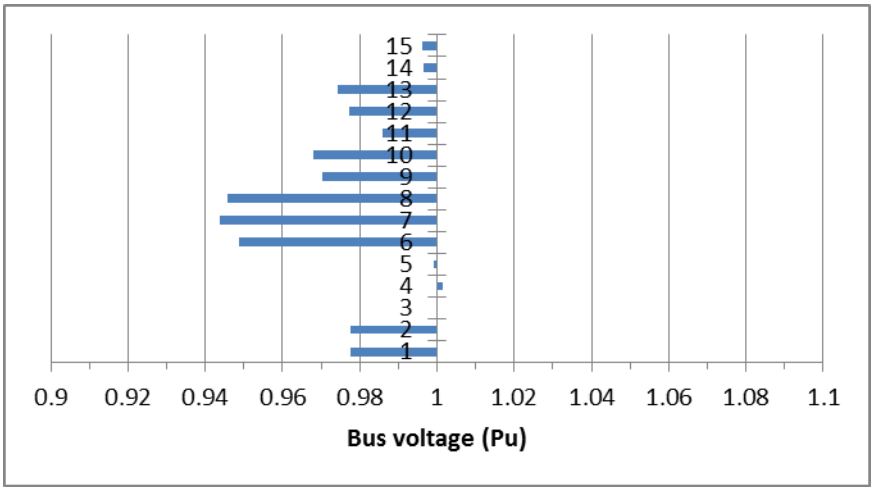


Figure 5.17- Average Bus Voltages

<u>Scenario 1: Summer day-Diesel only-Flower Pollination Algorithm:</u>

When the same scenario is simulated using the modified MO flower pollination algorithm, the system shows a different behavior with the same optimization parameters. The active/reactive dispatch of generator sets 1, 2 is shown in Figures 5.18, 5.19. However, the voltage profile is almost similar with an average voltage of 0.9778Pu. This can be seen in Figure 5.20.

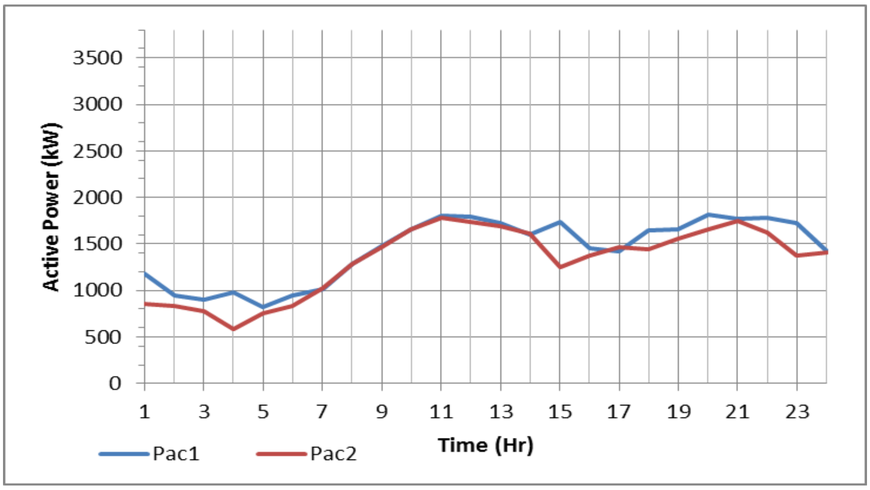


Figure 5.18- Active Dispatch of Generator Sets

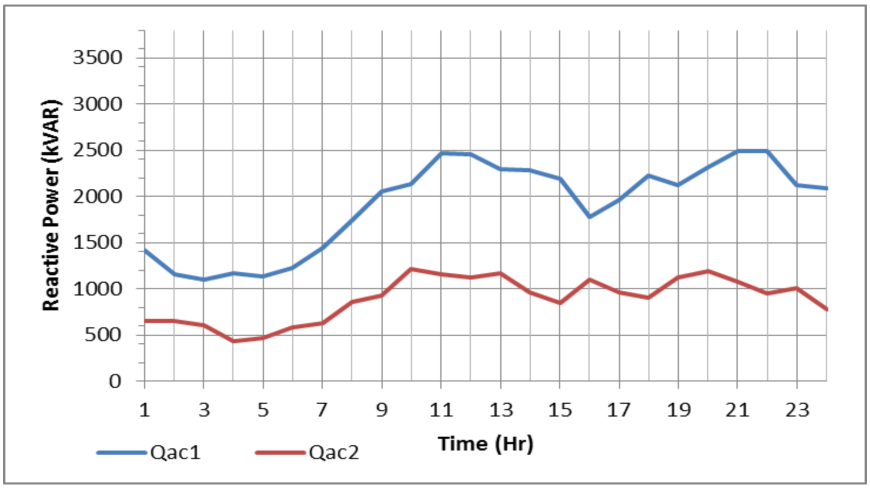


Figure 5.19- Reactive Dispatch of Generator Sets

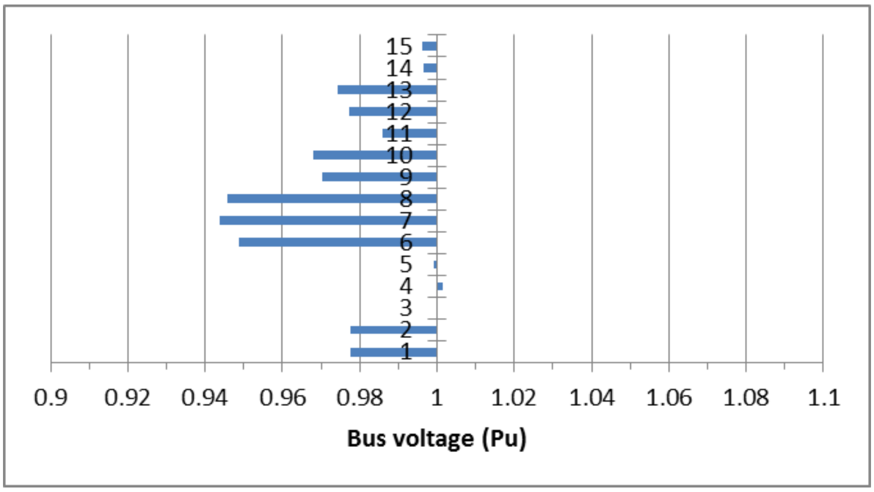


Figure 5.20- Average Bus Voltages

However, the modified flower pollination algorithm appears to obtain better results over the day. The total fuel costs in this scenario is 739,021$ with a 5.8% reduction compared to NSGA-II. The total line losses are 1986kWh. Thus, total line losses were increased by 1.28%. The lower cost is achieved by better load sharing among the generator sets. Unlike GA, in this scenario bus 3 was selected as slack bus for 23 hours out of 24.

Scenario 2: winter day-Diesel only-Genetic Algorithm:

In this scenario, the load profile for a winter day (Figure 5.4) is applied to the system. The load profile shows less daily energy demand. The active/reactive dispatch of each generator set is shown in Figures 5.21, 5.22.

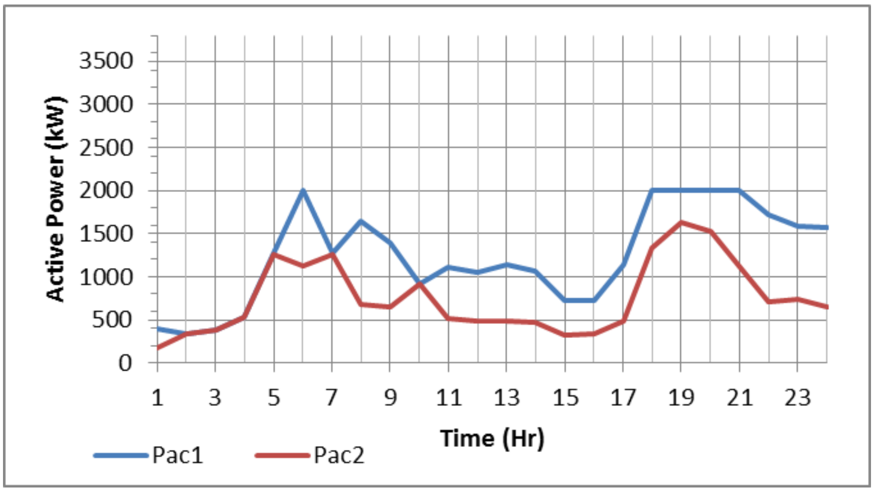


Figure 5.21- Active Dispatch of Generator Sets

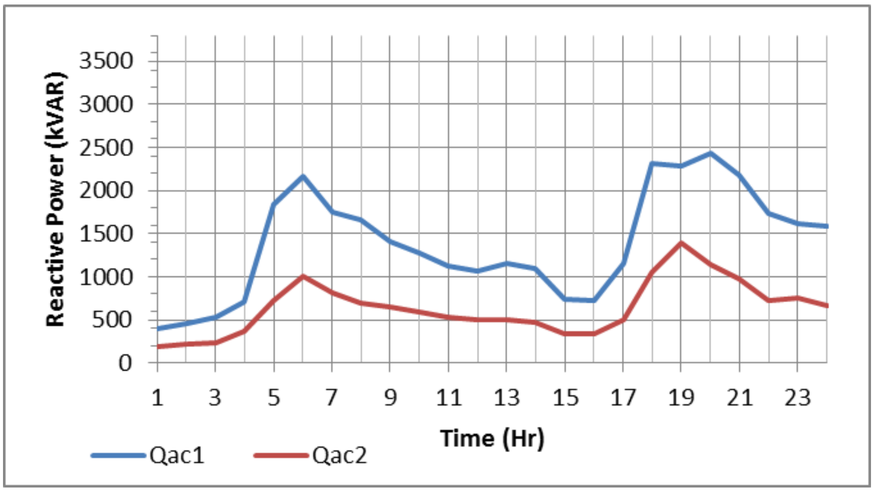


Figure 5.22- Reactive Dispatch of Generator Sets

The above Figures show that generator set 1 is also preferred. The share of each generator set is shown in Figures 5.23, 5.24. Where bus 4 was selected as slack bus only 8 times and bus 3 was selected for the remaining periods. The lower load demand resulted in a better voltage profile over the day. The average voltage deviations of buses are shown in Figure 5.25. An average voltage of 0.9837Pu was registered.

The system consumed fuel worthy of 470,944$ daily and total line losses of 1158.8kWh were lost.

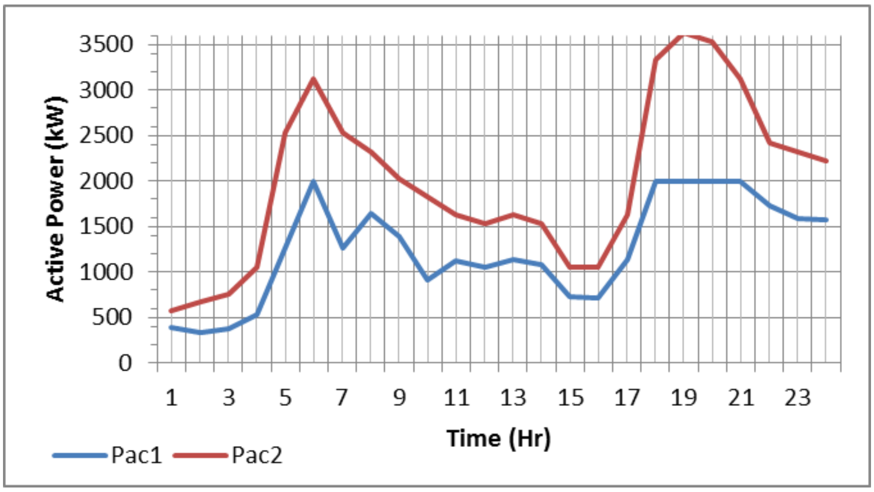


Figure 5.23- Active Dispatch of Generator Sets

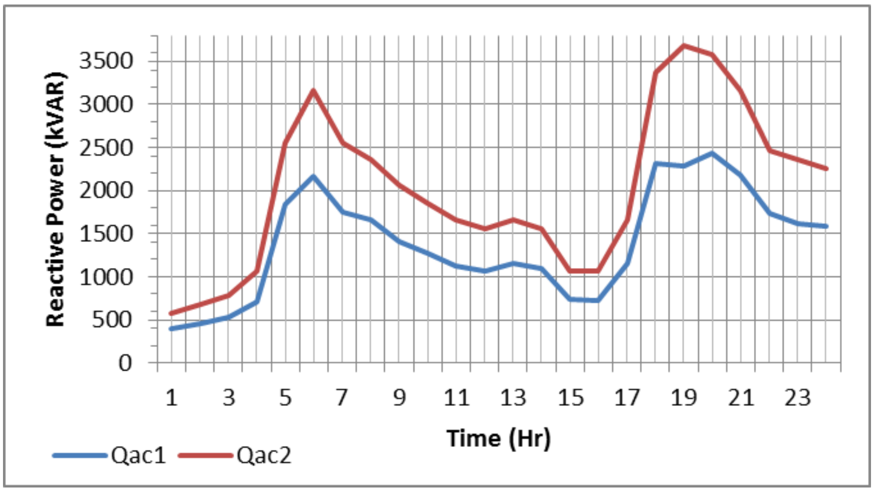


Figure 5.24- Reactive dispatch of Generator Sets

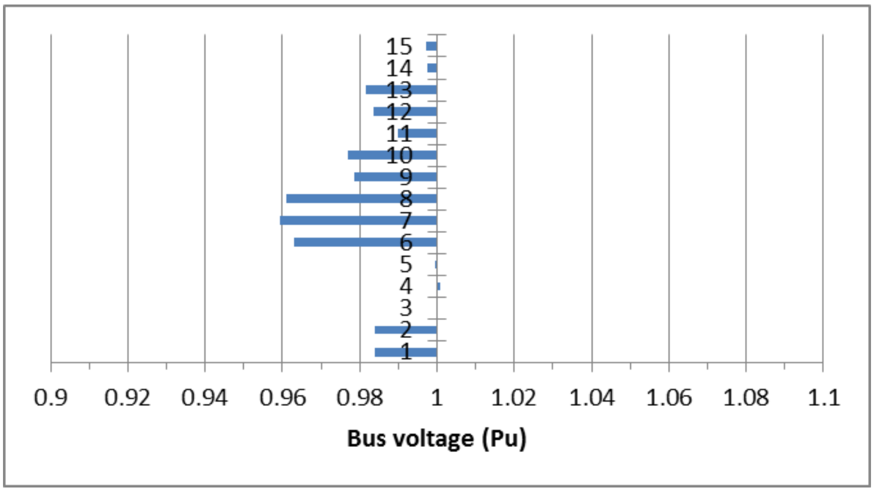


Figure 5.25- Average Bus Voltages

Scenario 2: winter day-Diesel only-Flower Pollination Algorithm:

When the same scenario is simulate using the modified FPA. It showed better load distribution among the two generator sets. This can be seen from the active/reactive dispatch shown in Figures 5.26, 5.27. The voltage profile remained almost the same with an average of 0.9837Pu. Bus 4 was selected as slack bus for 7 hours and bus 3 for 17 hours. The voltage profile is shown in Figure 5.28.

