Optimally-Sized Design of a Wind/Diesel/Fuel Cell Hybrid System for a Remote Community

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Remote communities, characterized by no connection to the main power grid, traditionally get their power from diesel generators. Long geographical distances and lack of suitable roads make the fuel transportation difficult and costly, increasing the final cost of electricity. A microgrid using renewable energy as the main source can serve as a viable solution for this problem with considerable economical and environmental benefits. The focus of this research is to develop a microgrid for a remote community in northern Ontario (Canada) that combines wind, as a renewable source of energy, and a hydrogen-based energy storage system, with the goal of meeting the demand, while minimizing the cost of energy and adverse effect on the environment. The existing diesel generators remain in the system, but their use is minimized.

The microgrid system studied in this research uses a wind turbine to generate electricity, an electrolyser to absorb the excess power from the wind source, a hydrogen tank to store the hydrogen generated by the electrolyser, a fuel cell to supply the demand when the wind resource is not adequate, and a diesel generator as a backup power.

Two scenarios for unit-sizing are defined and their pros. and cons. are discussed. The economic evaluation of scenarios is performed and a cost function for the system is defined. The optimization problem thus formulated is solved by solvers in GAMS. The inputs are wind profile of the area, load profile of the community, existing sources of energy in the area, operating voltage of the grid, and sale price of electricity in the area. The outputs are the size of the fuel cell and electrolyser units that should be used in the microgrid, the capital and running costs of each system, the payback period of the system, and cost of generated electricity. Following this, the best option for the microgrid structure and component sizes for the target community is determined.

Finally, a MATLAB-based dynamic simulation platform for the system under study with similar load/wind profile and sizing obtained in optimization problem is developed and the dynamic behaviour of microgrid at different cases is studied.

Acknowledgements

I would like to express my deepest gratitude to my supervisor, Professor Mehrdad Kazerani for his generous support and supervision.

I am also grateful to thesis readers Professor Claudio Canizares, and Professor Shesha Jayaram.

My great thanks to my parents, and brother for their encouragement, support, patience, and unconditional love.

Dedication

Dedicated to my dear brother, Abolfazl.

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List of Symbols - Parameters

C_{cap} : Capital cost of components

i : Annual interest rate

n : Project lifetime

i_{loan} : Interest for a loan

f : Annual inflation rate

C_{cap} : Replacement cost of units

n_{rep} : Lifetime of units needing replacement

T_{fc} : Total fuel consumption for lifetime of project

k_{fc} : Cost coefficient for fuel cell unit

k_{elec} : Cost coefficient for electrolyser unit

k_{diesel} : Cost coefficient for fuel cell unit

N : Sampling number in a year

$P_{wind,k}$: Wind power at any time k

$P_{load,k}$: Demand power at any time k

$P_{elec,base}$: Base size for electrolyser units

$P_{fc,base}$: Base size for fuel cell units

C_{H2} : Capacity of hydrogen tank

A_r : Swept area by wind turbine rotor

V_W : Wind velocity

C_p : Performance coefficient (or power coefficient)

ρ : Air density

λ : Tip speed ratio

β : Rotor blade pitch angle

ω_T : Angular speed of the turbine shaft (variable)

R : Rotor radius

N_{gear} : Gearbox ratio

V: Grid voltage

f : Grid frequency

R_s : Induction generator stator resistance

L_s : Induction generator stator inductance

R_r : Induction generator rotor resistance

L_r : Induction generator rotor inductance

L_m : Induction generator mutual inductance

J : Induction generator inetia

T : Absolute temperature

N_o : Number of cells in series

r : Ohmic loss

t_e : Electrical response time

r_{HO} : Ratio of Hydrogen to Oxygen

$f(v)$: Rayleigh PDF value at speed v

v : Wind speed

$f_{induction}$: Induction generator frequency

List of Symbols - Variables

$P_{fc,max}$: Rated size for fuel cell units

$P_{elec,max}$: Rated size for electrolyser units

$P_{diesel,k}$: Diesel generator power at any time k

$P_{fc,k}$: Fuel cell power at any time k

$P_{elec,k}$: Electrolyser power at any time k

a_{fc} : Integer variable for fuel cell units

a_{elec} : Integer variable for electrolyser units

P_T : Mechanical power extracted from wind turbine

T_T : Mechanical torque extracted from wind turbine

$w_{nominal}$: Induction generator nominal speed

E_a : Energy harvested by wind turbine

t : Time

P_d : Diesel generator power

$V_{induction}$: Induction generator voltage

Acronyms

ACC: Annual Capital Cost
ACS: Annual Cost of System
AFC: Annual Fuel Cost
AOC: Annual Operation Cost
ARC: Annual Replacement Cost
CF: Capacity Factor
CRF: Capital Recovery Factor
DE: Distributed Energy
FC: Fuel Cell
GAMS: General Algebraic Modeling System
IGBT: Insulated Gate Bipolar Transistor
MIP: Multiple Integer Programming
O&M: Operation and Maintenance
PCC: Point of Common Coupling
PF: Power Factor
PV: Photo Voltaic
RAPS: Remote Area Power Supply
RE: Renewable Energy
SFF: Sinking Fund Factor
SOFC: Solid Oxide Fuel Cell
TSR: Tip speed ratio

Chapter 1

Introduction

1.1 Research Motivation

Canada has over 300 remote communities with a total population of about 200,000. These communities, shown as stars in Fig. 1-1, are not connected to the North American electrical grid. Many of them are very dependent on imported oil and pay energy costs that can be up to 10 times higher than those in the rest of Canada [1].

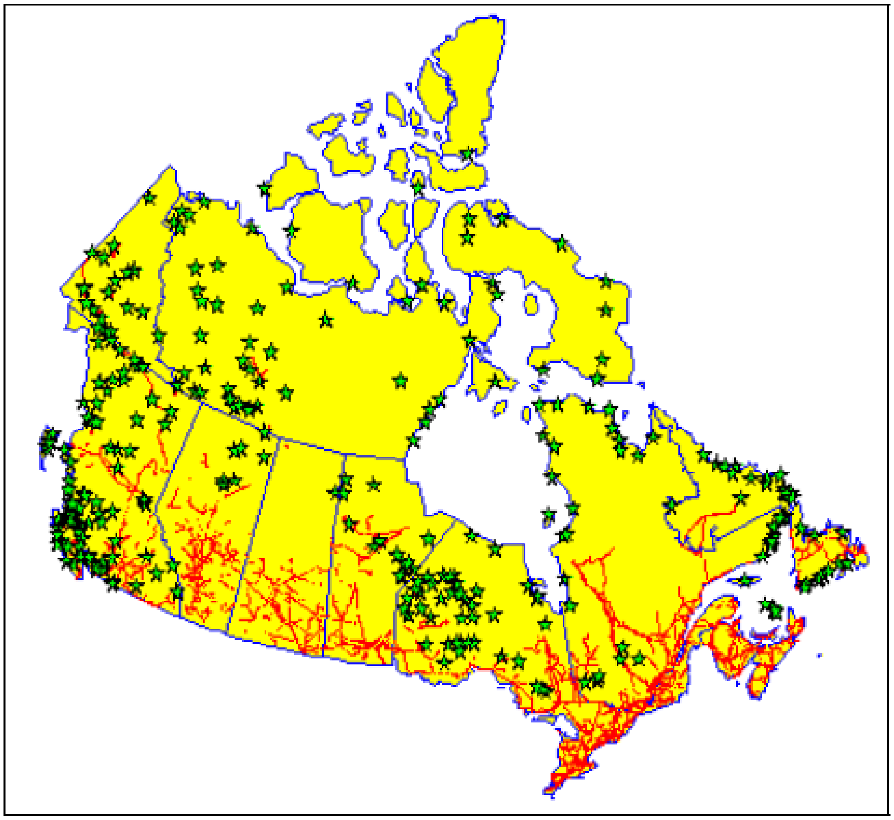


Fig. 1-1: Map of Canada's remote communities [1]

In recent years, wind energy projects in Canada's remote communities have been spurred by the improved reliability and affordability of wind energy systems and by the experience derived from earlier demonstration projects. Wind energy projects in Canada's remote communities are generally tied to isolated diesel grids to form wind-diesel hybrid systems in which wind essentially is used to save on fuel [1].

The wind-diesel systems designed for remote communities include storage devices like hydrogen storage or battery. In order to have an economical operation of such systems, an initial step is to economically size the components in this system. The unit-sizing of components in a system including renewable resources, diesel units, and storage devices aims for economical design of the system, lower cost of electricity, lower energy dump, and better environmental impacts.

1.2 Research contribution

Using a renewable resource in combination with diesel generator, the real load profile of a remote community in the northern Canada, a hydrogen-based energy storage system, long-term analysis of the data, and environmental impact consideration make this research prominent compared to the other studies in the field of hybrid systems unit-sizing. In order to study the complications of operation and long-term storage of energy, hydrogen storage has been chosen.

The load profile and the wind profile of the remote community are used to study the behaviour of the system during one year time period. This load and wind profile can be replaced with load and wind profile of any other community. As a result of this research, a renewable resource of energy can be combined with traditionally used diesel generators to supply the demand and meet the power balance using storage devices. This can be a good initial point to start renewable energy projects in remote communities. A pre-evaluation of such projects can save time and money, and can be an initial picture of a future system that needs to be implemented in the area.

The hybrid system studied in this research uses a wind turbine, as the main source of energy, an electrolyser to absorb the excess power from the wind source, a hydrogen tank to store the hydrogen generated by the electrolyser, a fuel cell to supply the power deficit when the wind resource is not adequate to meet the demand, and a diesel generator as a backup and frequency/voltage regulator.

The method used to optimize the sizes of components in the hybrid system is a general method and can be used in similar systems. The inputs of the model are the existing data from load, wind profile, and economical parameters, and the outputs are sizes of wind turbine, fuel cell unit, electrolyser unit, and hydrogen tank.

The developed model is capable of accepting different assumptions. Scenarios studied in this research can be extended to cover new cases. As mentioned before, this study can be regarded as a starting in making decisions about the future system needs.

A detailed dynamic model of microgrid is modeled in MATLAB. The sizes of components in microgrid are the sizes obtained in optimization problem. The dynamic behaviour of microgird is studied under different points to obtain power share between components of microgrid.

1.3 Thesis Objectives

Based on the state-of-the-art in hybrid systems modeling and sizing, the main objectives of this thesis are as follow:

1- Defining a microgird including renewable resources and develop a model for power flow between components of the system;

2- Developing an optimization method to size the components of microgrid in order to minimize the annual cost of system;

3- Considering all economical parameters to achieve a model close to the real system; and

4- Developing a microgrid model composed of wind turbine, fuel cell, electrolyser, and diesel generator to study the power share between components of microgrid obtained in optimization problem.

1.4 Thesis Structure

Chapter 2 is dedicated to historical background and literature survey. This chapter introduces the current state of microgrid research and application, with a focus on wind-diesel hybrid systems for remote areas. In this chapter, a brief history of integration of renewable resources in traditional, diesel-operated systems is given. Optimization methods for unit-sizing purposes are discussed; pros. and cons. of each method are mentioned.

Chapter 3 presents an overall model for the hybrid system, and an optimization problem to size the fuel cell, electrolyser and hydrogen tank and achieve minimum cost of electricity. The optimization problem modeling and formulation, as well as economical modeling of the problem to conduct optimal unit-sizing for the hybrid system components, is discussed in this chapter.

Chapter 4 starts with modeling of hybrid system components in MATLAB, and verification of models in starting and steady-state operations. The models of wind turbine, fuel cell and electrolyser are simulated and verified. Then, the components are integrated in an overall system model. The power balance at steady state in all components is investigated and presented.

Finally, chapter 5 summarizes the thesis main points and contributions and proposes direction and suggestion for future work.

Chapter 2

Background and Literature Review

2.1. Microgrid definition

A microgrid is a cluster of interconnected distributed generators, loads and intermediate energy storage units that co-operate with each to be collectively treated by the grid as a controllable load or generator. It is connected to the grid at only one point, the point of common coupling (PCC). The main objective of its conception is to facilitate the penetration of distributed generation and provide high quality and reliable energy supply. The components that constitute the microgrid may be physically close to each other or distributed geographically.