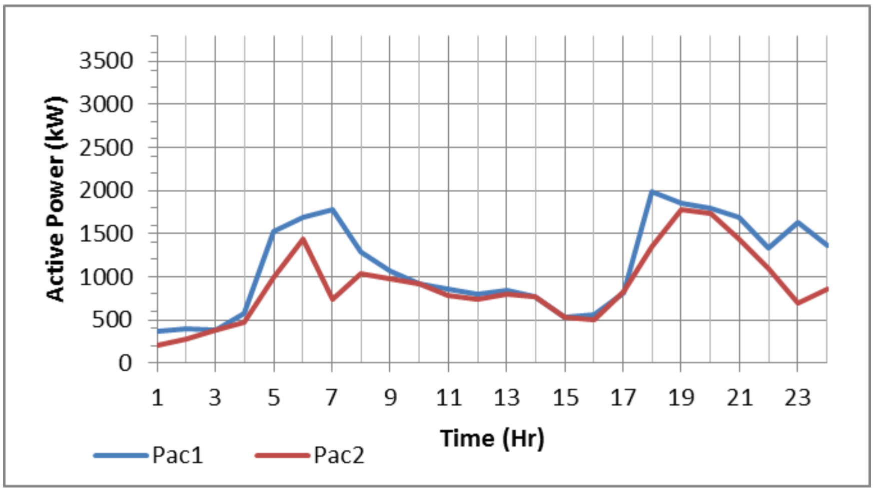


Figure 5.26- Active dispatch of generator sets

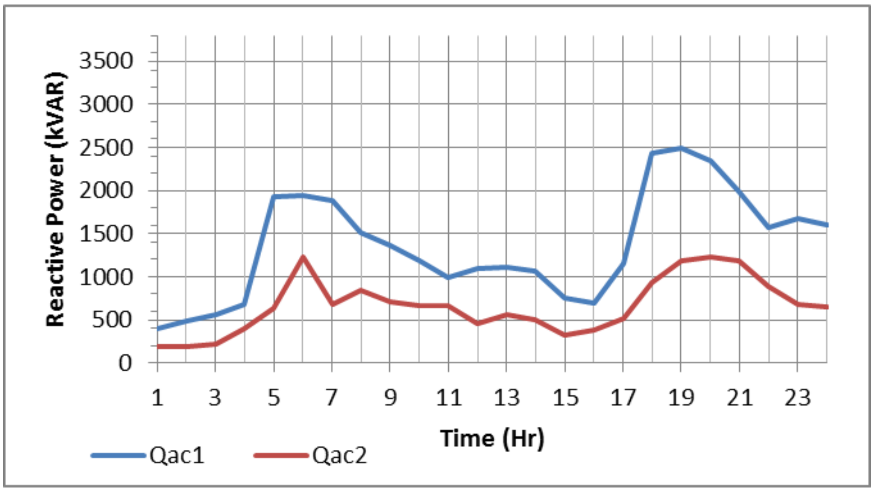


Figure 5.27- Reactive dispatch of generator sets

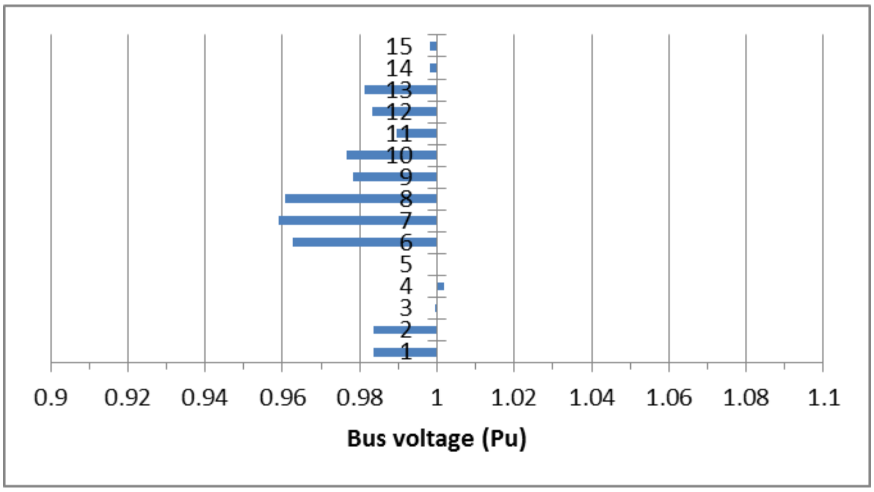


Figure 5.28- Average Bus Voltages

The modified FPA obtained better results as the system had total fuel cost of 451,007$ with a reduction of 4.2% compared to NSGA-II. Line losses also were reduced by 1.49% to become 1168.14kWh daily.

5.6.2 Case study 2: Hybrid system without storage

As the world is headed into an era of clean energy, renewable DERs are considered a very important component of modern microgrids. They do not require fuel consumption as they produce energy from environmentally available sources. The introduction of renewable DERs is expected to reduce the fuel costs and line losses, improve the system voltage profile.

In this case study, the algorithm will determine the power available from renewable DERs (PV, WT). This energy will be used to supply the active load demand. Diesel generators are then dispatched to supply the remaining active power, line losses, and the reactive power demand of the system.

for this case study the DERs shown in table 5.3 are installed at buses 1, 2, 3, 4. Power from PV and WT consumes zero fuel.

Table 5.3- DERs Data for Case Study 2

Bus number	DER type	Minimum operating limits	Maximum operating limits
1	10*Wind Turbines	0	100kW
2	PV power plant	0	1000kW
3	5*Diesel Generators (Pac1)	Pmin=0 Qmin=0	Pmax=400kW Qmax=500kVAR
4	5*Diesel Generators (Pac2)	Pmin=0 Qmin=0	Pmax=400kW Qmax=500kVAR

According to table 5.3, the system will have an installed capacity of 6000kW, divided into 1000kW from WTs, 1000kW from PVs and the rest from diesel generators. The oversizing of DERs is due to the uncertainty and intermittent nature of renewable DERs. For example, PVs only produce power at sunny days. Wind power has very high uncertainty and thus the installed diesel generators must be sufficient to supply the peak load at any time.

Like the previous case study, this case study has two scenarios; One representing a summer day, and the other representing a winter day. A summer day is characterized by high output from PVs due to the sunny conditions and low output from WTs due to the high temperature and lack of strong winds. On the other hand, a winter day shows a lower output from PVs and high output from WTs.

Both scenarios are simulated using the two optimization algorithms with the following parameters.

Table 5.4- Optimization Parameters

Algorithm	Population size	Stopping condition
NSGA-II	40	500
MOFPA	40	500

Scenario 1: Summer day-Hybrid System-Genetic Algorithm:

In this scenario, a summer load profile is used. Outputs from PVs and WTs at buses 1, 2 respectively are shown in Figures 5.29, 5.30. It is noted, as previously mentioned, that higher output will be available from PVs, and very low output from WTs.

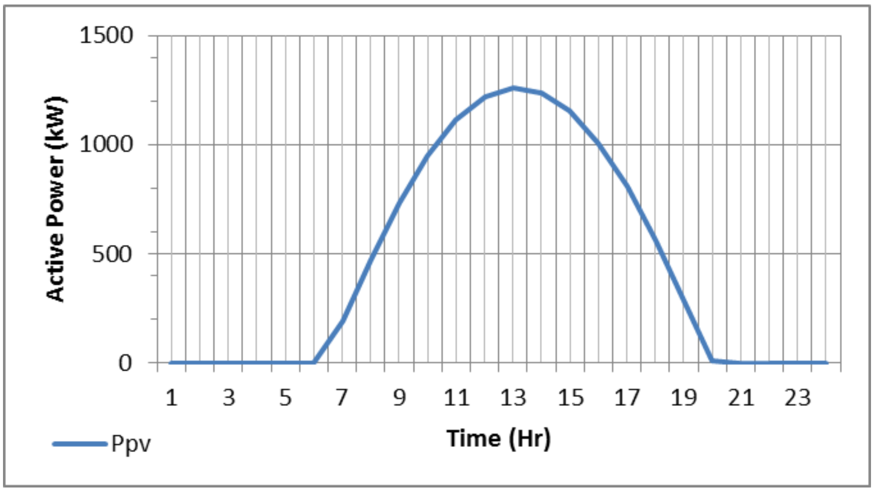


Figure 5.29- Output of Pvs for A Summer Day

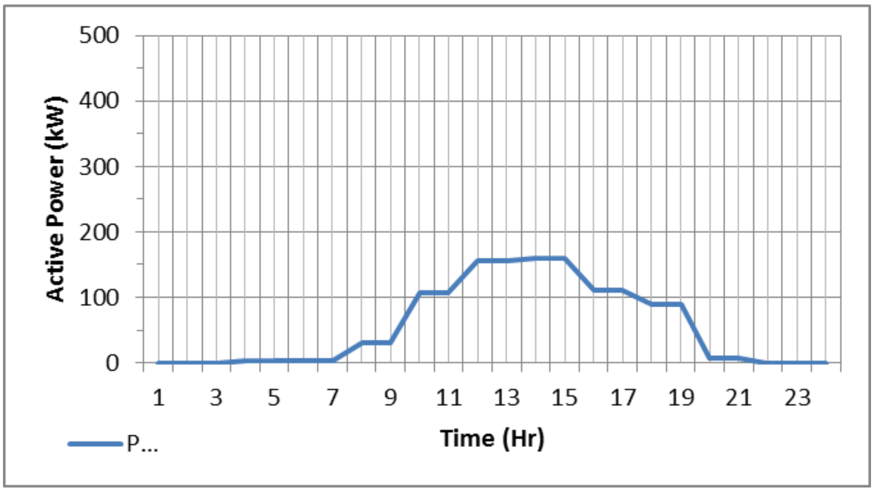


Figure 5.30- Wts Output for A Winter Day

The addition of renewable DERs removed the day peaks as can be seen in Figure 5.31. The reactive power supply is shown in Figure 5.32. An improved voltage profile was obtained (Figure 5.33).

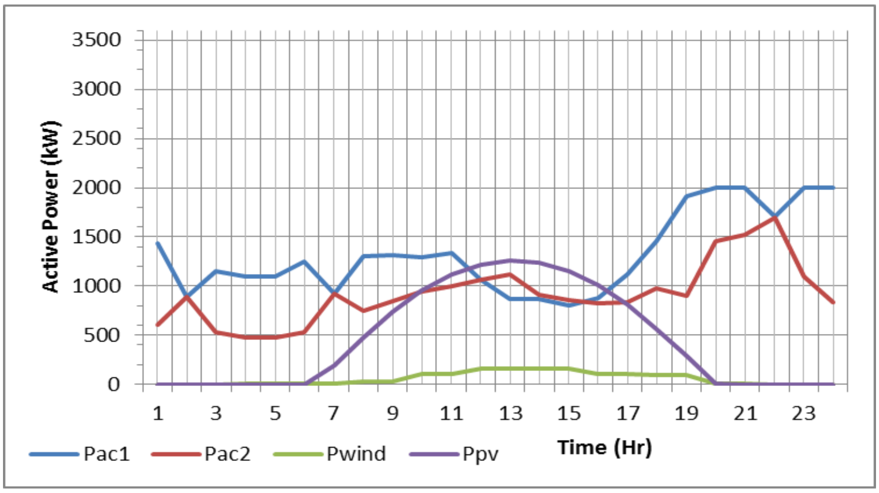


Figure 5.31-Load Sharing Among DERs

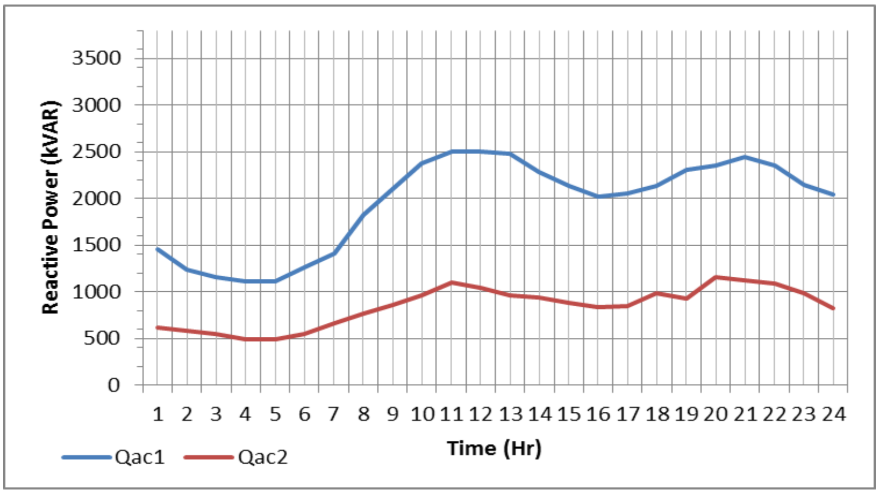


Figure 5.32- Reactive Power Output of Generator Sets

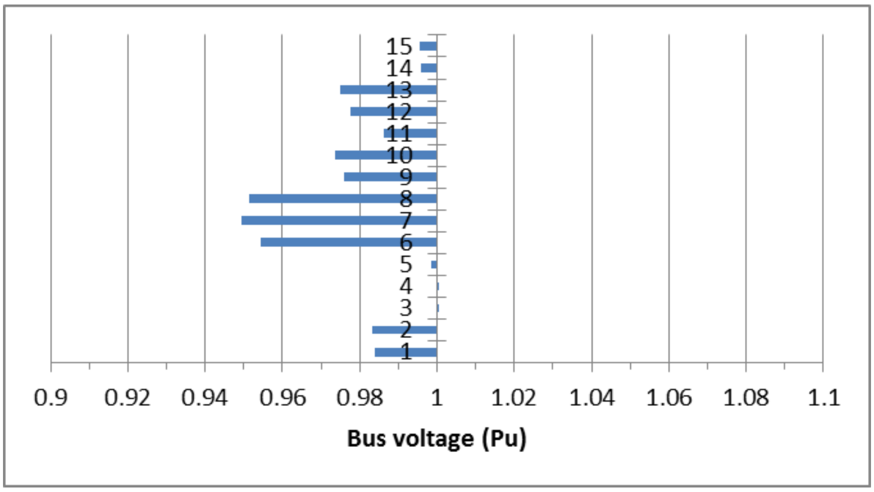


Figure 5.33- Average Bus Voltages

The average voltage in this scenario was 0.98011 which is better than the previously obtained value (case study 1-diesel only). The microgrid consumed daily fuel cost of 518,001$ and line losses were reduced to 1745.4kWh.

Scenario 1: Summer day-Hybrid System-Flower Pollination Algorithm:

When the same scenario is simulated using modified MOFPA, the daily fuel cost was reduced by 4.14% to become 596,548$. Line losses, however, increased to 1753.76 with an increase of 0.47%. The load sharing among DERs is shown in Figures 5.34, 5.35. Voltage profile remained almost similar with an average of 0.98007Pu (Figure 5.36).

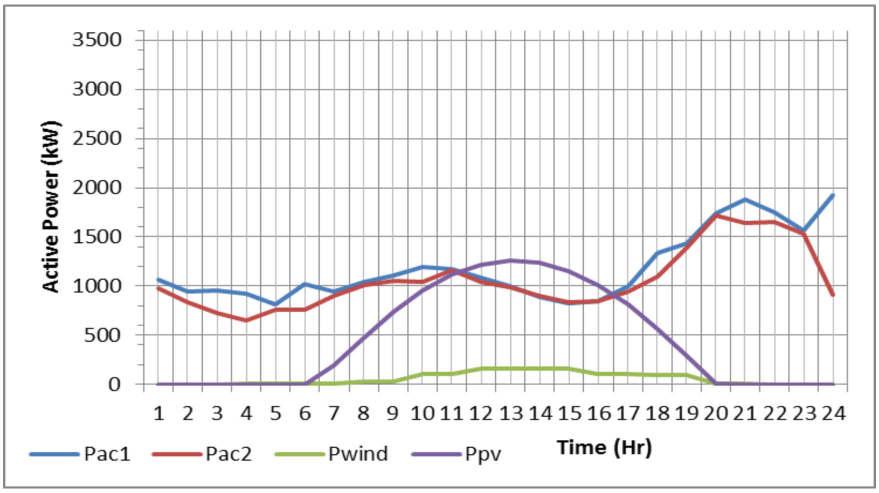


Figure 5.34- Load Sharing Among DERs

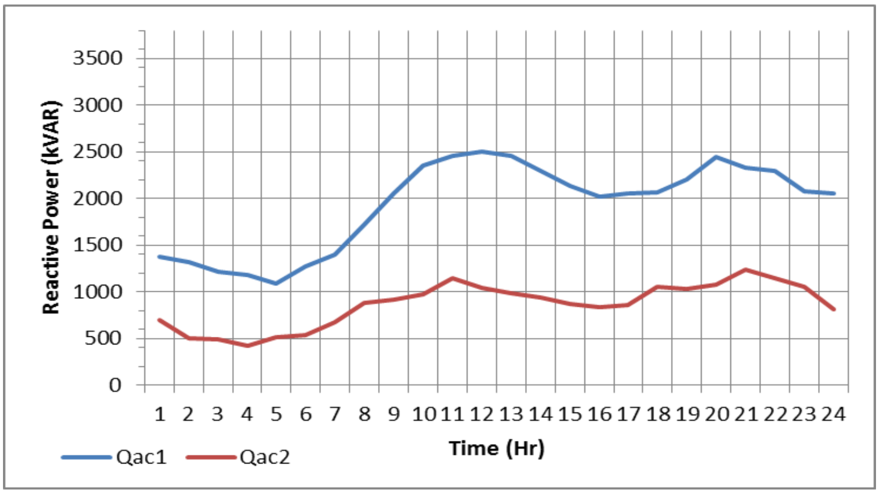


Figure 5.35- Reactive Power Output of Generator Sets

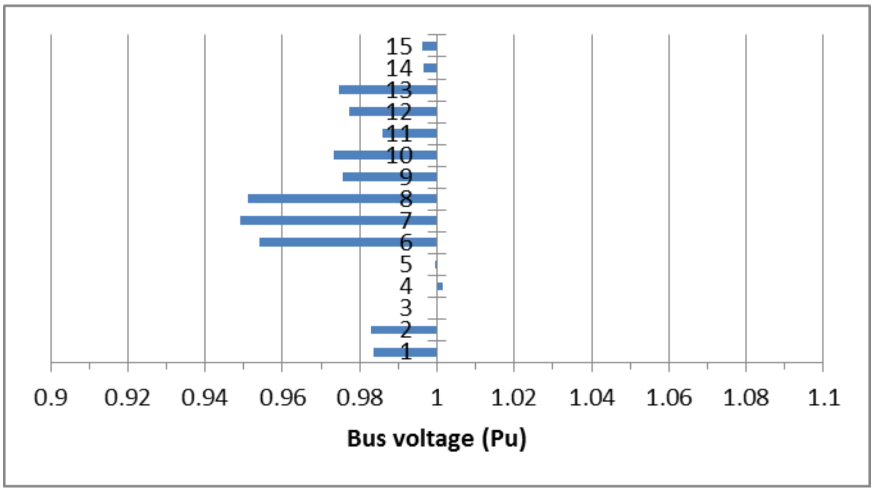


Figure 5.36- Average Bus Voltages

<u>Scenario 2: Winter day-Hybrid System-Genetic Algorithm:</u>

In this scenario, the winter daily load profile was applied to the system. The power output from PVs is noticeably less compared to a summer day. However, higher WT output is expected due to windy conditions. This is shown in Figures 5.37, 5.38.

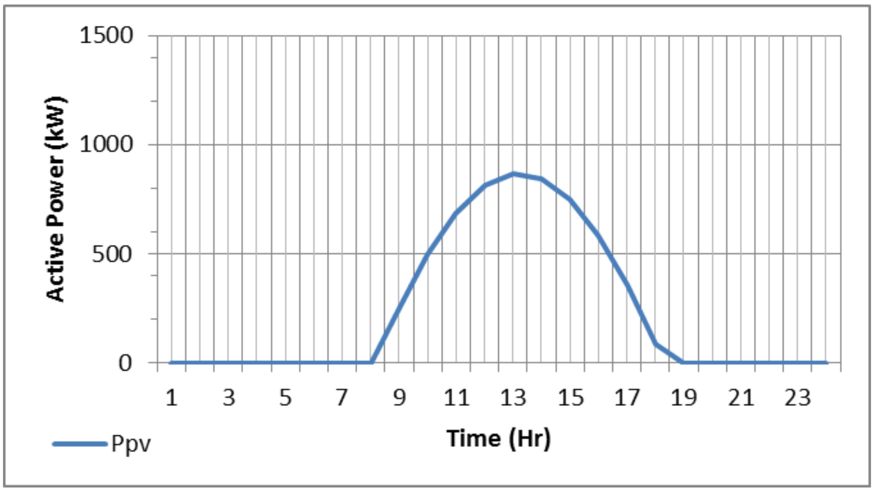


Figure 5.37-PVS Output for A Winter Day

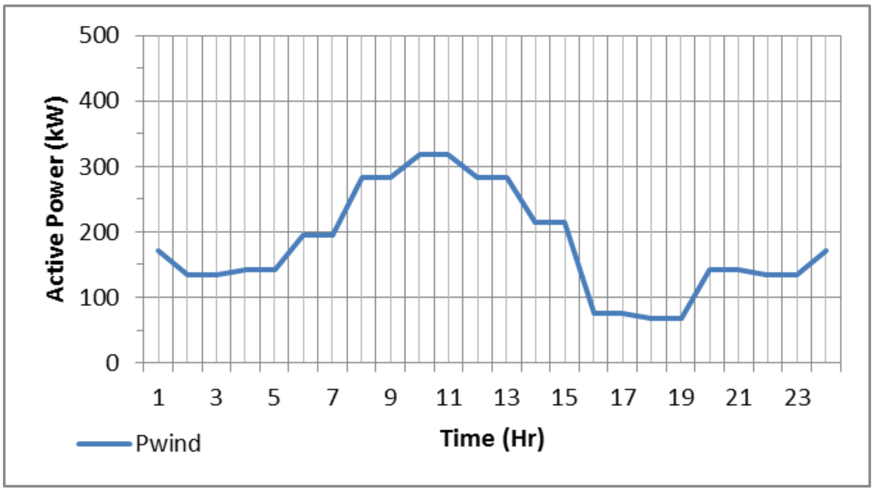


Figure 5.38- Wts Output for A Winter Day

The active/reactive dispatch of diesel generators, as shown in Figure 5.39, 5.40 vary greatly. This is due to the variation of the winter load profile. Also, due to the time difference between peak demand times and peak PV time. During peak sun hours, PVs produce their maximum output and the demand is very low; this results in a very low output from generator set 1 (Bus 3). Bus 4 is preferred in this case as the contribution of DERs at buses 1, 2 will reduce the total line losses.

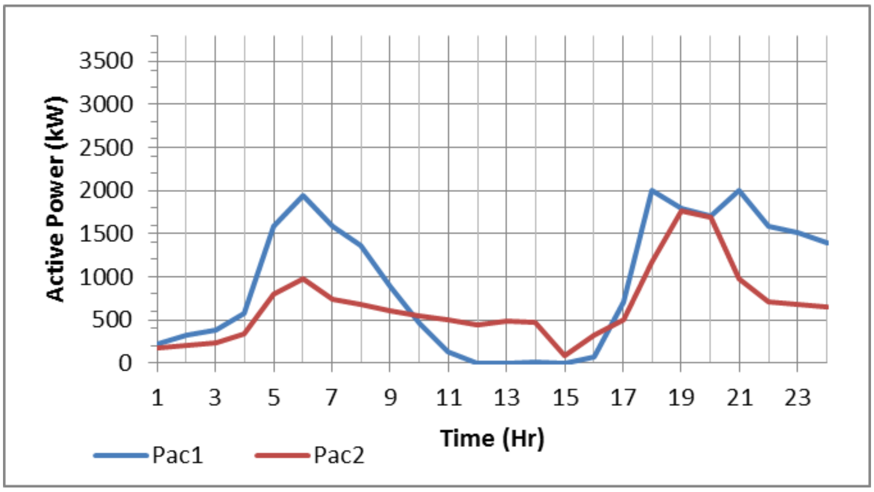


Figure 5.39- Active Dispatch of Generator Sets

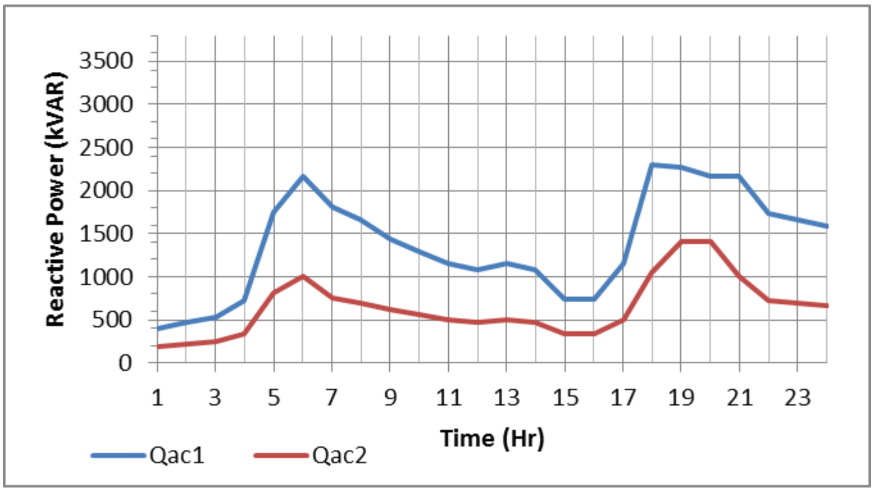


Figure 5.40- Rective Dispatch of Generator Sets

The load sharing among DERs is shown in Figures 5.41, 5.42. An improved voltage profile was also obtained by adding DERs as shown in Figure 5.43. The average voltage was recorded at 0.98588Pu.