Figure 2-1 depicts a typical microgrid. The energy sources may be rotating generators or distributed energy (DE) sources directly connected to grid or interfaced by power electronic inverters. The installed DE may be wind, solar, fuel cells, geothermal, biomass, steam and gas turbines.

The connected loads may be critical or non-critical. Critical loads require reliable source of energy and demand stringent power quality. These loads have a backup source of energy that is shown as G in the figure. Non-critical loads may be shed during emergency situations and when required as set by the microgrid operating policies. The intermediate energy storage device is an inverter-interfaced battery bank, hydrogen storage, supercapacitors or flywheel [2].

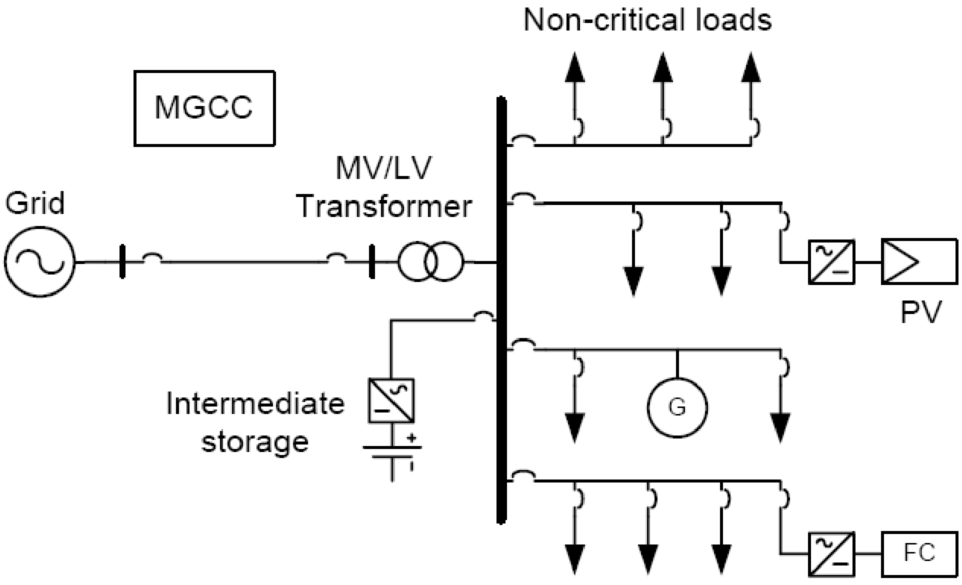


Fig. 2-1: An example of microgrid

The microgrid components are controlled using a decentralized decision making process in order to balance demand and supply coming from the microsources and the grid. A central controller (microgrid central controller or MGCC) controls the actions of all components of the microgrid. The MGCC optimizes operation by maximizing the value of the microgrid. It is also capable of implementing demand side management.

The microgrid can operate in grid-connected mode or in islanded mode. In grid-connected mode, the microgrid either draws or supplies power to the main grid. The microgrid components are controlled using a decentralized decision making process in order to balance demand and supply coming from the sources and the grid.

2.2. Historical background and literature survey

Remote communities, characterized by no connection to the main power grid, traditionally get their power from diesel generators. Long geographical distances and lack of suitable roads make the fuel transportation difficult and costly, thus increasing the final cost of electricity. A microgrid using renewable energy as the main source can serve as a viable solution for this problem with considerable economical and environmental benefits.

Studies have shown that the integration of wind power into traditionally diesel-only remote area power supply (RAPS) systems can significantly reduce the harmful emissions and life-cycle costs. Due to the very high costs of installing and maintaining transmission lines, islands and small villages located away from main grids often have their own power supply system. These stand-alone systems are typically powered by conventional diesel generators as they have high reliability, low capital cost and are easily deployable. In recent years however, there has been a trend towards renewable installations for both economic and environmental reasons. While the cost of renewable energy sources is dropping and the diesel fuel price is increasing and its supply diminishing, hybrid systems are already an attractive option [3].

The Ramea wind-diesel project is the first medium penetration wind installation integrated to a diesel generator-based power supply system in Canada. Integration of renewable energy (RE) sources into fossil-fuel based power generation systems for remote areas offers attractive economical and environmental merits including considerable fuel savings and carbon dioxide emission reductions. However, intermittent aspect of RE sources along with highly variable nature of load demand for these applications may lead to significant degradation of RE utilization due to the excess RE losses [4].

Various optimization techniques, such as probabilistic approach, graphical construction method and iterative technique, have been recommended for renewable energy system designs. Besides these optimization techniques for designing solar and/or wind systems, some diesel generator control strategies have been reported for the design of power generation systems including diesel generators [5].

In [4], an energy-flow model developed for performance analysis and unit sizing of an autonomous wind-diesel microgrid has been introduced. A remote community is used as the study system, for which a wind power plant has been integrated at a medium penetration level into a system served by diesel generators. Lack of an energy storage component in this system is considered a disadvantage.

Reference [5] recommends an optimal model for the design of stand-alone hybrid solar-wind-diesel systems. The optimum configuration ensures that the annual cost of the system is minimized, while satisfying the load demand for a 5-year period, resulting in zero load rejection with minimum cost. The objective function minimization is implemented using genetic algorithm.

Reference [6] performs an economical evaluation of a hybrid wind-photovoltaic-fuel cell generation system. In this configuration, the combination of a fuel cell stack, an electrolyser, and hydrogen storage tanks is used as the energy storage system.

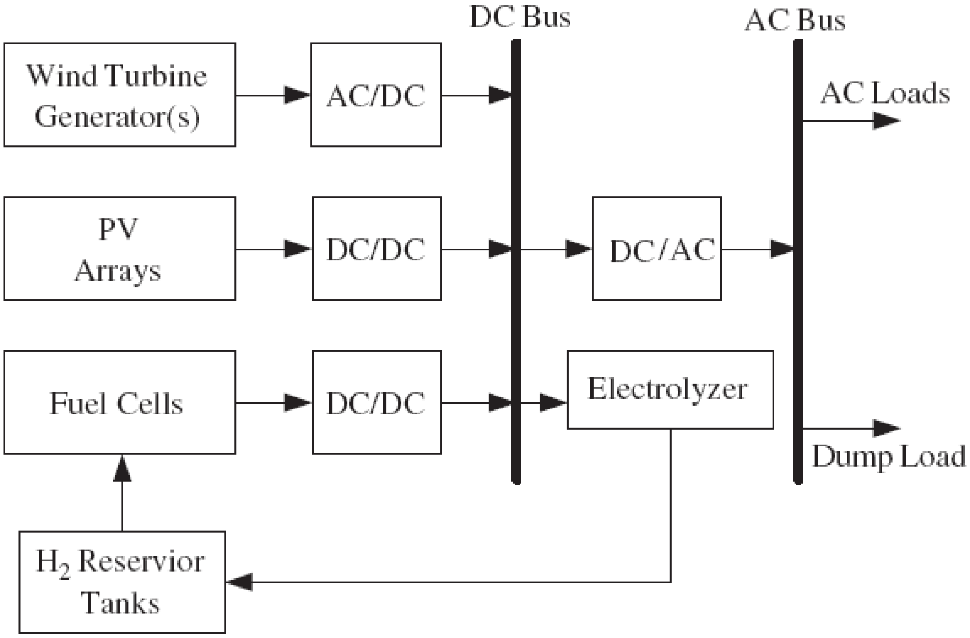


Fig. 2-2: Proposed wind-PV system with FC-electrolyser storage in [6]

The optimization of a hydro-solar-wind-battery hybrid system in context of minimizing the excess energy and cost of energy has been discussed in [7]. The configuration of the hybrid system is derived based on a theoretical domestic load at a remote location.

Reference [8] proposes an optimal design for a wind-PV-diesel-battery hybrid system. CO_2 emissions have been considered in this study, and the optimization has been done based on genetic algorithm.

A method for calculation of the optimum size of a battery bank and the PV array for a standalone hybrid wind-PV system is developed in [9]. For a given load, the optimum number of batteries and PV modules were calculated based on the minimum cost of the system.

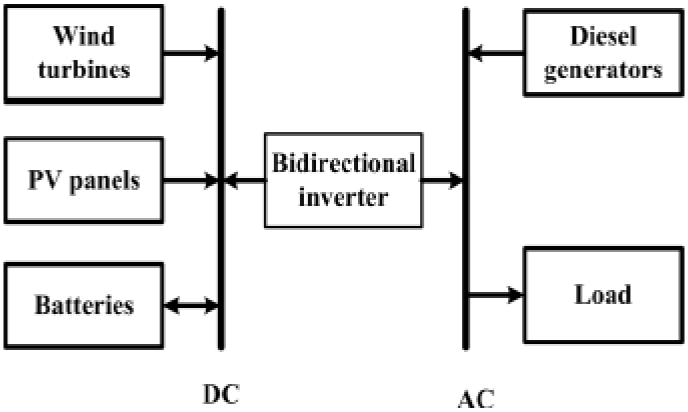


Fig. 2-3: Configuration of hybrid system in [8]

The hybrid system studied in this thesis uses a wind turbine, as the main source of energy, an electrolyser to absorb the excess power from the wind source, a hydrogen tank to store the hydrogen generated by the electrolyser, a fuel cell to supply the power deficit when the wind resource is not adequate to meet the demand, and a diesel generator as a backup.

Using a renewable resource in combination with diesel generator, the real load profile of a remote community in northern Canada, a hydrogen-based energy storage system, long-term analysis of the data, and environmental impact consideration make this study prominent compared to other studies in the field of hybrid systems unit-sizing. In order to study the complications of operation and long-term storage of energy, hydrogen storage has been chosen.

2.3. The proposed microgrid

The microgrid that will be developed and studied is shown in Fig. 2-4. It includes wind turbine connected to the AC bus via a squirrel-cage induction generator, a diesel generator, load of the area, and electrolyser-hydrogen storage-fuel cell system.

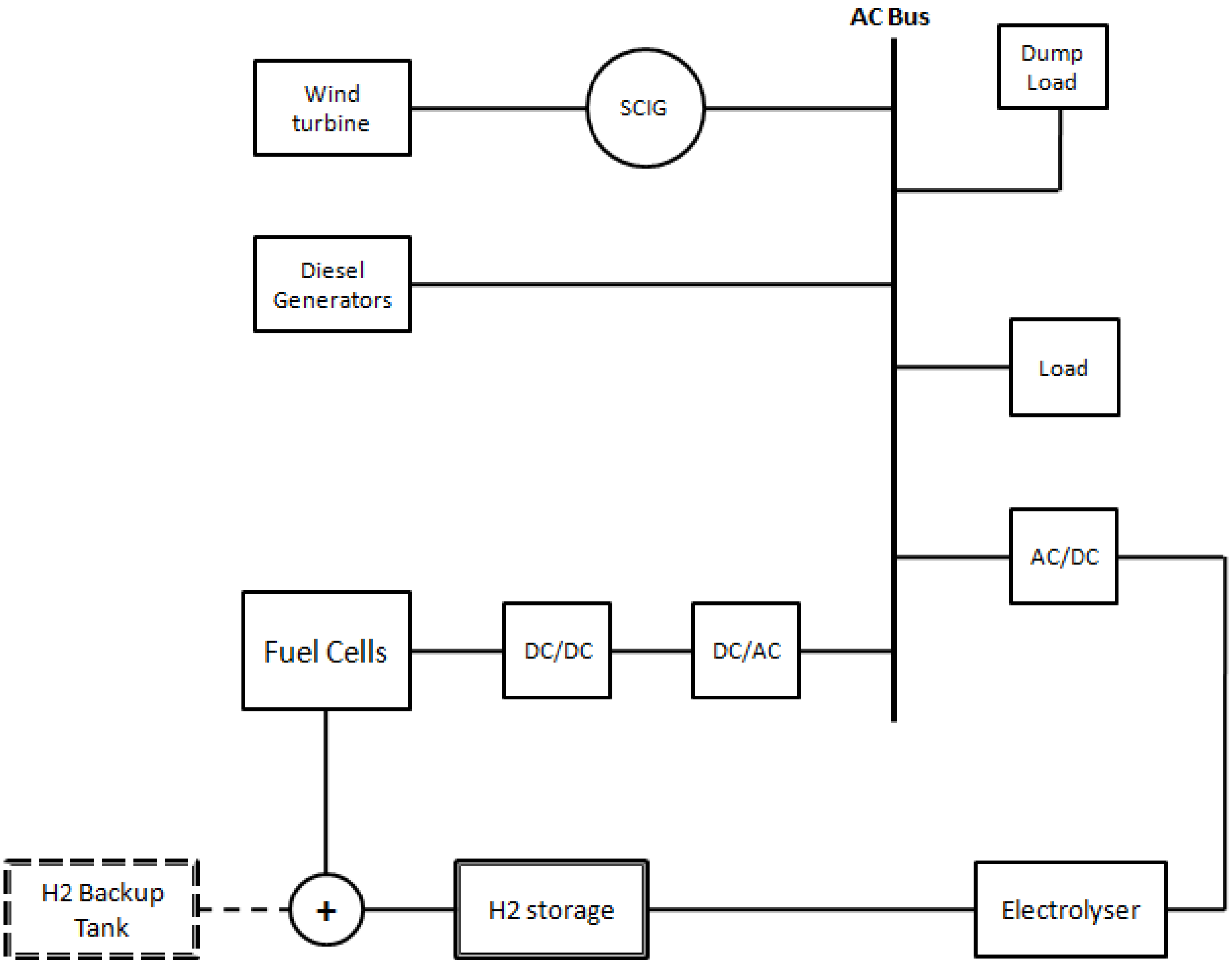


Fig. 2-4: Block diagram of the microgrid under study

The fuel cell system is connected to the AC bus through two cascaded power converters (a DC/DC and a DC/AC); electrolyser is connected to the AC bus through an AC/DC converter; and there is a hydrogen tank that has been used as hydrogen storage unit. A back-up hydrogen tank is sometimes used in the simulations.

A simple power management algorithm has been used to operate the system. It should be mentioned that an optimal operating strategy can be derived for the system; however, this is beyond the scope of this work and is planned as future work.

This system uses a wind turbine, as the main source of energy, an electrolyser to absorb the excess power from the wind source, a hydrogen tank to store the hydrogen generated by the electrolyser, a fuel cell to supply the power deficit when the wind resource is not adequate to meet the demand, and a diesel generator as a backup, and in some cases as frequency and voltage regulator.

Chapter 3

Unit-sizing of Microgrid

3.1 Introduction

The microgrid proposed in Chapter 2 uses a wind turbine as the main source of energy, hydrogen storage device including electrolyser to absorb the excess power from the wind source, a fuel cell to supply the power deficit when the resources is not adequate to meet the demand, a hydrogen tank to store the hydrogen generated by electrolyser, and a diesel generator as a back-up source.

A simple power management algorithm has been used to operate the system. It should be mentioned that an optimal operating strategy can be derived for the system; however, this is beyond the scope of this work and is planned as future work.

The three scenarios used for the purpose of unit-sizing are as follows:

1- **Diesel-only operation:** The system is operating in its traditional mode, and it uses diesel generators as power source. This scenario can be considered as the base operating mode. The advantages of this scenario are low capital cost, low maintenance, no dumped energy, and simple power management algorithm. The disadvantages are dependence on fuel and very high greenhouse gas emissions.

2- **All renewable:** In this scenario, all the demand will be met by the renewable energy sources (wind energy in this research). The diesel generator unit will be used as backup for this system and will be operated in the case where the power generated by renewable source and fuel cell is not adequate to meet the demand. The rated power of wind turbine will be calculated considering two parameters: (i) average demand of the system, and (ii) capacity factor of wind generation system. The flowchart of this scenario can be seen in Fig. 3-1, where the decision making algorithm is illustrated.

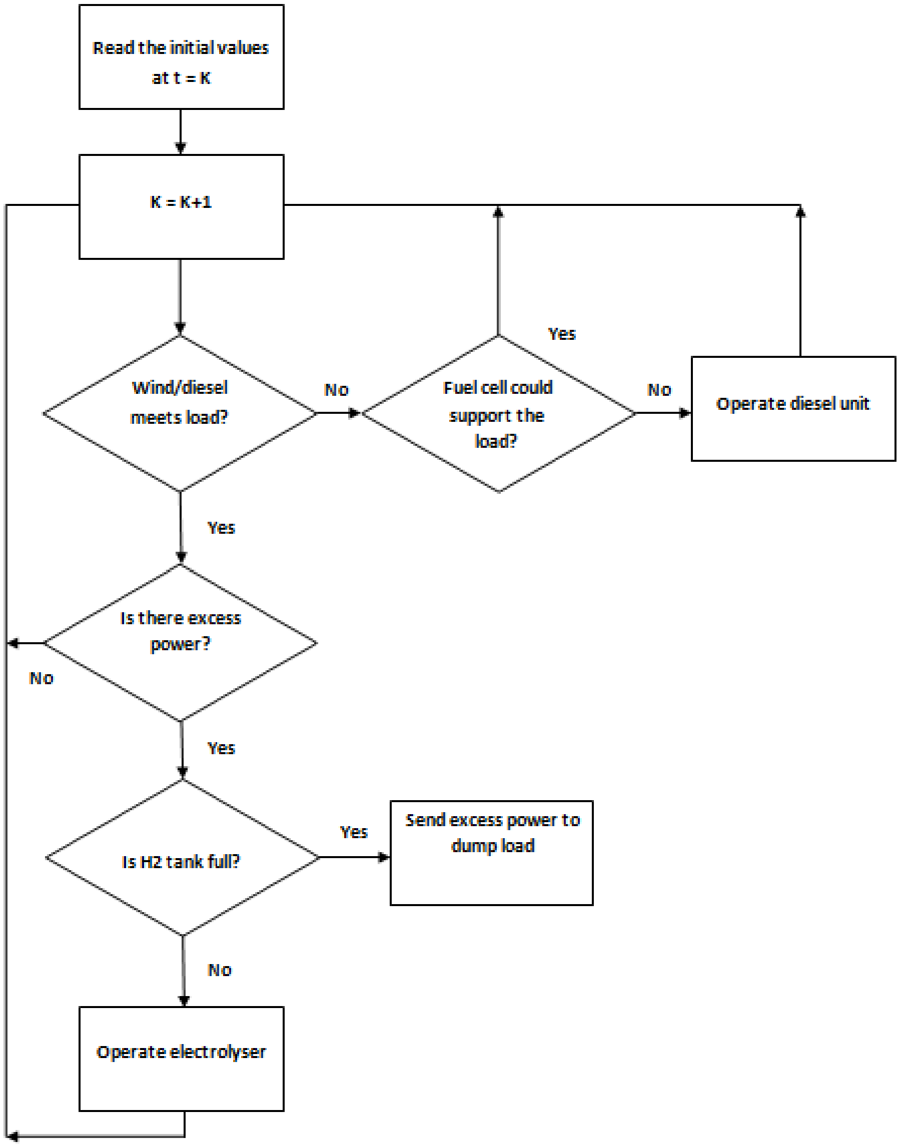


Fig. 3-1: The flowchart of all-renewable operation

In the case where wind and diesel together cannot meet the demand, the algorithm goes to check the availability of power by fuel cell. If there is hydrogen in the tank, and the extra demand to be met is less than capacity of fuel cell, fuel cell will supply the demand. Otherwise, diesel generator will start to work, or will increase its power to meet the demand. There is some reserved power capacity that is met by diesel generator. It is assumed that there is no load shedding. The advantages of this scenario are very low operating cost, very low emissions, and independence from fuel price variations. The disadvantages are intermittent nature of wind energy, high capital cost of system, and inefficient operation of diesel generators.

3- **Parallel:** In this scenario, the diesel generator unit is operating in parallel with renewable sources, and is responsible for feeding part of the load. As a constraint, the diesel unit always should work in its most efficient power region. The rest of the demand should be met by renewable and hydrogen sources.

The advantage of this scenario is having parallel operation of sources resulting in higher reliability, lower capital cost, and more efficient operation of diesel unit. On the other hand, the adverse environmental impact is more strongly pronounced, and the acceptability of system is dependent on fuel price.

To find the rated power of the wind turbine required in the first scenario, the average load of the area under study $(550\ kW)$ and the capacity factor of wind used are as follows:

$$P_{wind\_full\_renewable} = \frac{550}{0.125} = 4400\ kW \qquad (1)$$

The wind turbine units used in this study are $25\ kW$ each; then *176* wind turbine units are required. In the second scenario, the diesel generator is supposed to supply the base load of the area. The base load is $400\ kW$ hence a $600\ kW$ diesel generator unit is used for this purpose. The rest of load should be met by wind turbine. Same calculations as in the previous case give:

$$P_{wind\_parallel} = \frac{550-400}{0.125} = 1200\ kW \qquad (2)$$

thus *48* wind turbines are required.

3.2 Economical modeling

The economical model used in this study is based on annual cost of system (ACS) in order to find the minimum cost of electricity. Annual cost of system is composed of annual capital cost (ACC), annual replacement cost (ARC), annual fuel cost of diesel generators (AFC) and annual operation and maintenance cost (AOC) [8]. The components to be considered in the equations are wind turbine, electrolyser, fuel cell, hydrogen storage tank, diesel generator, and dump load. ACS can be calculated from (1) as:

$$ACS = ACC + ARC + AFC + AOC \tag{3}$$

1. Annual Capital Cost (ACC):

   Annual capital cost of units that do not need replacement during project lifetime is as follows:

   $$ACC = C_{cap} * CRF(i,n) \tag{4}$$

   where

   C_{cap}: Capital cost of components

   CRF: Capital recovery factor, defined as:

   $$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{5}$$

   n: project lifetime (year)

   i: Annual interest rate, consisting of nominal interest rate and annual inflation rate, defined as:

   $$i = \frac{i_{loan} - f}{1+f} \tag{6}$$

   where

   i_{loan}: Rate at which a loan can be obtained

   f: Annual inflation rate

2. Annual replacement cost (ARC):

Units that need to be replaced during lifetime of the project are the units that have lifetimes less than project lifetime. The annual replacement cost can be calculated from the following equation:

$$ARC = C_{rep} * SFF(i, n_{rep}) \qquad (7)$$

where

C_{rep}: Replacement cost of units

n_{rep}: Lifetime of units

SFF: Sinking fund factor, a ratio that calculates the future value of a series of equal annual cash flow as follows:

$$SFF(i, n_{rep}) = \frac{i}{(1+i)^{n_{rep}} - 1} \qquad (8)$$

3. Annual fuel cost (AFC):

   Fuel cost of diesel generators can be expressed as follows:

   $$AFC = T_{fc} * CRF(i, n) \qquad (9)$$

   where

   T_{fc}: Total fuel consumption for lifetime of the project

4. Operation and maintenance:

   Maintenance cost of units can be calculated as follows:

   $$AOC = AOC(1) * (1 + f)^n \qquad (10)$$

   $AOC(1)$ is the maintenance cost for the first year of project.

3.3 Optimization problem formulation

This section presents the proposed optimization model for the system under study. The formulation of the problem has been done based on power dispatch algorithm presented in 3-1. To define a cost function, the system has been operated during the entire year. The mathematical formulation is described in (9)-(18). This model is formulated as MIP (Multiple Integer Programming) in GAMS environment, and the solver is BDMPL.