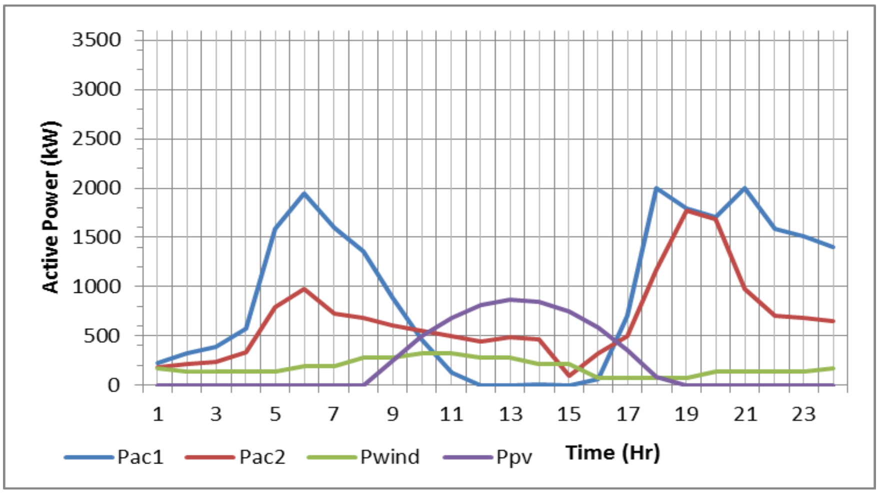


Figure 5.41- Load Sharing Among DERs

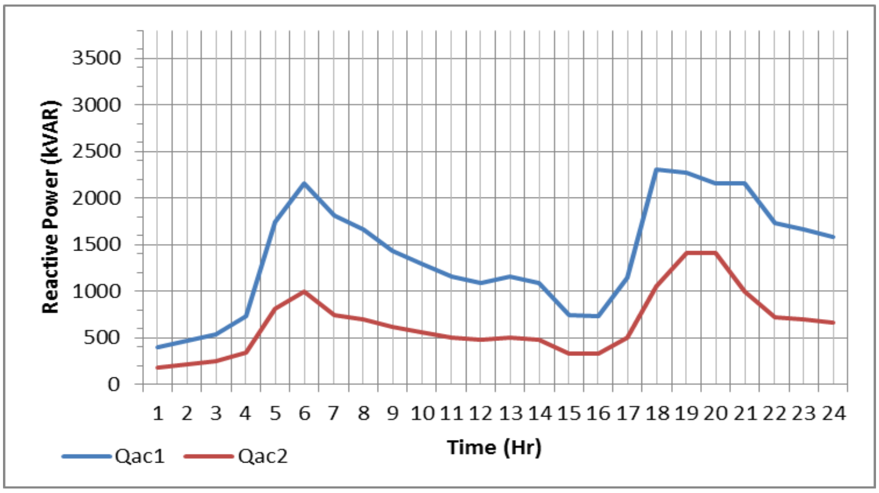


Figure 5.42- Reactive Power Output of Generator Sets

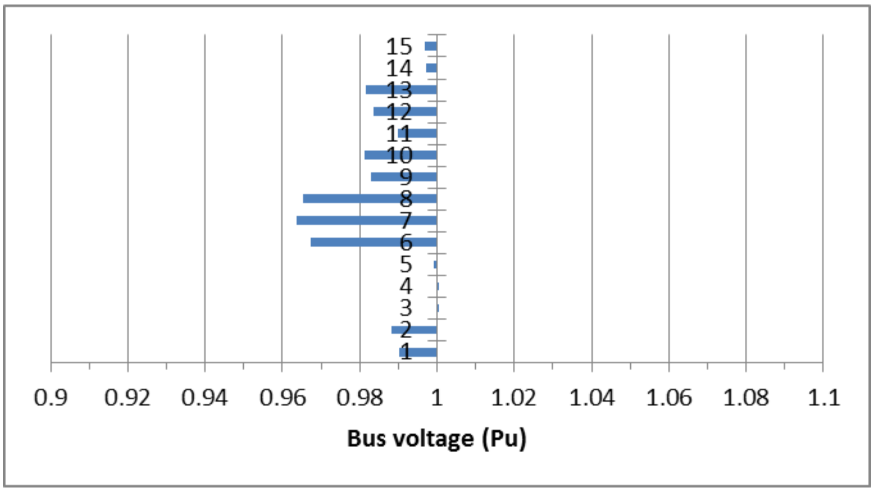


Figure 5.43- Average Bus Voltages

The microgrid had daily fuel cost of 364,853$ which is a noticeable reduction compared to the diesel only case study. Daily line losses were reduced to 1095.93kWh.

<u>Scenario 2: Winter day-Hybrid System-Flower Pollination Algorithm:</u>

Using modified FPA, the active/reactive dispatch of Diesel generator sets was obtained as shown in Figures 5.44, 5.45. The voltage profile was improved as shown in Figure 5.46. An average voltage of 0.9861 was observed.

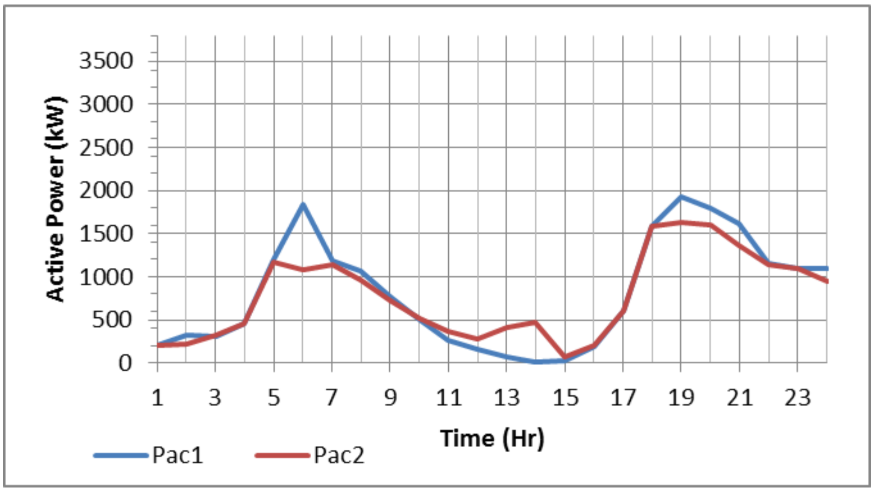


Figure 5.44- Active Dispatch of Generator Sets

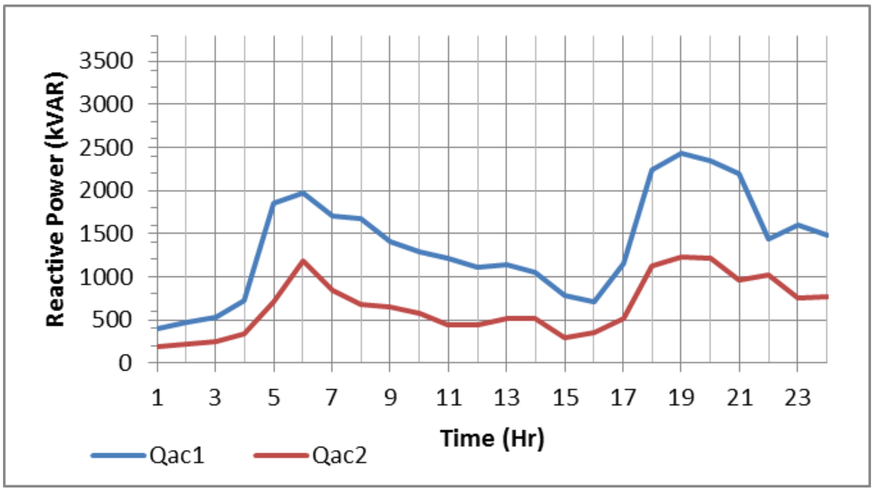


Figure 5.45- Reactive Dispatch of Generator Sets

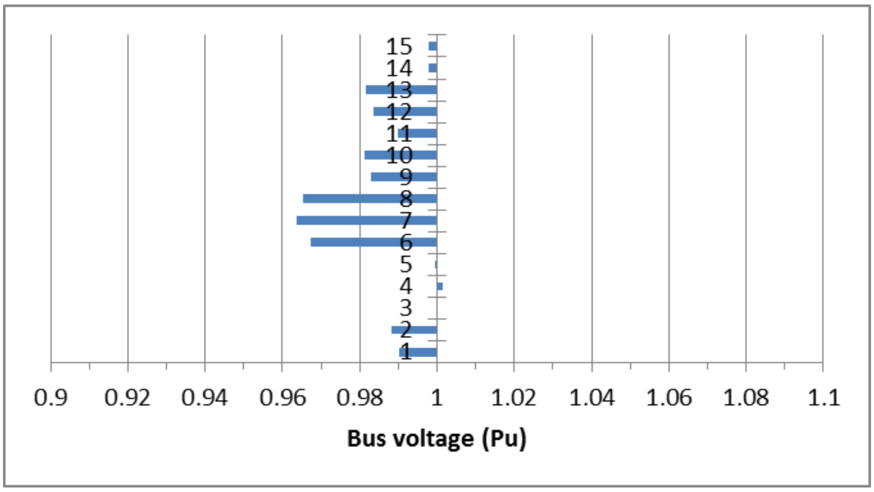


Figure 5.46- Average Bus Voltages

By using the modified FPA, daily fuel cost was reduced by 6.4% to reach 341,381$. Line losses increased slightly to become 1102.7kWh (0.61% increase) when compared to the same scenario simulated by NSGA-II.

5.6.3 Case study 3: Hybrid system with Hydrogen storage

In this case study, Hydrogen storage system is added to the microgrid. The microgrid now has a peak shaving feature, which means that during day, renewable DERs will be responsible for supplying the peak demand, while in night time; peak demand will be supplied by fuel cells using the energy stored during day.

The algorithm will calculate the energy required during night time peaks. Divided by the storage system cumulative efficiency and the peak sun hours, the energy required for storage every hour will be evaluated. When this energy is available from renewables, it will be stored. However, during day time peaks priority will be given to supplying the load demand.

This operation is expected to reduce the fluctuations in diesel generator output seen in the previous cases. Also fuel costs and line losses are expected to drop. However, it should be noted that Hydrogen energy storage systems are economically infeasible in the current time due to the high cost/ low efficiency of hydrogen energy systems i.e. fuel cells, electrolyzers.

Moreover, due to the presence of storage devices, downsizing of diesel generators can be considered as they are not required to supply the full load but only a base load.

The microgrid is supplied by DERs shown in table 5.5. The specifications of the hydrogen energy storage system are show in table 5.6. The base load is at 2500kW and Hydrogen has a lower heating value of 33.33kWh/kgH2. The electrolyzer must be able to withstand all the power output from PVs., while FC only needs to cover the peak demand of 1000kW.

Table 5.5- DERs Data for Case Study 3

Bus number	DER type	Minimum operating limits	Maximum operating limits
1	10*Wind Turbines	0	100kW
2	PV power plant	0	3500kW
3	4*Diesel Generators (Pac1)	Pmin=0 Qmin=0	Pmax=400kW Qmax=500kVAR
4	4*Diesel Generators (Pac2)	Pmin=0 Qmin=0	Pmax=400kW Qmax=500kVAR

Table 5.6- Hydrogen Energy Storage System Specs

Bus number	Device	Minimum operating limits	Maximum operating limits	Specifications
2	Fuel cell array	0kW	1000kW	η_{FC} 38.36%
2	Electrolyzer array	0kW	3500kW	η_{elyz} 34.35%
-	Hydrogen tank	0 kg	300kg	-

The two (summer and winter) scenarios were simulated using NSGA-II and FPA and the obtained results are discussed below. The following optimization parameters were used for the study:

Table 5.7- Optimization Parameters

Algorithm	Population size	Stopping condition
NSGA-II	40	500
MOFPA	40	500

Scenario 1: Summer day-Hybrid System with storage-Genetic Algorithm:

In this scenario, the summer load profile was used. The high peak demands most of the day results in high amounts of energy storage and consumption from FCs. The output from PVs is very high due to high irradiation values as shown in Figure 5.47. The low output from WTs is shown in Figure 5.48.