A. Objective Function

The objective is to minimize the cost of electricity produced by the hybrid system. The cost of electricity depends on capital and operating costs of components. The sizes of units and the energy used by diesel generators reflect the cost of system. The simulation has been done for a year; so, the objective function can be described as follows:

$$Cost = k_{fc} * P_{fc,max} + k_{elec} * P_{elec,max} + k_{diesel} \sum_{k=1}^{N} P_{diesel,k} \qquad (11)$$

where $P_{fc,max}$ and $P_{elec,max}$ are the rated sizes of fuel cell and electrolyser, respectively, and $P_{diesel,k}$ is the power of diesel generator at any time k. Parameters k_{fc}, k_{elec}, and k_{diesel}, are extracted from economical equations of the system and determine the weight of each component in optimization problem.

$$k_{fc} = ACC_{fc} + ARC_{fc} + AOC_{fc} \qquad (12)$$

$$k_{elec} = ACC_{elec} + ARC_{elec} + AOC_{elec} \qquad (13)$$

$$k_{diesel} = AOC_{diesel} + AFC_{diesel} \qquad (14)$$

$$AOC_{diesel} = 1000 * (1 + f)^{n1} \qquad (15)$$

$$AFC_{diesel} = diesel_c * 20 * diesel_e * CRF_1 + {CO_2}_{cost} * 20 * diesel_e * CRF_1 \qquad (16)$$

where $diesel_c$ and $diesel_e$ are diesel fuel price and diesel generator energy in one year, and ${CO_2}_{cost}$ is the carbon tax to be paid for each energy unit.

N depends on time interval of simulation and the sampling time. Samples are obtained once in an hour during a year, so N is 8760.

B. Constraints

1) Power flow equation

$$P_{fc,k} + P_{diesel,k} + P_{wind,k} - P_{elec,k} - P_{load,k} = 0 \qquad (17)$$

$$\forall k = 1 \; to \; N$$

2) Ratings of FC and electrolyser

$$\left(P_{wind,k} + P_{diesel,k} - P_{load,k}\right) - P_{elec,max} \leq 0 \qquad (18)$$

$$(P_{load,k} - P_{wind,k} - P_{diesel,k}) - P_{fc,max} \leq 0 \qquad (19)$$

$$P_{fc,k} - P_{fc,max} \leq 0 \qquad (20)$$

$$P_{elec,k} - P_{elec,max} \leq 0 \qquad (21)$$

$$\forall k = 1 \; to \; N$$

3) Discrete sizes of FC and electrolyser units

$$P_{fc,max} = a_{fc} P_{fc,base} \qquad (22)$$

$$P_{elec,max} = a_{elec} P_{elec,base} \qquad (23)$$

where a_{fc} and a_{elec} are integer variables, and $P_{fc,base}$ and $P_{elec,base}$ are base units of FC and electrolyser, respectively.

4) Hydrogen tank state of charge

$$\sum_{K=1}^{N} (P_{fc,k} - P_{elec,k}) \leq 0 \qquad (24)$$

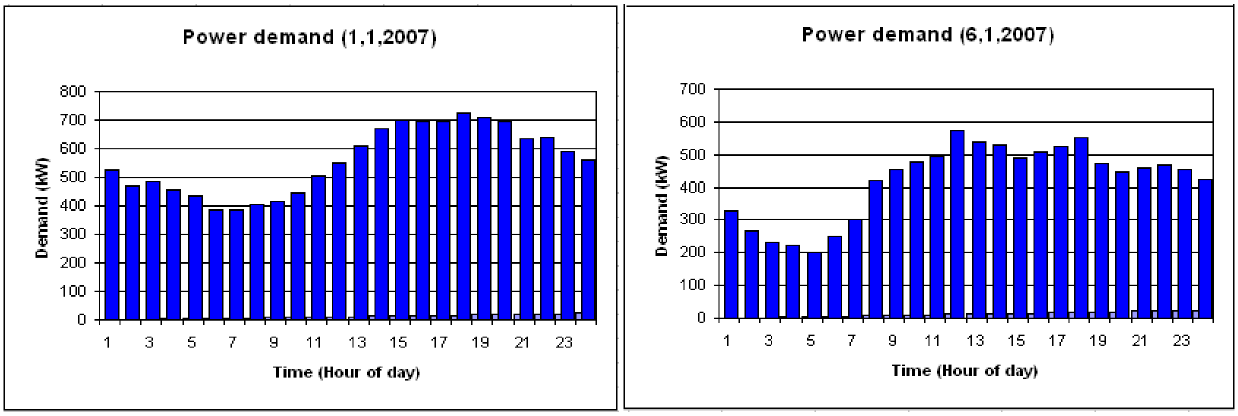
$$\sum_{K=1}^{N} (P_{elec,k} - P_{fc,k}) \leq C_{H2} \qquad (25)$$

$$\forall k = 1 \; to \; N$$

where C_{H2} is the capacity of hydrogen tank.

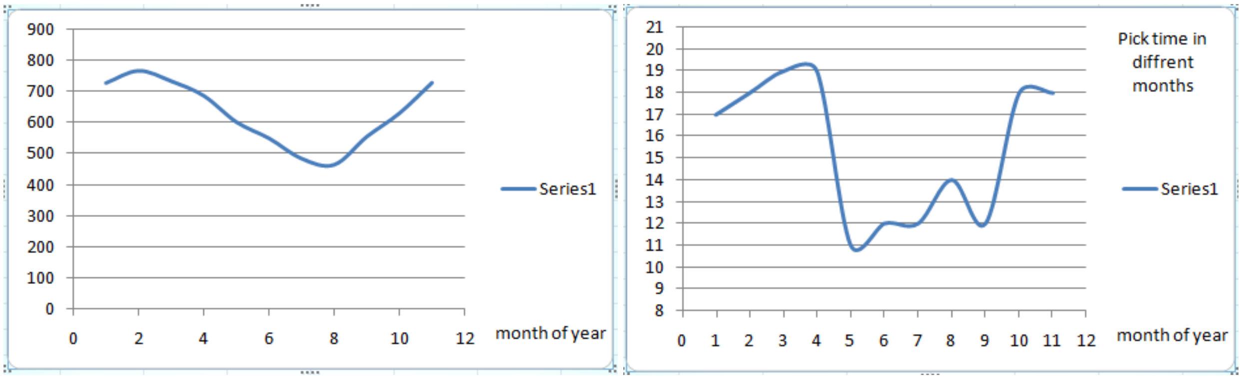
3.4 Case study

In order to simulate and study the behaviour of microgrid, the data collected from a real community is considered. This community is a remote area in northern Ontario (Canada). The load profile of the area is shown in Fig. 3-2. In Fig. 3-3 the seasonal electrical load profile and seasonal electrical load pick time are shown.



(a) (b)

Fig. 3-2: (a) Power demand for January 2007; (b) Power demand for Jun 2007



(a) (b)

Fig. 3-3: (a) Seasonal electrical load profile (pick load); (b) Seasonal electrical load pick time

The wind generation of the area is obtained from the Canadian Wind Energy Atlas Environment Canada [10]. The wind speed and wind direction are given in Table 3-1 for the period January to December.

Table 3-1: Average wind speed and direction

Speed/Month	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Wind Speed (km/h)	3.9	3.9	3.9	4.2	4.2	16	4.2	4.2	4.4	5	4.4	3.9
Wind Direction	W	NW	NW	N	N	S	NW	NW	NW	NW	NW	W

The information on microgrid components including wind turbine, fuel cell, electrolyser, hydrogen tank, is given in Table 3-2. [6]

Table 3-2: Microgrid components specifications

	Wind turbine	**Fuel cell**	**Electrolyser**	**Power Converter**	**Diesel generator**
Rated output power per unit (kW)	25	3	3	3	400/600/1000
Cut-in speed (m/s)	5	NA	NA	NA	NA
Cut-out speed (m/s)	25	NA	NA	NA	NA
Rated speed	20 (m/s)	NA	NA	NA	NA
Swept area (m2)	81.67	NA	NA	NA	NA
Capital cost ($)	100,000	20,000	20,000	2,000	NA
O&M cost ($)	100	15	15	15	1000
Replacement cost ($)	NA	1,400	1,400	NA	NA
Efficiency (%)	NA	50	74	95	90
Lifetime (year)	20	5	5	5	20
Fuel consumption (litre/hour)	NA	NA	NA	NA	120/180/300
CO_2 emissions (kg/kWh)	NA	NA	NA	NA	0.699

Two different models for optimization problem have been developed, one in GAMS to minimize the cost of electricity and another one in MATLAB to verify the results of GAMS. In this model, the minimization of the cost has been performed by sweeping the entire possible area.

A. Model in GAMS

GAMS model is based on operation of system in a year. The system is operated and the share of power among system components in order to achieve the minimum electricity cost is investigated. Simulation results for a typical day have been shown in Figs. 3-4 and 3-5. The generation and demand, diesel generator power, and fuel cell and electrolyser power shares can be seen in Fig. 3-4.The electrolyser and fuel cell power during charge and discharge of the energy storage system and state of charge of hydrogen tank can be seen in Fig. 3-5.

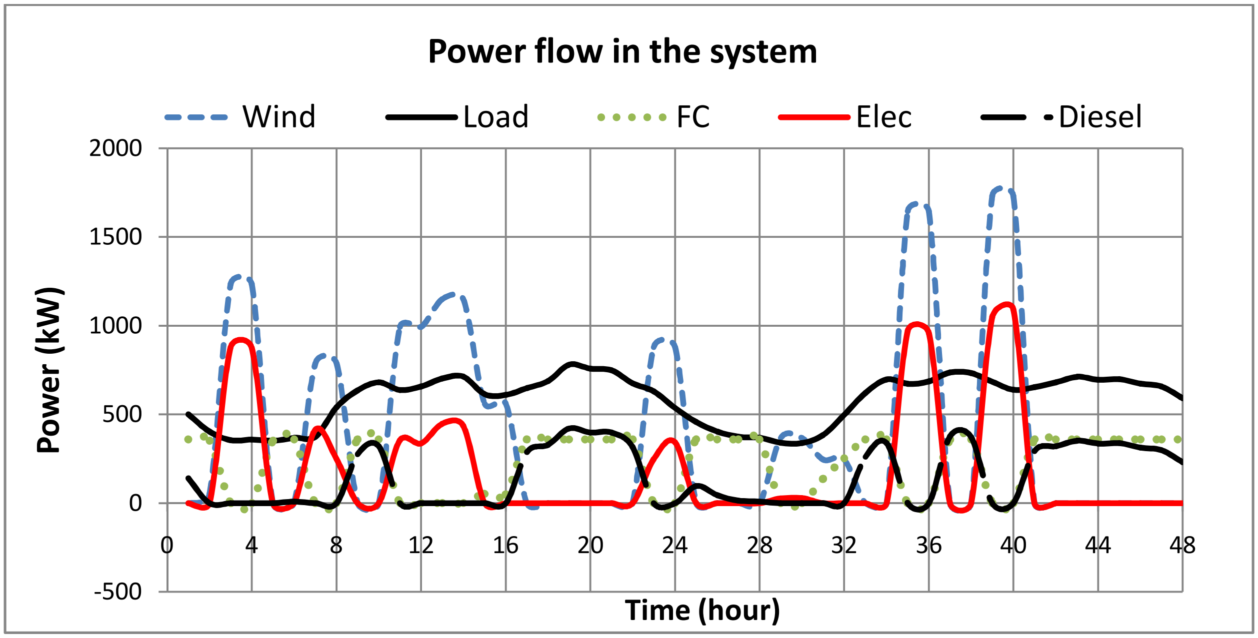


Fig. 3-4: Load, wind, diesel, fuel cell, and electrolyser power share

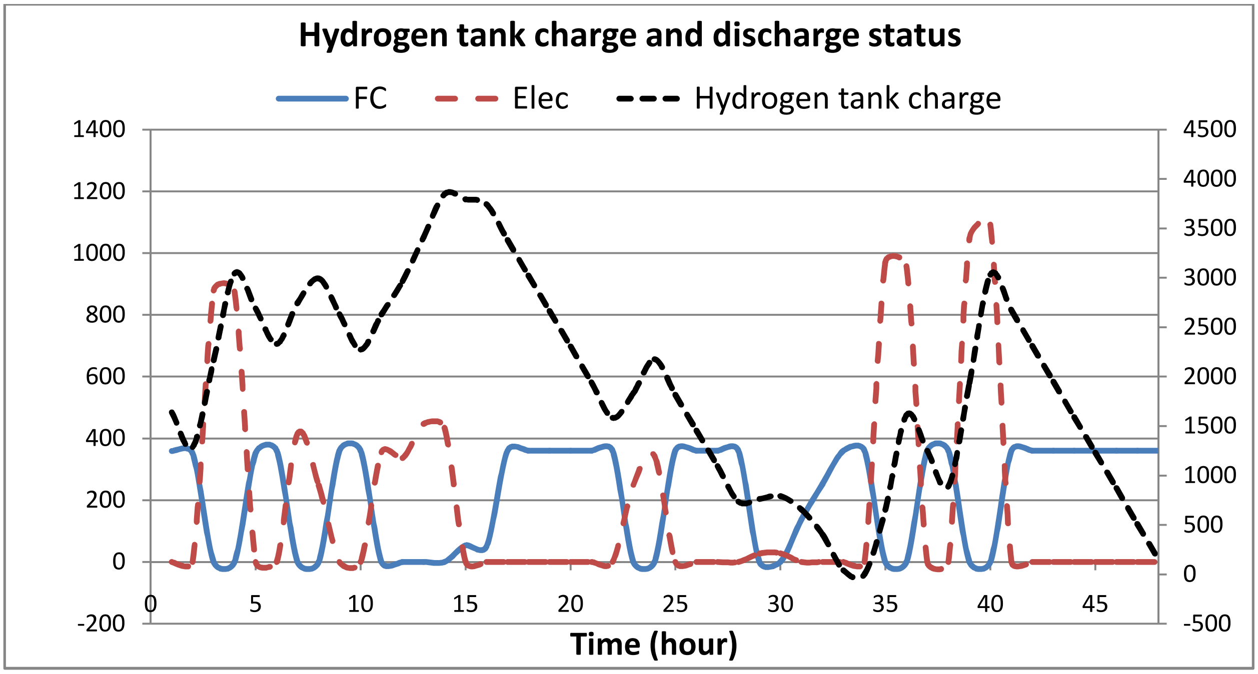


Fig. 3-5: Fuel cell and electrolyser power, and state of charge of hydrogen tank

The GAMS model, as explained before, is based on power share of the components with the objectives of satisfying the demand of the area and minimizing the operating cost of the system that results in minimum cost of electricity.

B. Scenarios

Three main scenarios considered in this study vary from a traditional diesel-based system to a partially renewable system to a fully renewable system. The parameters for each scenario have been put in the GAMS optimization model and the outputs of the optimization are included in Table 3-3.

1. Only Diesel

In this scenario, the system is operated in its traditional mode, where diesel generators are used as the only power source. This scenario can be considered as the base operating mode. There are 3 diesel generators G1 to G3, with the rated powers of 1000, 400, 600kW, respectively.

Depending on the power demand level, the demand will be met by a different generator, as shown in Fig. 3-9. The switching strategy is as below:

Power between 420 and 460: the generator switches from unit1 to unit3.
Power between 520 and 550: the generator switches from unit3 to unit1.
Power between 250 and 280: the generator switches from unit3 to unit2.
Power between 350 and 380: the generator switches from unit2 to unit3.

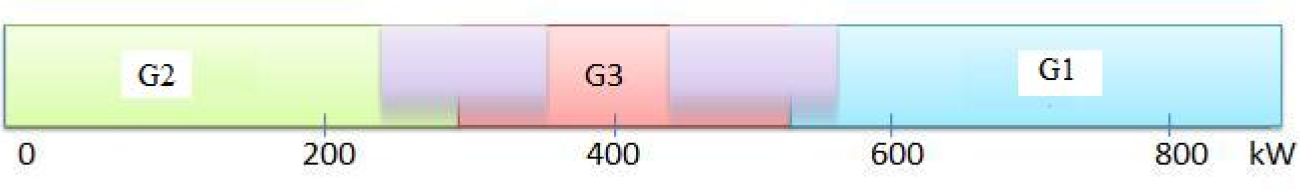


Fig. 3-6: Generator switching strategy

Energy and infrastructure costs in remote northern communities of Canada are very high compared to those in the grid-connected communities for a variety of reasons. These include higher transportation costs for fuel and equipment, smaller and more dispersed population, higher operating and maintenance costs, specialized infrastructure required for use in cold climates, and greater need for space heating [6]. The cost of electricity in the remote community under study is more than 10 times that in grid-connected communities in Canada, somewhere in the range 1.2 to 1.8 $/kWh.

2. Fully-renewable

In this scenario, wind turbines capacity is chosen based of the average load of the area. In the long term, if there is enough storage capacity, the wind resources available are able to supply the load. The advantages of this scenario are low fuel consumption, very low gas emissions, and independence of cost of electricity from fuel price.

3. Partially-renewable

The load of the area will be shared by renewable and diesel sources. This scenario is the midpoint between fully-renewable and only-diesel cases. The optimization problem results show what should be the share of power between wind and diesel.

The number of wind turbines, FCs, electrolysers, the size of hydrogen tank, the economical parameters, annual capital, replacement, maintenance and fuel costs, and the cost of electricity for three main scenarios explained above are presented in Table. 3-3. The diesel-only scenario is operated based on two possible price for diesel fuel. The higher fuel price is $2\ \$/kWh$, and the lower fuel price is $0.9\ \$/kWh$.

Table3-3: Three main scenarios studied

	Fully-Renewable	**Partially-Renewable**	**Diesel-Only (high fuel price)**	**Diesel-Only (low fuel price)**
Rated power of wind turbines (kW)	176×25	48×25	-	-
Diesel generators capacity (kW)	400	600+400	1000+600+400	1000+600+400
Fuel Cell capacity (kW)	10×20	3×20	-	-
Electrolyser capacity (kW)	18×20	4×20	-	-
Hydrogen tank size (kWh)	8000	4000	-	-
Loan interest rate (%)	5	5	5	5
Inflation rate (%)	2	2	2	2
Project lifetime (yrs)	20	20	20	20
Annual capital cost ($1000)	2006.4	532.3	-	-
Annual replacement cost ($1000)	49.3	12.3	-	-
Annual fuel cost ($1000)	1802.1	4132.9	4874	2959
Annual O&M cost ($1000)	41	18.9	8.9	10.9
Dumped energy cost ($1000)	158.3	48.1	-	-
CO_2 emissions (tonne/yr)	623.7	1430.5	1699	1699
Electricity cost ($/kWh)	1.6040	1.9322	2.1387	1.2033
Annual cost of system ($1000)	**3899**	**4696.7**	**4874.7**	**3071.6**

In order to observe the effect of available wind energy in the system, different sizes of diesel generators is considered, and the output of the optimization problem is reported in Table 3-4. In the first column, the 400kW diesel generator is operated in its most efficient region. The second column is for using 600kW in its most efficient region. In these two different scenarios, the number of wind turbines is different. The last case studies the effect of having renewable sources covering more than the average load of the area.

Table 3-4: The optimization results for different diesel sizes

	Partially-Renewable	**Partially-Renewable**	**Fully-Renewable**
Rated power of wind turbines (kW)	74×25	24×25	200×25
Diesel generators capacity (kW)	80%*400	80%*600	400
Fuel Cell capacity (kW)	3×20	3×20	18×20
Electrolyser capacity (kW)	5×20	4×20	31×20
Hydrogen tank size (kWh)	6000	4000	8000
Loan interest rate (%)	5	5	5
Inflation rate (%)	2	2	2
Project lifetime (yrs)	20	20	20
Annual capital cost ($1000)	735.2	371.9	2769.2
Annual replacement cost ($1000)	14.1	12.3	86.2
Annual fuel cost ($1000)	3751.1	4557.1	1645.8
Annual O&M cost ($1000)	22.9	15.3	47.7
Dumped energy cost ($1000)	76.2	24.8	170.9
CO_2 emissions (tonne/yr)	1538.2	1337.4	1629.5
Electricity cost ($/kWh)	1.8610	2.0392	1.8715
Annual cost of system ($1000)	**4523.3**	**4956.6**	**4548.9**

C. Model in MATLAB

The same system modeled in GAMS is modeled and operated in MATLAB. In this simulation, the minimum cost of system is achieved by sweeping the whole possible search area. This model can be trusted more since the whole area has been tried and minimum cost is found.

The simulation results for fully-renewable case are as follows. There should be 18 units (360kW) of electrolyser and 10 units (200kW) of FC, with a total system cost of 3,900,000$. The annual cost of system based on the number of electrolyser and fuel cell units is shown in Fig. 3-6. A top view of the simulation results can be seen in Fig. 3-7. The annual cost of system in fully-renewable case is seen in Fig. 3-8. Table 3-3 shows the simulation results for GAMS program. The results from the two methods are in agreement.

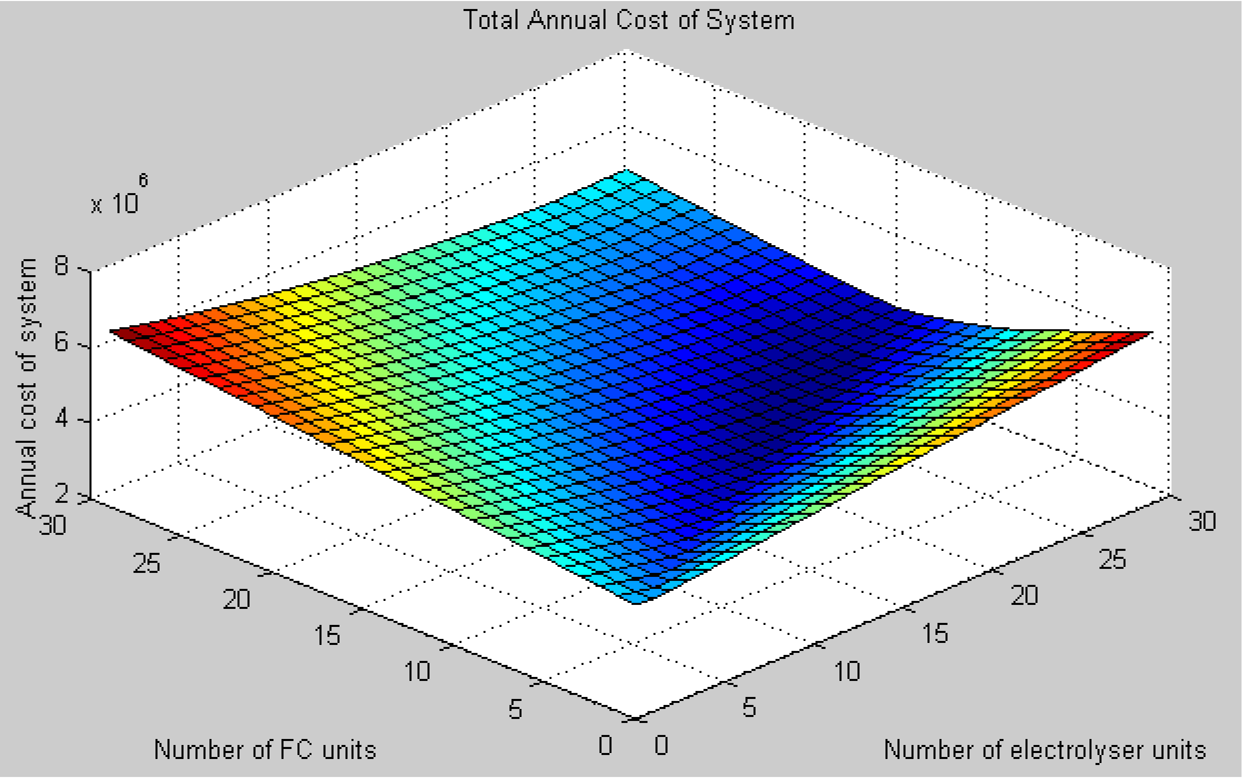


Fig. 3-7: Total annual cost of system based on number of electrolyser and fuel cell units (fully-renewable case)