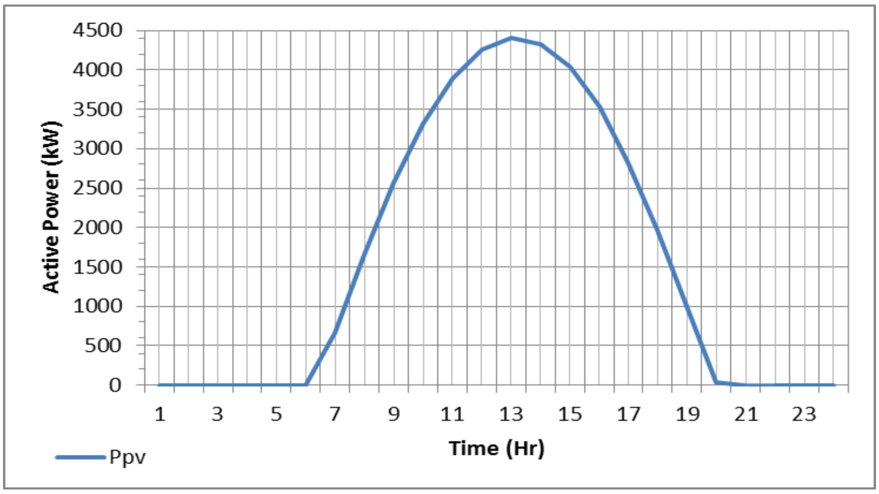


Figure 5.47-Pvs Output for A Summer Day

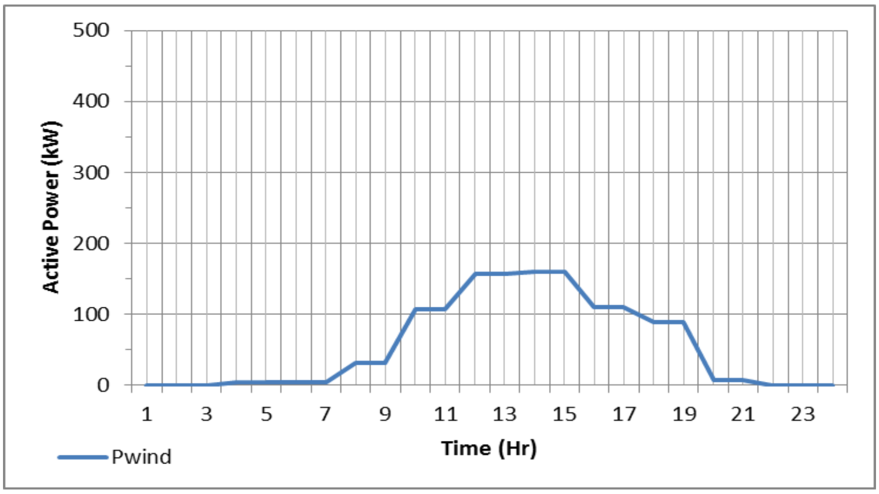


Figure 5.48-Wts Output for A Summer Day

The application of the peak shaving technique resulted in less fluctuations in the output of diesel generator sets. This can be seen in Figures 5.49, 5.50 where the active/reactive dispatch of diesel generators is shown.

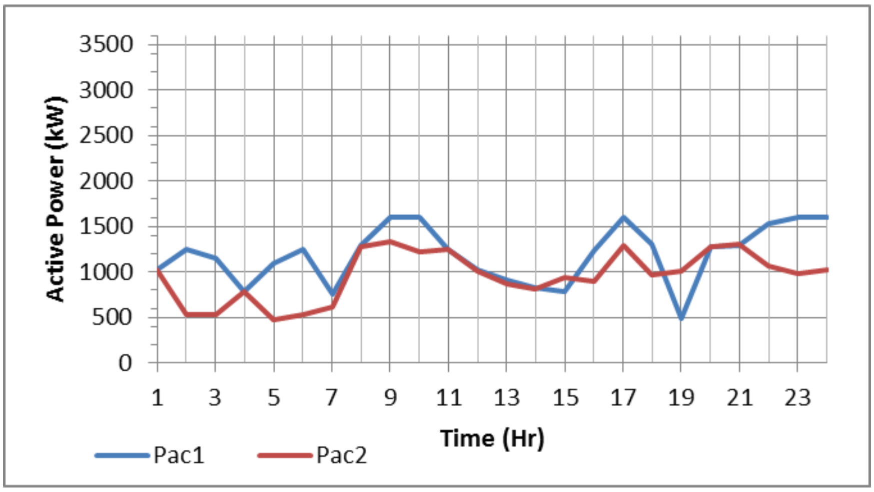


Figure 5.49- Active Dispatch of Generator Sets

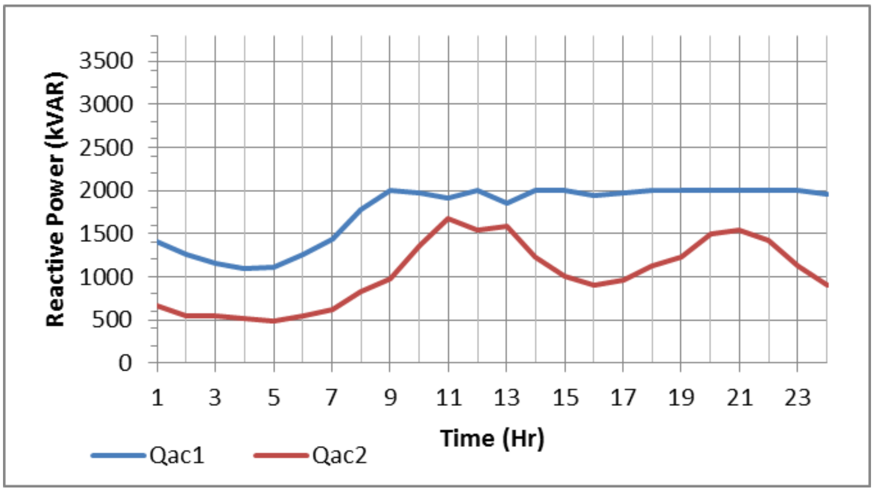


Figure 5.50- Reactive Dispatch of Generator Sets

The results also show that the power from the PV modules was used to both supply the load demand and store energy by the electrolyzer. The fuel cells supplied the night loads exceeding 2500kW. This is obvious in Figure 5.51. The stored hydrogen amount in kg is shown in Figure 5.52. Hydrogen is accumulated during day hours then consumed during night peak hours. A better voltage profile was also obtained by adding the storage system as in Figure 5.53. The average voltage is 0.98049Pu.

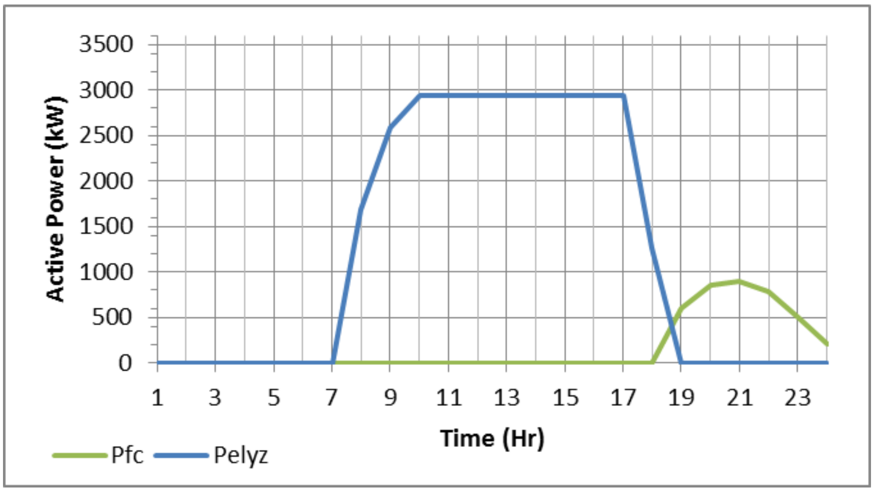


Figure 5.51-Electrolyzer And Fuel Cell Power

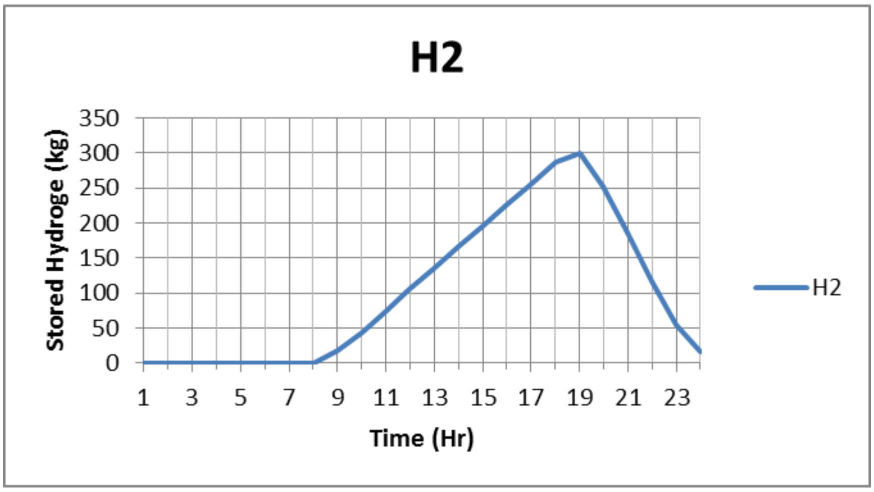


Figure 5.52- Stored Hydrogen

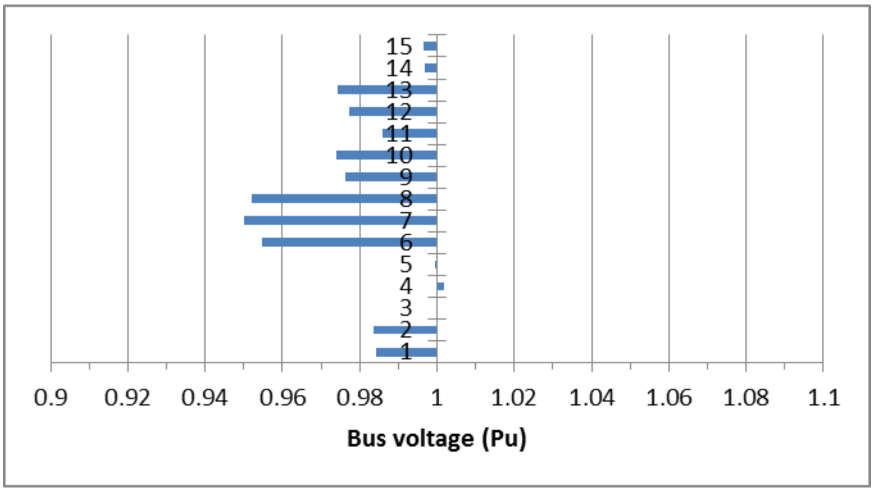


Figure 5.53-Average Bus Voltages

The addition of Hydrogen storage system along with renewable DERs helped reduce daily fuel costs to 455,670$, these can be dramatically reduced in the future due to the improvements in Hydrogen energy systems. Line losses also dropped to 1717.12kWh daily.

Scenario 1: Summer day-Hybrid System with storage-Flower Pollination Algorithm:

When FPA is applied to the same scenario with similar parameters, better results were obtained as the fluctuations in diesel generators' output were reduced. The output of each diesel generator set can be seen in Figures 5.54, 5.55.

The daily fuel costs were reduced to 444,321$ (2.5%decrease) and line losses increased to 1721.2kWh (0.23% increase).

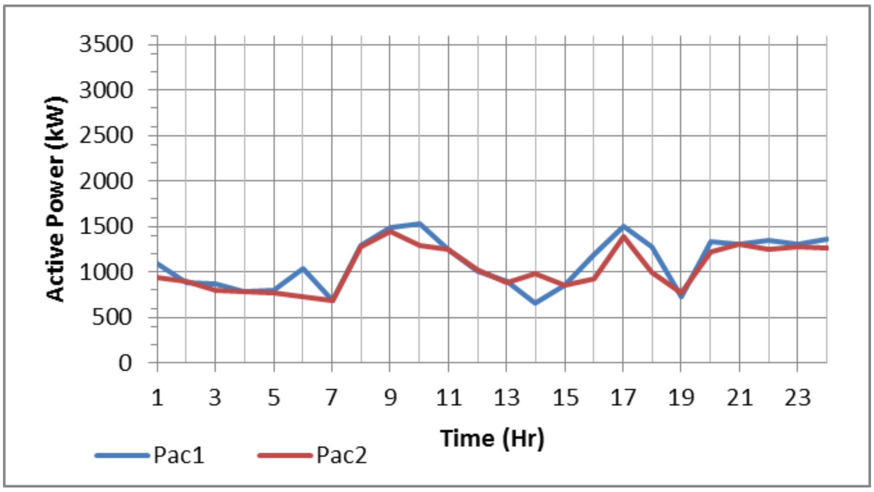


Figure 5.54- Active Dispatch of Generator Sets

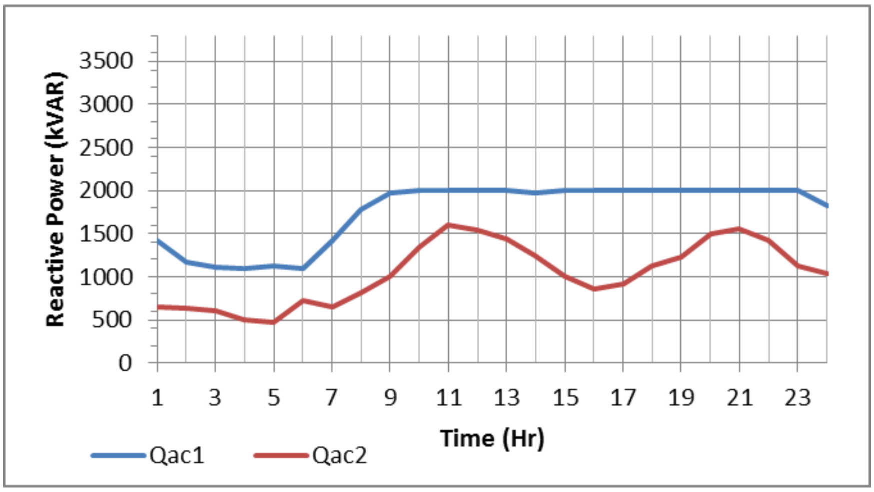


Figure 5.55- Reactive Dispatch of Generator Sets

Scenario 2: Winter day-Hybrid System with storage-Genetic Algorithm:

As previously mentioned, reduced output from PVs and higher output from WTs can be obtained during a winter day. In this scenario, the output of PVs and WTs is shown in Figures 5.56, 5.57.