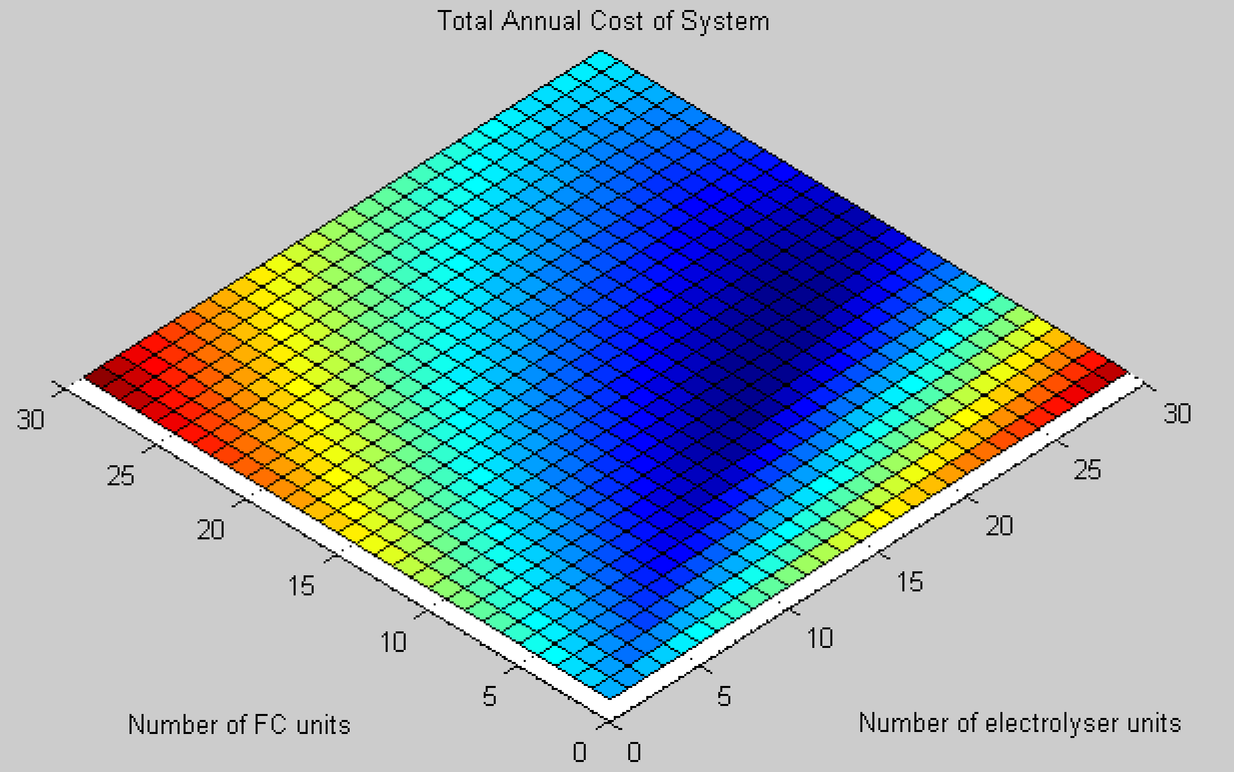


Fig. 3-8: Minimum annual cost of system at 18 electrolyser units and 10 FC units

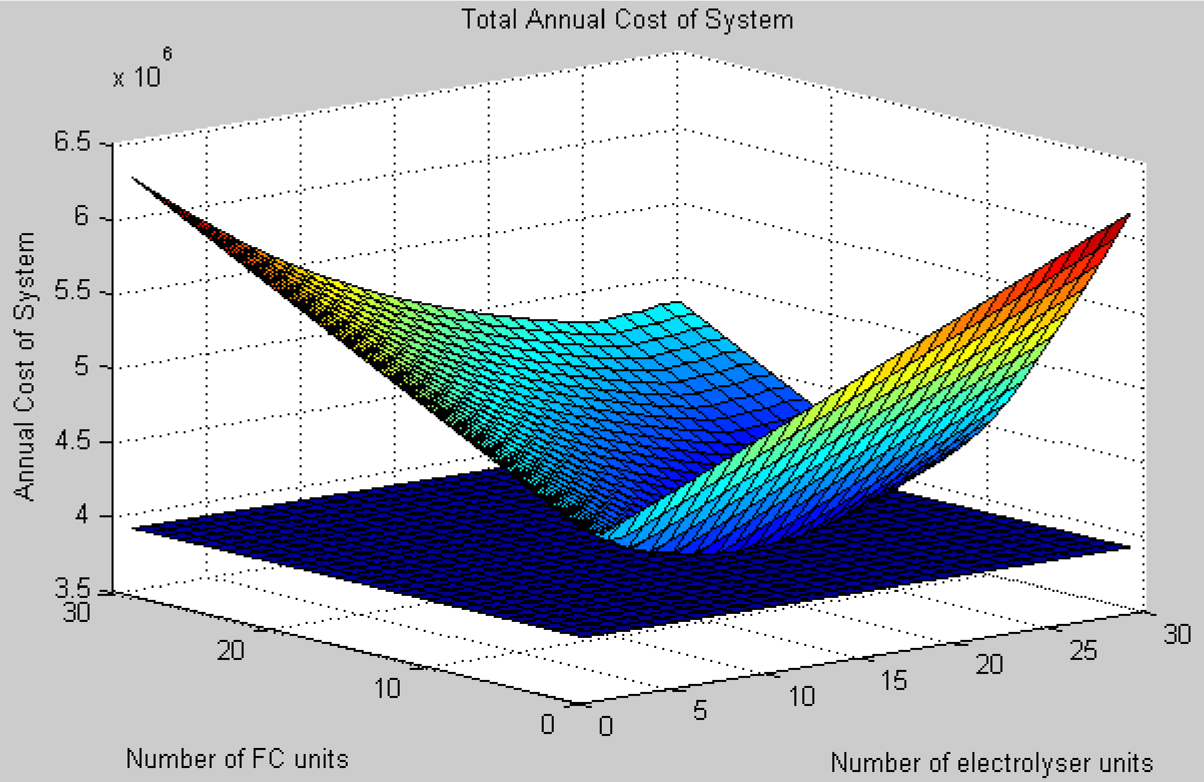


Fig. 3-9: Total annual cost of system at optimal point is 3,900,000$.

In order to compare the results, the simulation for partially-renewable case is done. There should be 4 units (80kW) of electrolyser and 3 units (60kW) of FC, with a total system cost of 4,700,000$. The annual cost of system based on the number of electrolyser and fuel cell units is shown in Fig. 3-9. The results confirm the data obtained in GAMS model.

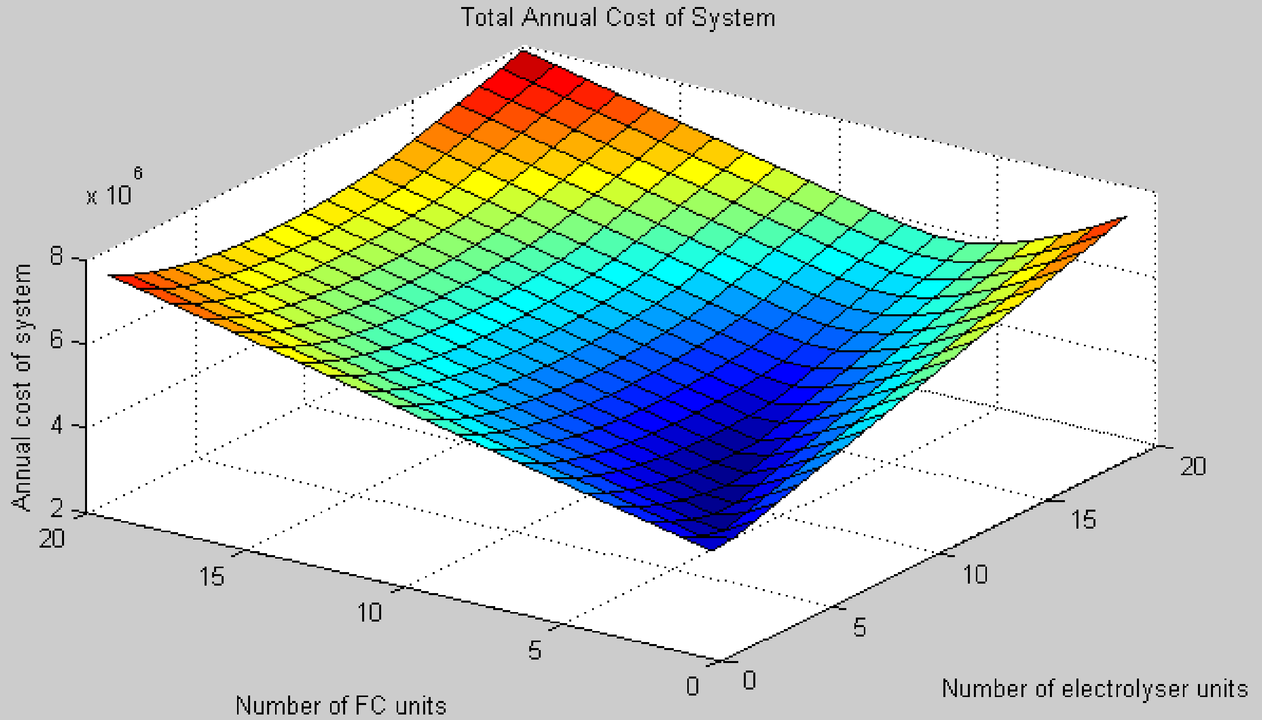


Fig. 3-10: Total annual cost of system based on number of electrolyser and fuel cell units (partially-renewable case)

3.5 Discussion and Conclusion

In this section, an optimization problem for a hybrid system is defined and solved. The optimization problem is defined and developed based on a simple power management algorithm to operate the system under study. The modeling of the optimization problem has been done in both GAMS and MATLAB.

The lowest cost of system is found for the fully-renewable case. In this case, there are 176 units of 25kW wind turbines that supply the average load of area. To minimize the cost of system, the only diesel unit operated in this case is 400kW unit that is used as back up for the periods where there is power deficit (i.e., wind turbines cannot supply the demand). There should be 10 units of fuel cell and 18 units of electrolyser.

The partially renewable case results in an electricity cost more than fully-renewable case and less than traditional diesel-based case. In this case, 48 units of 25kW wind turbines are needed, and two of diesel units are operating in parallel with wind turbine to supply the demand. Depending on the average load, one of the diesel units runs under optimum operating conditions and the other one is used to supply the power deficit. The numbers of fuel cell and electrolyser units in this case are 3 and 4, respectively.

Since the excess power that can happen in fully-renewable case is more than that in partially renewable case, the hydrogen tank sized for the first case is larger. The hydrogen tank for first case is 8000kWh, and for second case is 4000kW.

In diesel-only case, there are no wind turbines and the entire demand of the community is supplied by diesel units. In this case, the diesel units are operated based on the generator switching strategy explained before.

Annual fuel cost of the system is the highest for the diesel operated case as expected. The cost of fuel is the main component of the cost in this case. There is a huge decrease in fuel cost in fully-renewable case.

The capital cost of system is very high for fully-renewable case. The main reason is the vast wind turbine farm that should be installed in the community. With decrease in the price of wind turbines in the future, this cost is decreased, causing even lower price of electricity when using renewable resources.

As expected, carbon emission has the lowest value for fully-renewable case, and it is very high for diesel-based case. Based on the carbon tax policies that most governments in different countries implement, the carbon tax should be increased in the next decades. This increase is considerable and can accelerate the research on and implementation of renewable resources and hybrid electrical systems.

The results show that using the renewable resources combined with diesel units is an economical choice and also has environmental benefits.

Chapter 4

Modeling of the Microgrid Components

Beginning with the modeling of the system components, this chapter describes the Simulink modeling of the microgrid whose optimization was presented in Chapter 3. The model, which is based on an aerodynamic model of a wind turbine, includes a wind turbine that uses an induction generator as the electrical medium. Simulations of both the starting and steady state operation were performed.

A solid-oxide fuel cell (SOFC) connected to a three-phase infinite bus through an IGBT inverter was used for the simulation. The inverter uses hysteresis switching and controls active power by adjusting the direct-axis current while holding the reactive power at zero. The diesel generator used is a synchronous machine that operates at 60 Hz; the input to the generator represents the reference power. A controllable three-phase load was used to adjust the load of the system to correspond with its real value. The infinite bus used is a three-phase 60Hz bus bar.

The total system model was developed in MATLAB in order to investigate the steady state operation. A step function was used to compare the output of the model with the values already obtained from the optimization problem.