The energy required during night peak times is less in a winter day (from the daily load profile of a winter day). Thus, less energy is required by the elctrolyzer. The energy is stored by electrolyzer and then consumed by the fuel cell arrays. This process is shown in Figure 5.58. Less Hydrogen will be accumulated during day. This can be seen in Figure 5.59.

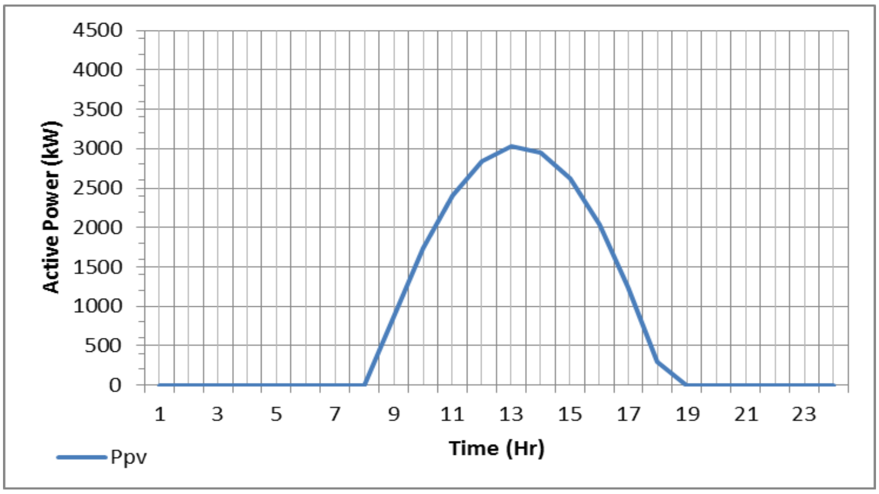


Figure 5.56- Pvs Output for A Winter Day

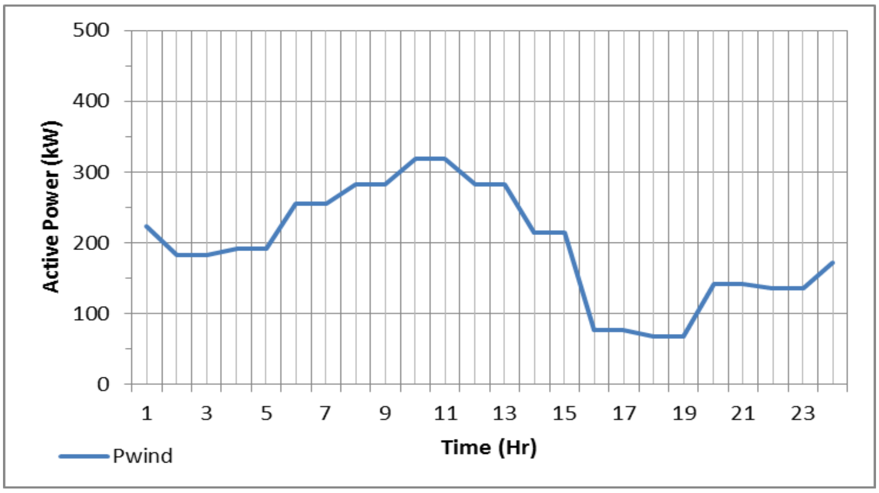


Figure 5.57- WTS Output for A Winter Day

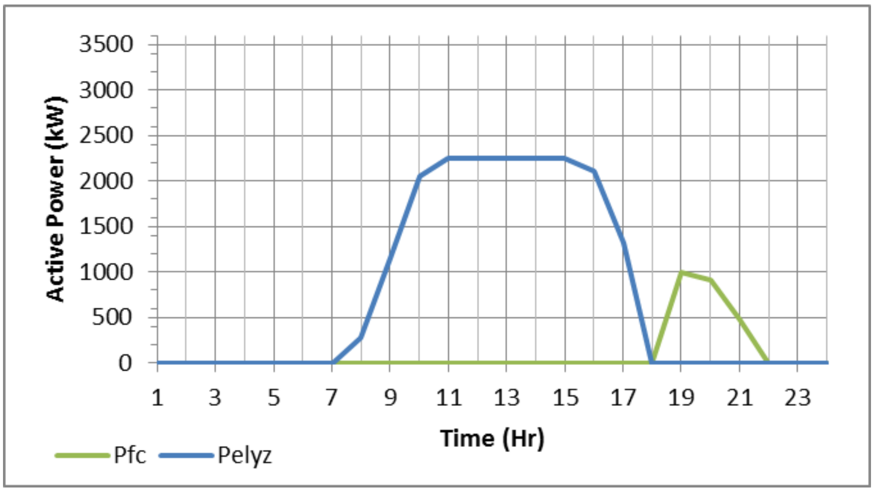


Figure 5.58- Electrolyzer And Fuel Cell Power

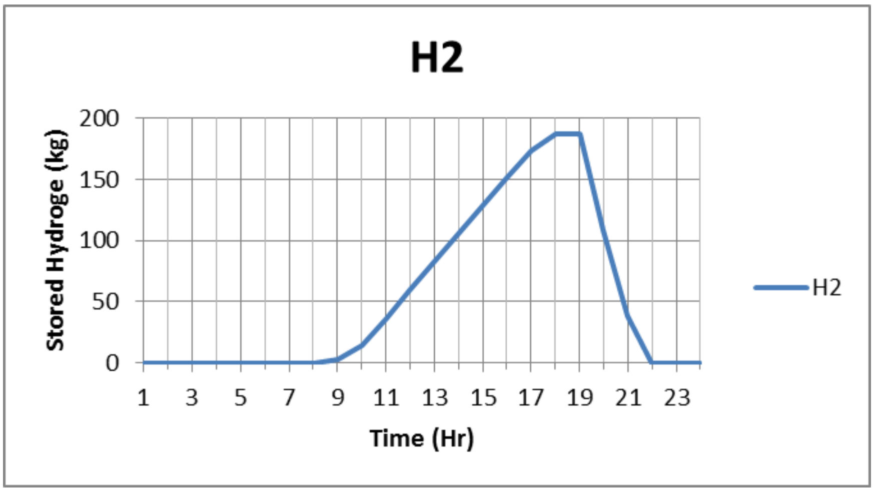


Figure 5.59- Stored Hydrogen

The active/reactive dispatch of each generator set is shown in Figures 5.60, 5.61. The daily fuel cost is 325,942$ and line losses are 1061.4, which represents a significant reduction from the previous, no storage, case study.

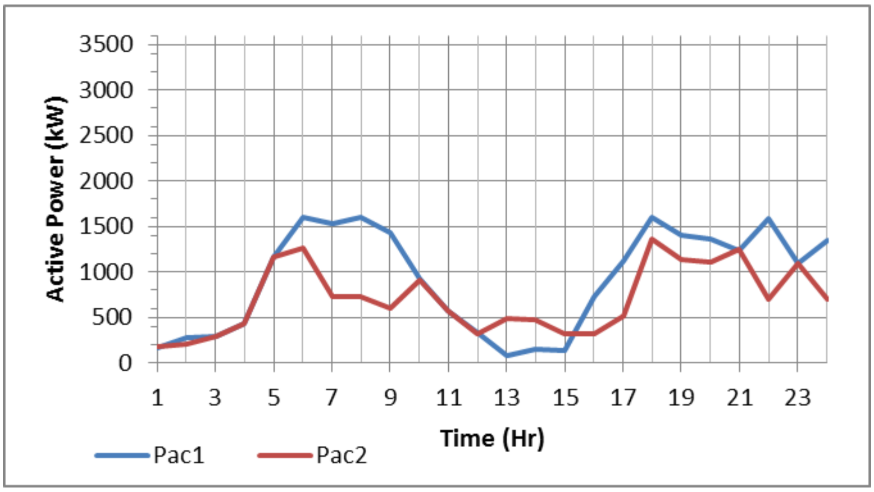


Figure 5.60- Active Dispatch of Generator Sets

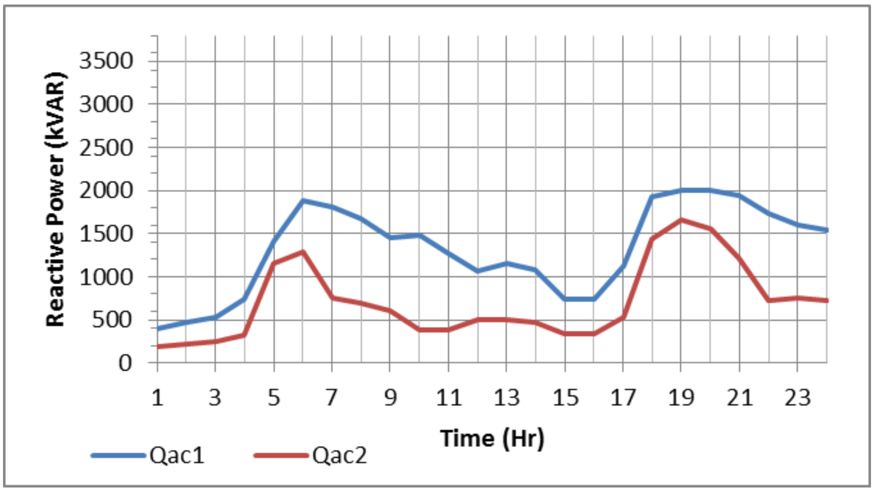


Figure 5.61- Reactive Dispatch of Generator Sets

Scenario 2: Winter day-Hybrid System with storage-Flower Pollination Algorithm:

The active/reactive dispatch of each generator set is shown in Figures 5.62, 5.63. Daily fuel costs were reduced by 4.2% compared to NSGA-II, the daily fuel cost obtained by FPA is 312,211$. Line losses were almost similar with an increase of 0.1% to 1062.84kWh daily.

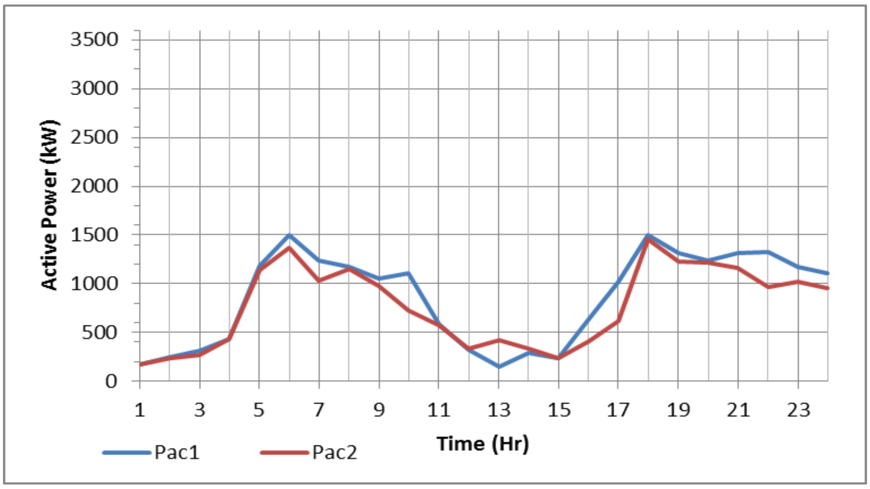


Figure 5.62- Active Dispatch of Generator Sets

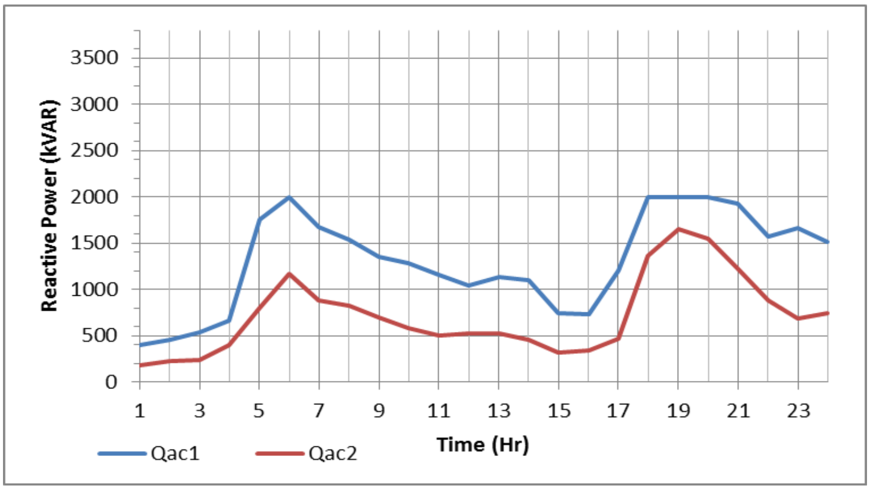


Figure 5.63- Rective Dispatch of Generator Sets

5.7 RESULT ANALYSIS SUMMARY

From the case studies and simulation scenarios conducted, various observations can be made. A comparison can be made between different options of generations, different optimization algorithms can be made.

From the previous illustrated results it can be concluded that the addition of renewable DERs achieved lower fuel costs and less line losses. This could provide cheaper energy for consumers of a microgrid, and moreover, higher energy efficiency is obtained.

The addition of Hydrogen storage system was beneficial that it reduced fuel costs, improved the form factor of diesel generator sets, introduced the option of downsizing the generators.

The improvements in microgrid performance were more noticeable during summer days when the demands are higher and the output from PVs is high and has high degree of certainty. Table 5.8 shows a comparison between the different options of supplying the microgrid for a summer day.

Table 5.8- Comparison Between Different Case Studies (summer day)

Case	Parameter	NSGA-II	MOFPA
Diesel only	Fuel cost ($)	784722.8	739021.4
	Losses (kWh)	1960.944	1985.983
	Average voltage (Pu)	0.977529	0.97778
Hybrid	Fuel cost ($)	518001.3	496548.2
	Losses (kWh)	1745.399	1753.757
	Average voltage (Pu)	0.980114	0.980069
Hybrid with storage	Fuel cost ($)	455669.7	444320.9
	Losses (kWh)	1717.116	1721.197
	Average voltage (Pu)	0.980488	0.980516

From table 5.8 it can be seen that adding renewable DERs reduced daily fuel costs by 33.9% in case of GA and 32.8% in case of FPA. Line losses were also reduced by 10.1%, 11.6%.

The further addition of Hydrogen storage reduced the costs by 12% in case of GA and 10.5% in case of FPA.

This makes the total reduction in fuel cost from a diesel only system to a complete hybrid system with storage 41.93% and 39.87% in case of GA and FPA respectively.

Figures 5.64, 5.65 illustrate the comparison between the three case studies.

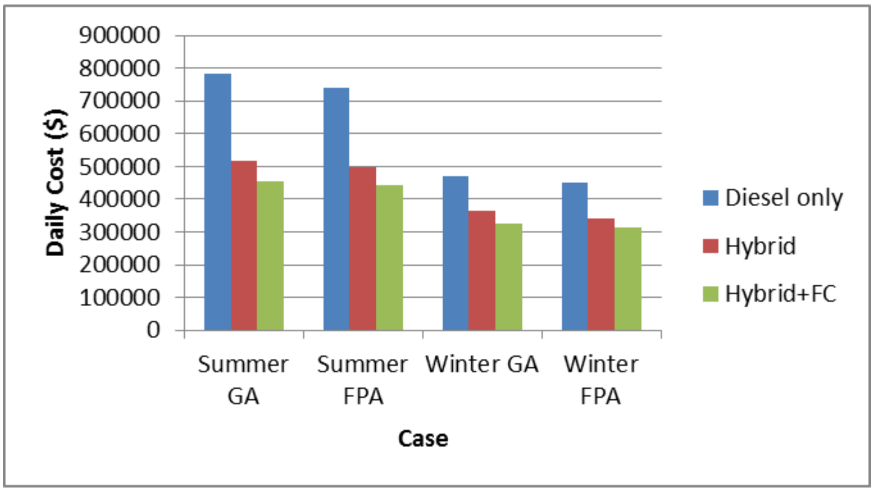


Figure 5.64- Case Studies Daily Cost

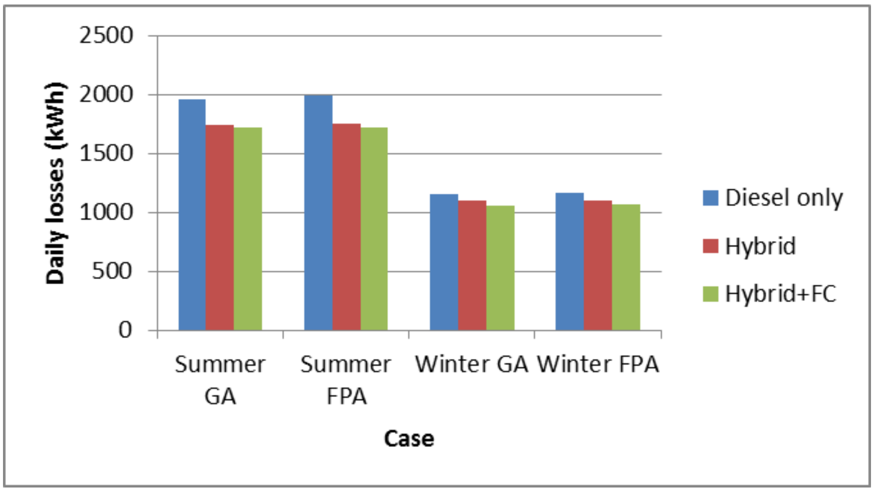


Figure 5.65- Case Studies Line Losses

The comparison between the traditional NSGA-II and the proposed modified FPA is, in fact, in favor of the proposed algorithm. When using the same optimization parameters, the proposed algorithm obtained better fuel costs in all cases compared to NSGA-II. The improvements range from 2% to 6.5% in some cases, with a compromise of very small ratios in the second objective (line losses).

Figures 5.66, 5.67 show a comparison between the two algorithms in all cases with respect to both objectives.

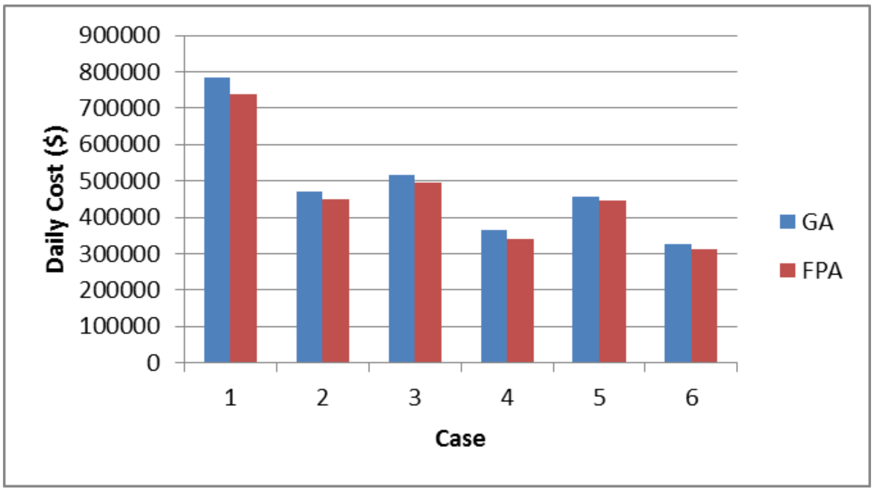


Figure 5.66- Daily Costs GA Vs. FPA

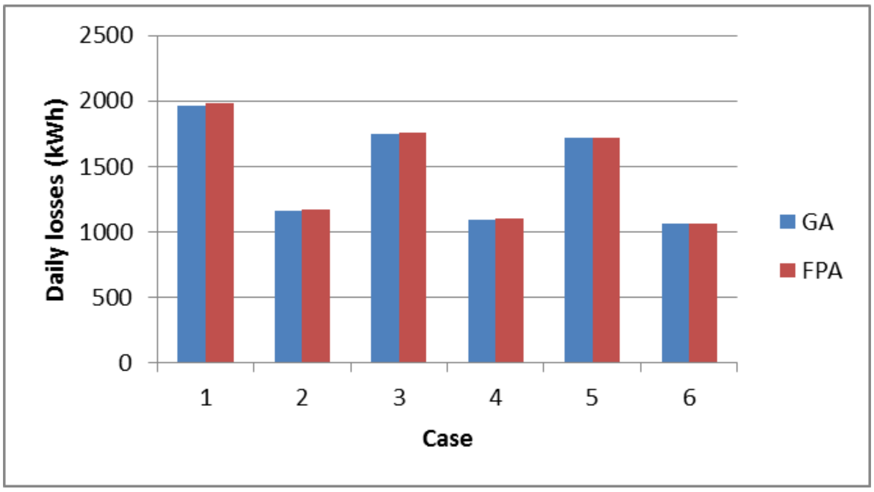


Figure 5.67- Line Losses GA Vs. FPA

When compared on hourly bases, FPA obtains better results in a vast majority of the cases. As observed in Figures 5.68-5.73. The Figures show complete domination of FPA in all cases.