4.1 Wind energy conversion system

A wind turbine model based on an aerodynamic model of a turbine was developed in Simulink and was verified for both starting and steady state operation.

Fig. 4-1 shows the block diagram of the wind turbine, which is a combined aerodynamic and electric wind turbine model. The aerodynamic model was used to extract the output torque of the turbine based on blade radios, wind speed, and the rotor speed of the generator. The aerodynamic wind turbine model is shown in Fig. 4-2 [12].

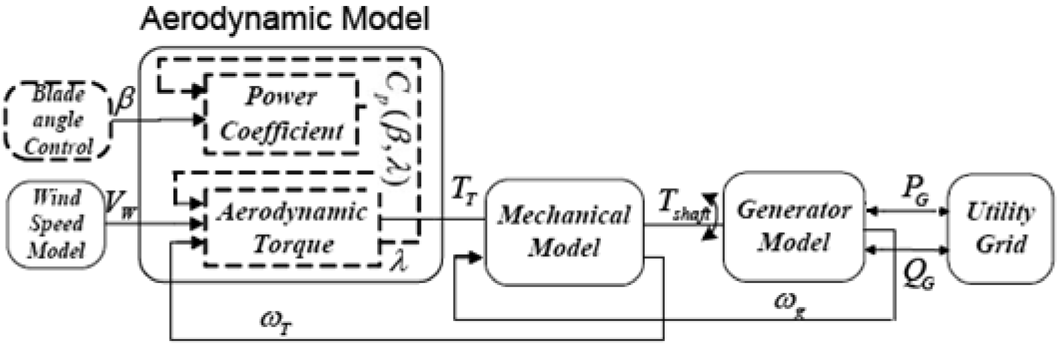


Fig. 4-1: Block diagram of the model of the overall wind turbine system [12]

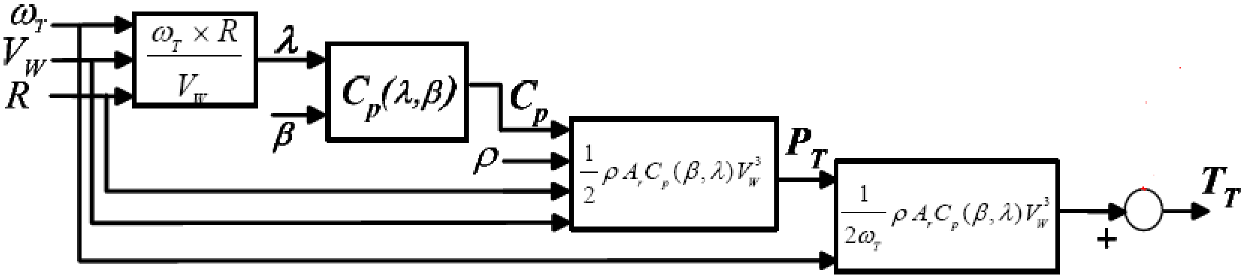


Fig. 4-2: Block diagram of the model of the aerodynamic wind turbine [12]

The mechanical power and the mechanical torque on the wind turbine rotor shaft are given by (1) and (2), respectively:

$$P_T = \frac{1}{2}\rho A_r C_p(\beta,\lambda) V_W^3 \qquad (1)$$

$$T_T = \frac{1}{2\omega_T}\rho A_r C_p(\beta,\lambda) V_W^3 \qquad (2)$$

where

P_T = mechanical power extracted from the turbine rotor

T_T = mechanical torque extracted from the turbine rotor

A_r = area covered by the rotor = πR^2 where R is the rotor radius of the turbine (m)

V_W = velocity of the wind (m/s)

C_p = performance coefficient (or power coefficient)

ρ = air density (kg/m^3)

λ = tipspeedratio (TSR)

β = rotor blade pitch angle (rad)

ω_T = angular speed of the turbine shaft (rad/s)

The blade tipspeedratio was defined as follows:

$$\lambda = \frac{blade\ tip\ speed}{wind\ speed} = \frac{\omega_T \times R}{V_W} \qquad (3)$$

In this study, the$C_p$curve was approximated analytically according to the following:

$$C_p(\lambda,\beta) = (0.44 - 0.0167\beta) sin\left[\frac{\pi(-3+\lambda)}{15-0.3\beta}\right] - 0.00184(-3+\lambda)\beta \qquad (4)$$

The parameters of the wind turbine, the induction generator, and the three-phase grid are listed in Table 4-1.

Table 4-1: Parameters of wind turbine, induction generator, and grid

Wind turbine	**Induction generator**	**Three-phase grid**
$R = 10m$ $N_{gear} = 20$	$V_{rated} = 460V$ $f = 60Hz$ $P = 25kW$ $\omega_{nominal} = 1785rpm$ $R_s = 0.0302ohms, L_s = 0.283mH$ $R_r = 0.01721ohms, L_r = 0.283mH$ $L_m = 0.01095H$ $J = 2\ kgm^2$	$V = 460V$ $f = 60Hz$ $\frac{X}{R} = 7$

The connection of the wind turbine model to the induction generator is shown in Figs. 4-3 and 4-4. The terminals of the induction generator (with a-b-c sequence) were connected to a three-phase balanced grid with a nominal voltage of 460 V, and a frequency of 60 Hz.

In the turbine model, the tip speed ratio and power coefficient were calculated based on the wind speed, the generator speed, and the turbine blades radius. The output power and output torque of the turbine were calculated as in equations (1) and (2). The output torque on the shaft that is coupled to the induction generator is the torque after the gearbox. This torque, when applied to the induction generator, generates electrical power.

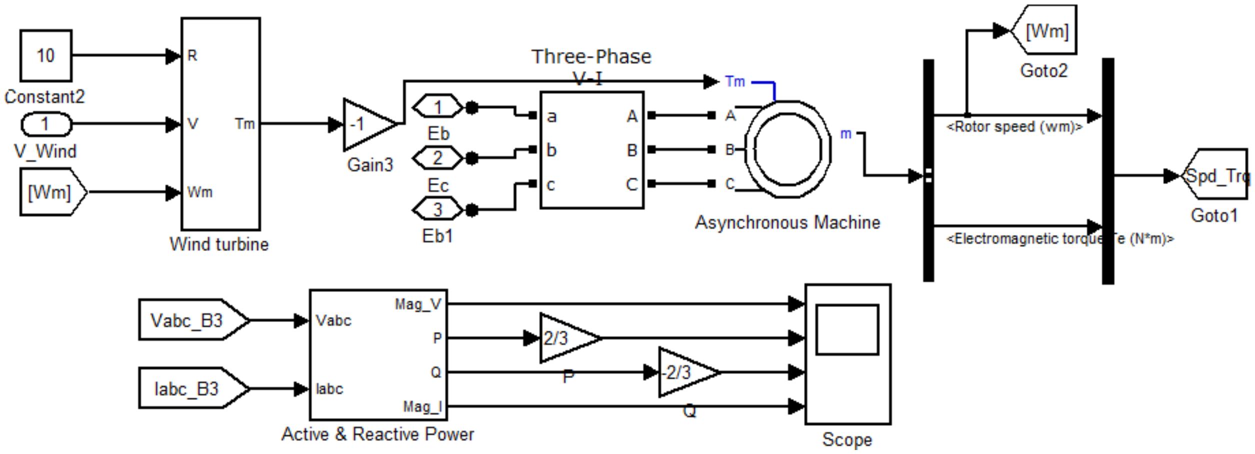


Fig. 4-3: Block diagram of the wind turbine connected to the induction generator and three-phase grid

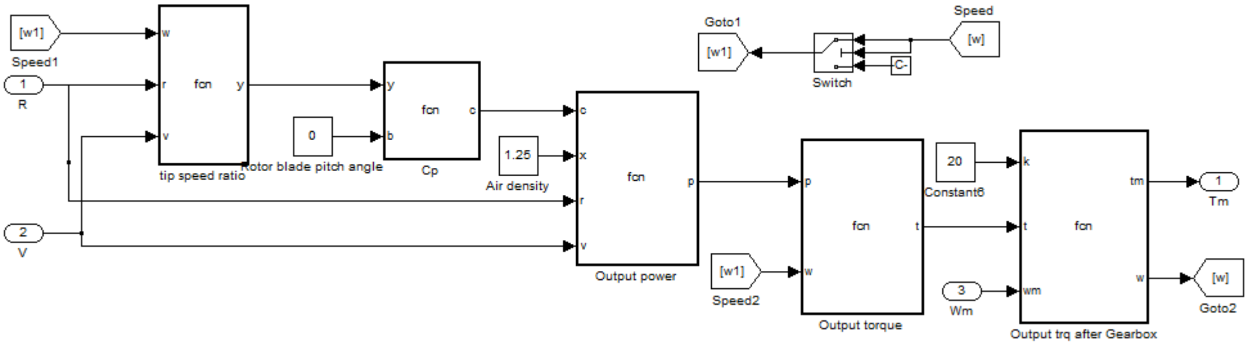
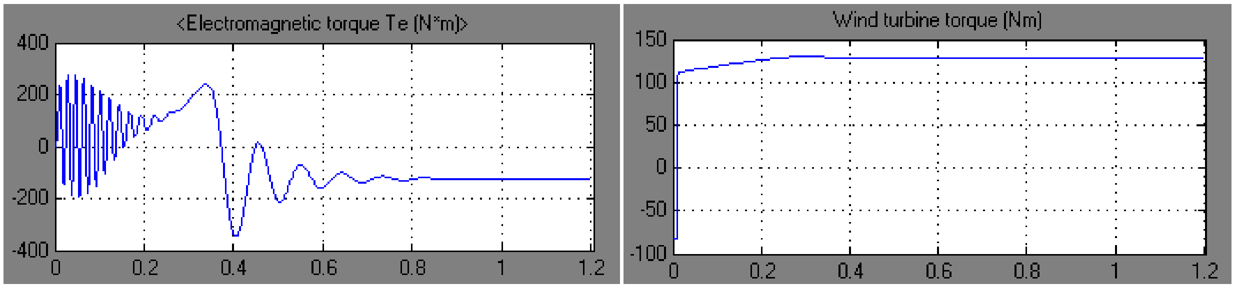


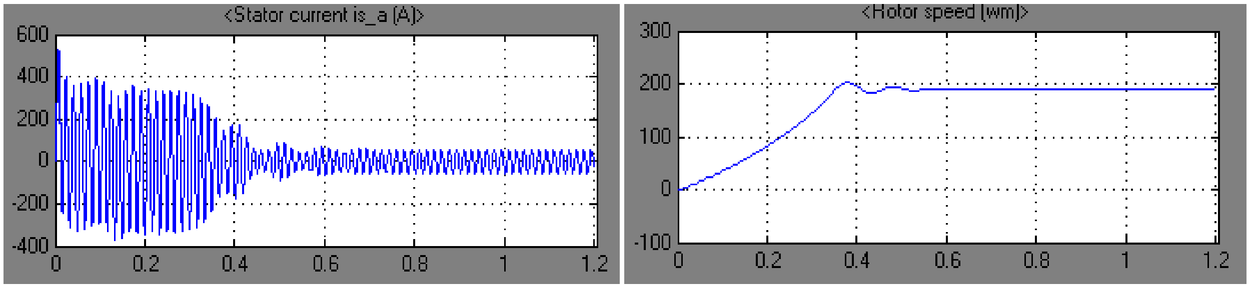
Fig. 4-4: Block diagram of the wind turbine

To verify the accuracy of the model, the turbine was operated in both starting and steady state modes; the response of the model is shown in Fig. 4-5 to Fig. 4-12. Fig. 4-5 to Fig. 4-8 show the response of the model in starting mode.