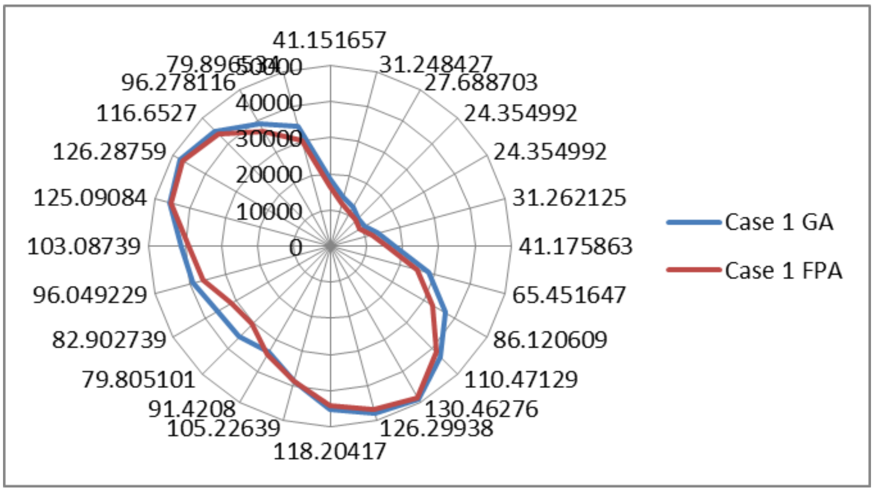


Figure 5.68- Results Comparison for Case 1-Scenario 1

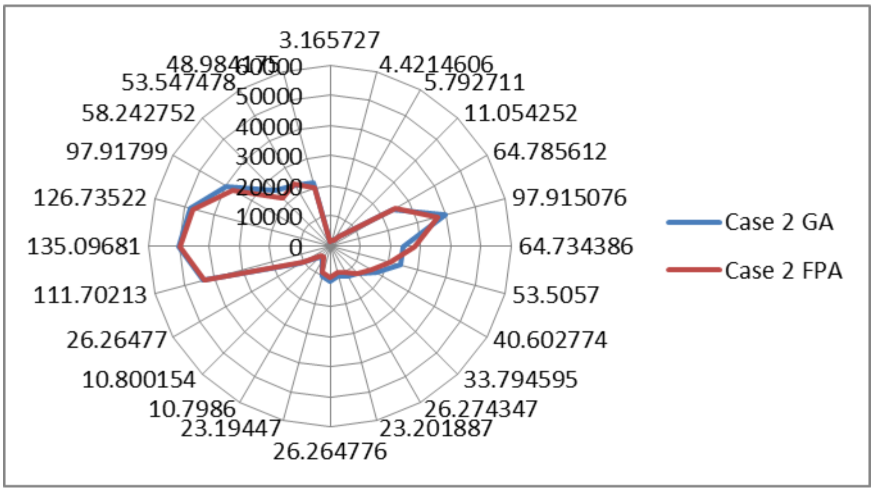


Figure 5.69- Results Comparison for Case 1-Scenario 2

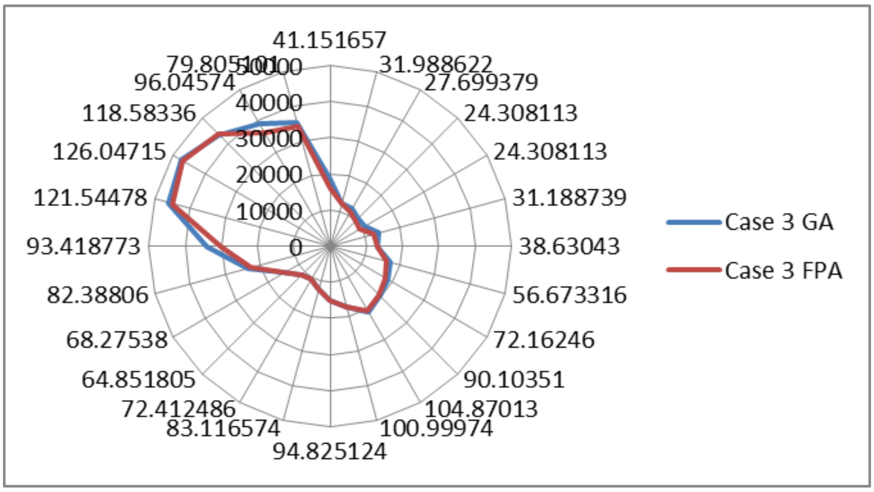


Figure 5.70- Results Comparison for Case 2-Scenario 1

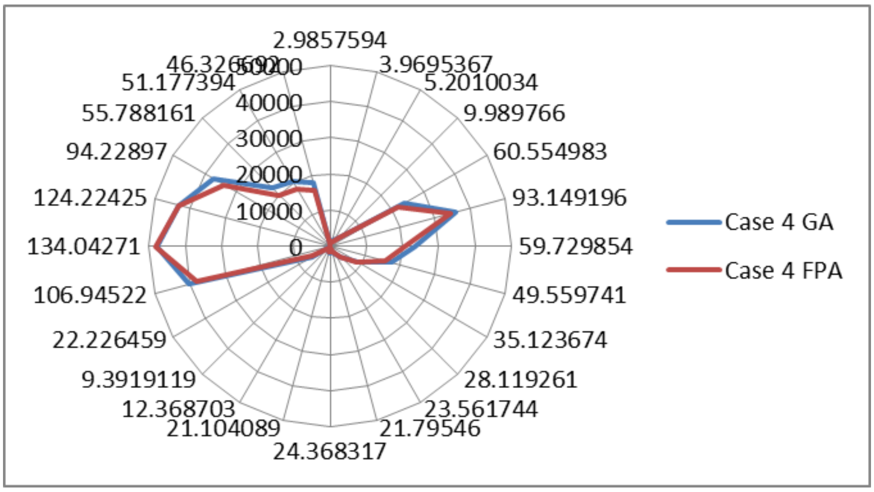


Figure 5.71- Results Comparison for Case 2-Scenario 2

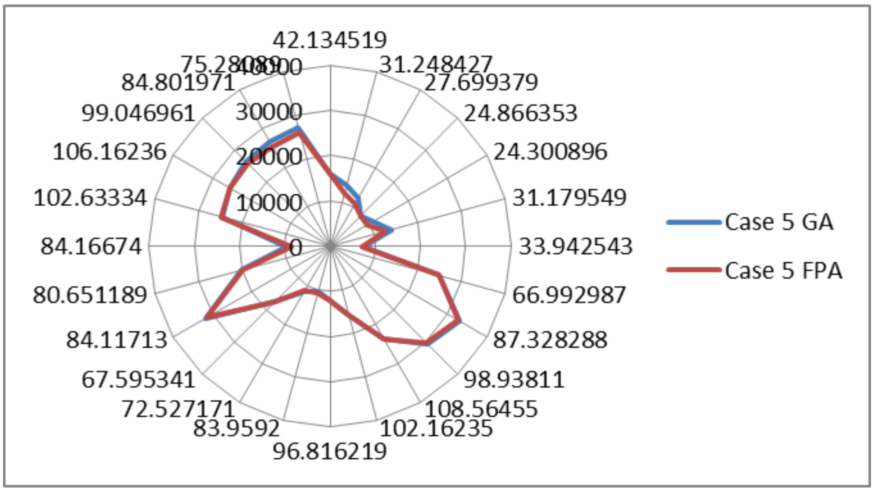


Figure 5.72- Results Comparison for Case 3-Scenario 1

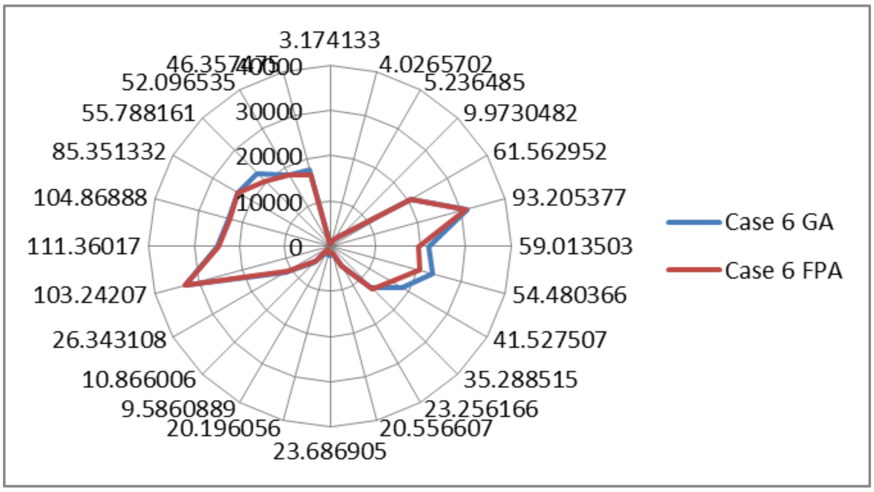


Figure 5.73- Results Comparison for Case 3-Scenario 2

A comparison between the two optimization algorithms regarding the convergence time will show a substantial advantage for modified FPA. When the stopping condition was changed to a threshold criteria (i.e. the process stops when a solution is reached that is better than a certain threshold). The two algorithms were tested 10 times each. Table 5.9 shows the results obtained from the simulation.

Table 5.9- Convergence Times of NSGA II Vs. MOFPA

Simulation Run	Elapsed Time (sec)	
	NSGA-II	MOFPA
1	27.957	5.059
2	27.347	5.412
3	49.094	7.27
4	114.222	5.012
5	117.903	3.706
6	2.227	4.413
7	2.82	4.35
8	18.742	2.473
9	14.043	5.866
10	35.921	5.332
Average	41.0276	4.8893

It is obvious that while NSGA-II has very low convergence times in rare cases (6, 7). However, it also has very high times up to 117.9 seconds (cases 4, 5). The convergence time of NSGA-II varies greatly in a very wide range. On the other hand, MOFPA maintained a very narrow range of 2.4-7.3 seconds. The average convergence time is incomparable; with NSGA-II requiring an average 10 times the time required by MOFPA.

Chapter Six

6 CONCLUSION & FUTURE WORK

6.1 CONCLUSION

In this thesis, extensive research in the field of microgrid optimization was carried out. An isolated microgrid was modeled accommodating different types of DERs, such as diesel generator, PV, WT and fuel cell utilized through a hydrogen storage system consisting of an electrolyzer and a hydrogen tank. Two different optimization techniques were used to investigate the performance of the microgrid under different case studies. NSGA-II optimization technique was initially used according to its high accuracy as previously mentioned in the literature, while the second optimization technique used is a proposed modified MOFPA. Although MOFPA was not previously used in similar applications, however it showed a significant improvement in the results obtained. The optimization objective is to minimize fuel costs and line losses in the system under equality and inequality constraints such as bus voltages, generation lower and upper limits and hydrogen storage capacity, using three main parameters; active power, reactive power and slack bus selection.

Reactive power was rarely optimized in previous research. However, including reactive power as an optimization parameter helped to reduce line losses and improve the overall performance of the grid. Moreover, this thesis highlighted a common problem in isolated microgrid; the absence of slack bus to be used in order to analyze the power flow in the microgrid. Thus, the traditional NR power flow analysis was modified to include the slack bus as an optimization variable, solved by mixed encoding GA.

An overview of the obtained results shows that the addition of renewable DERs reduced the systems fuel cost by a large percentage of 33% and decreased daily line losses by 11%. The further usage of energy storage techniques reduced the costs by 11% more and slightly reduced daily line losses. The total improvement due to the usage of a complete hybrid system was 41% in fuel costs and 12% in line losses.

Hydrogen energy storage techniques although proved economically unfeasible in the present, require more research and improvements in order to improve the efficiencies and fixed costs of different elements.

The proposed modified MO FPA proves worthy of consideration as it obtained results better by 2-6% in most cases. Moreover, the algorithm proved to converge towards an optimum solution 10 times faster than NSGA-II in most cases.

6.2 FUTURE WORK

More research can be carried out in light of the previous results, some future contributions are:

1- The addition of more generation types to the system.

2- Testing the algorithm on larger scale and more complex problems.

3- More research is required on Hydrogen energy storage applications.

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ملخص الرسالة

تعتبر الطاقة وستظل العمود الفقرى للاقتصاد العالمى، و بارتفاع اسعار الطاقة و حدوث التغيرات المناخية و التقدم التكنولوجى، تغير شكل صناعة الطاقة لتصبح اهم اولويات العالم. احد التقنيات الحديثة و الواعدة فى مجال الطاقة هى الشبكات الكهربية الذكية و التى تتكون من مجموعات من الشبكات الكهربية متناهية الصغر.

بواسطة استخدام المولدات صغيرة الحجم و الطاقات المتجددة جنبا الى جنب، يمكن لهذه الشبكات ان تغذى احمال كهربية بشكل اقتصادى و صديق للبيئة. لذلك بدأت دول عديدة تشجع على استخدام موارد الطاقة المختلفة و تكوين الشبكات المتناهية الصغر. فى هذه الرسالة، تم تمثيل شبكة متناهية الصغر معزولة رياضيا. هذه الشبكة توظف مصادر طاقة متعددة كالطاقة الشمسية و طاقة الرياح و تم تزويد الشبكة بنظام لتخزين الطاقة باستخدام خلايا الوقود و المحللات الكهربية و خزانات الهيدروجين.

تم تحليل التحكم الأمثل لهذه الشبكة باستخدام طريقتين: الخوارزمية الجينية بالفرز غير المهيمن، وخوارزمية تلقيح الزهور والتى لم يتم استخدامها فى مثل هذه المشاكل من قبل. و التحكم الأمثل فى هذه الحالة متعدد الأهداف، و اهدافه تخفيض تكاليف الوقود المستخدم فى توليد الطاقة و تخفيض فقد الطاقة فى الشبكة. يتم هذا التحكم الأمثل عن طريق تحديد الحل الأفضل للقدرة الفعالة و الغير فعالة و اختيار القضيب المرجعى الأمثل.و تم محاكاة حالات مختلفة و تمت دراسة و مقارنة النتائج لقياس أداء الشبكة و تأثير استخدام المصادر المختلفة.

تتكون هذه الرسالة من ستة أبواب، الباب الأول يستعرض مشكلة البحث و اهميتها و الدوافع للبحث فيها. كما يتم استعراض بعض الامثلة للشبكات المتناهية الصغر. يتم ايضا فى هذا الباب استعراض الترتيب العام للرسالة. يتم فى الباب الثانى استطلاع مصادر البيانات و المعلومات. و استطلاع اخر ما وصلت اليه الابحاث فى مجالات الشبكات المتنهاية الصغر و تمثيلها رياضيا و سريان القدرة، التحكم الأمثل و طرقه المختلفة، تخزين طاقة الهيدروجين و التحكم فى القدرة الغير فعالة. اما الباب الثالث فيشرح الانظمة المختلفة لتشغيل الشبكات متناهية الصغر. كما يتم استعراض فوائدها و مميزاتها و المعوقات التى تواجه تنفيذها و المتطلبات التقنية المختلفة. يتم ايضا استعراض المصادر المتعددة للطاقة كطاقة الرياح و الطاقة الشمسية و تقنية تخزين الطاقة باستخدام خلايا الوقود و المحلل الكهربى و خزانات الهيدروجين كحل محتمل لمشاكل الطاقات المتجددة. يليهم فى الباب الرابع يوفر شرحا موجزا لمبدأ التحكم الأمثل و الخوارزمية الجينية، حيث يتم استعراض مميزات الخوارزمية الجينية بالفرز غير المهيمن كالنخبوية و معاملة القيود. علاوة على ذلك تم اقتراح طريقة مبتكرة و هى خوارزمية تلقيح الزهور و التى لم يتم استخدامها فى المشاكل متعددة الاهداف من قبل.حيث تم تعديل الخوارزمية لتستطيع معاملة المشاكل متعددة الاهداف بطريقة الفرز غير المهيمن و اظهرت الطريقة المقترحة نتائج افضل من نظيرتها. اما المحاكاة والنتائج فيتم استعراضها فى الباب الخامس حيث يتم فى هذا الباب شرح عملية التمثيل الرياضى لعناصر الشبكة المختلفة، ثم دمجها و حل مشكلة غياب القضيب المرجعى فى الشبكات متناهية الصغر. وتلك المشكلة تم حلها عن طريق اختيار القضيب المرجعى الامثل كجزء من الخوارزمية. ثم اضافة القدرة غير الفعالة كعنصر مؤثر فى اداء الشبكة.

يلى هذا شرحا لطريقة عمل نموذج المحاكاة و الذى يتم تطبيقه على الشبكة فى حالات توليد مختلفة، بوجود مصادر الطاقة المتجددة، و بعد اضافة نظام تخزين الطاقة. كما يتم محاكاة النظام فى مواسم الصيف و الشتاء لدراسة اداء الشبكة فى ظروف مختلفة. يتم استعراض وتحليل نتائج المحاكاة و تقديم الاستنتاجات فى الباب السادس والأخير.

الأكاديمية العربية للعلوم و التكنولوجيا و النقل البحرى
كلية الهندسة و التكنولوجيا - القاهرة

تحليل التحكم الأمثل متعدد الأهداف فى الشبكات المتناهية الصغر المعزولة

إعداد

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لإستكمال متطلبات نيل الماجستير في

(الهندسة الكهربية والتحكم)

الأستاذ الدكتور / محمود مجدى عتيبة
مشرف
الدكتور / ايمان حسن بشر
مشرف

الأستاذ الدكتور /
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