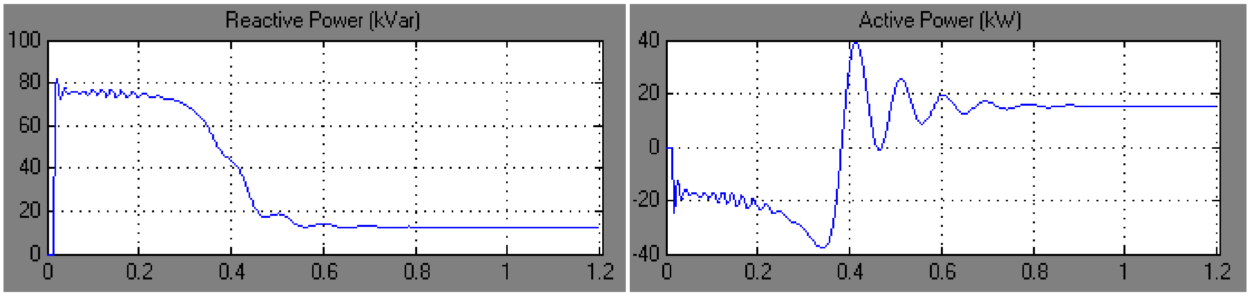
(a) (b)

Fig. 4-5: (a) Electromagnetic torque of the induction generator (Nm); (b) Output torque of the wind turbine (Nm)



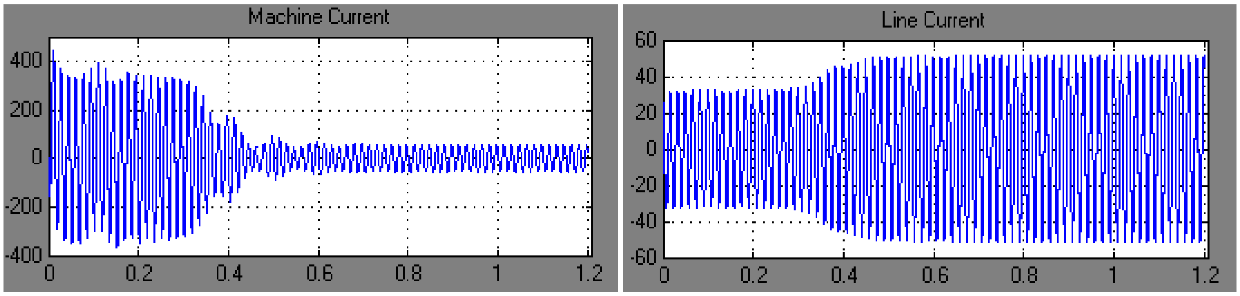
(a) (b)

Fig. 4-6: (a) Stator current (A); (b) Rotor speed (rad/s)



(a) (b)

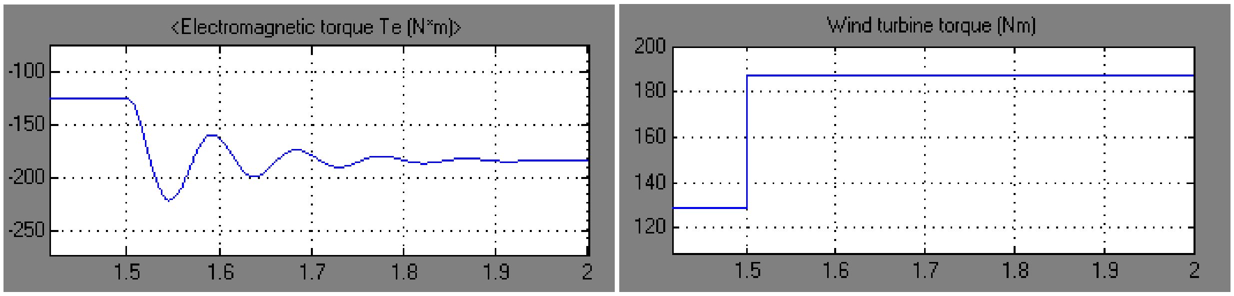
Fig. 4-7: (a) Reactive power (kVar); (b) Active power (kW)



(a) (b)

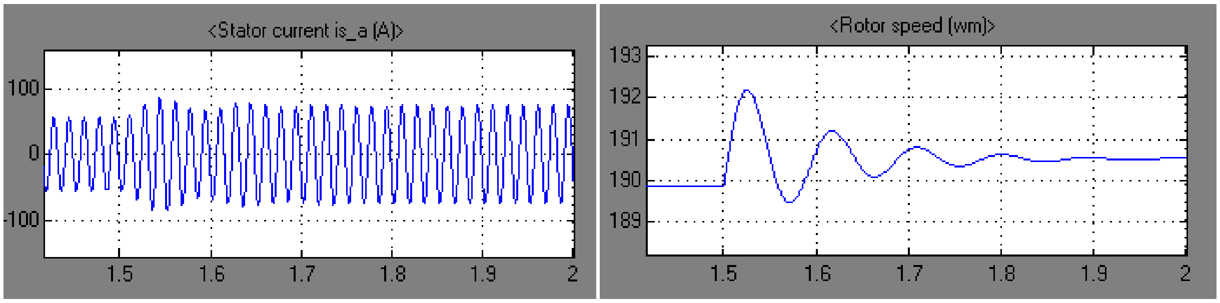
Fig. 4-8: (a) Machine current (A); (b) Line current (A)

Fig. 4-9 to Fig. 4-12 show the output of the model for a step input to the model. The wind is at a steady state value of 10 m/s, when, at t =1.5 s,a step input increasing the wind to 12 m/s is applied.



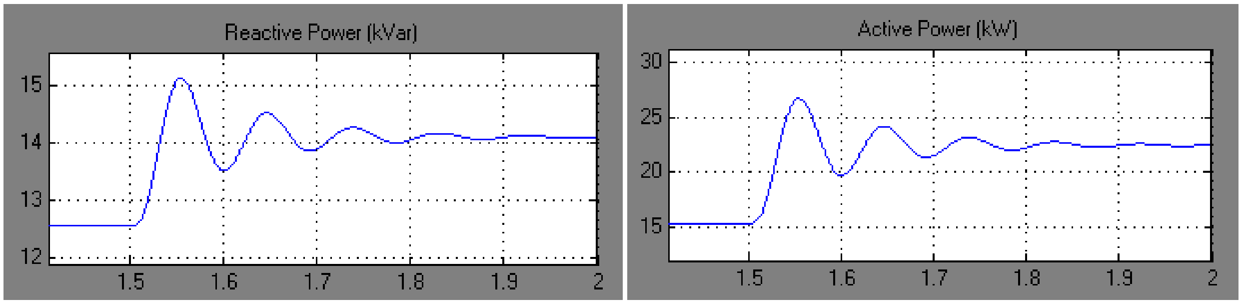
(a) (b)

Fig. 4-9: (a) Electromagnetic torque of the induction generator (Nm); (b) Output torque of the wind turbine (Nm)



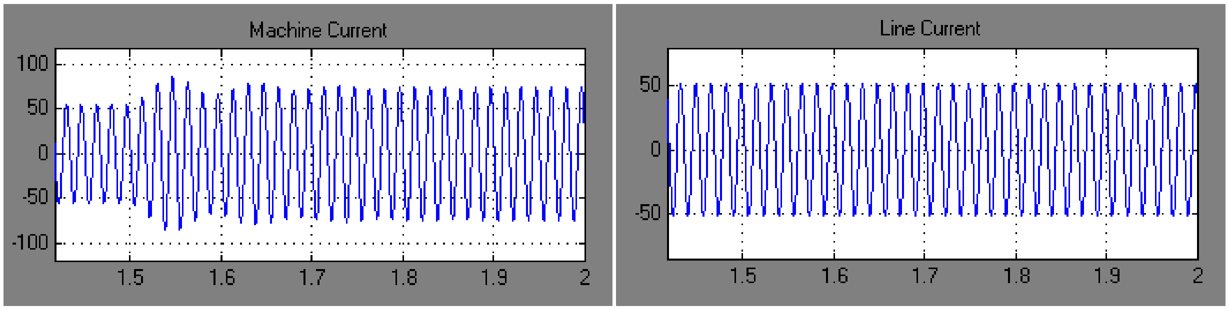
(a) (b)

Fig. 4-10: (a) Stator current (A); (b) Rotor speed (rad/s)



(a) (b)

Fig. 4-11: (a) Reactive power (kVar); (b) Active power (kW)



(a) (b)

Fig. 4-12: (a) Machine current (A); (b) Line current (A)

4.2 Fuel cell and electrolyser

Fig. 4-13 shows a block diagram of the solid-oxide fuel cell (SOFC) connected to the three-phase electrical power system. The SOFC is connected to a three-phase infinite bus through an IGBT inverter. The inverter uses hysteresis switching and controls active power through manipulation of direct-axis current while holding the reactive power at zero.

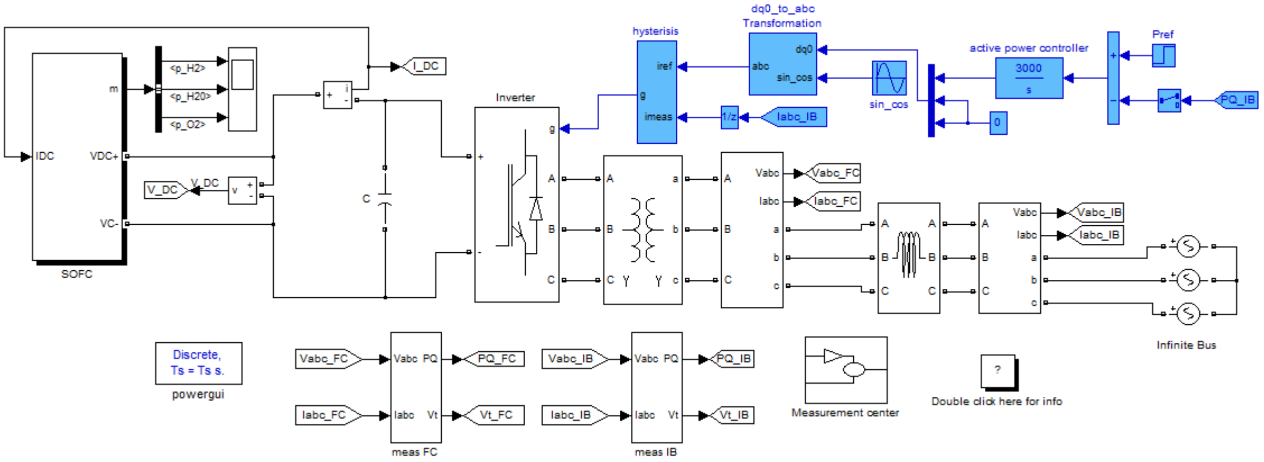
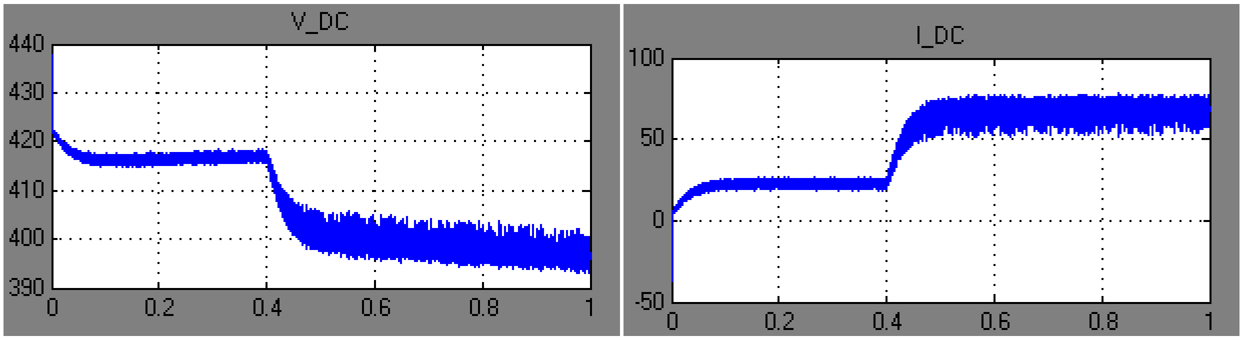


Fig. 4-13: Solid-oxide fuel cell connected to the three-phase power system

SOFC block diagram is shown in Fig. 4-13; the parameters are listed in Table 4-2 and the system response to a step change in active power reference is given in Figs. 4-14 and 4-15. The model for the SOFC is from the MATLAB library and was developed based on the dynamic model presented in [13].

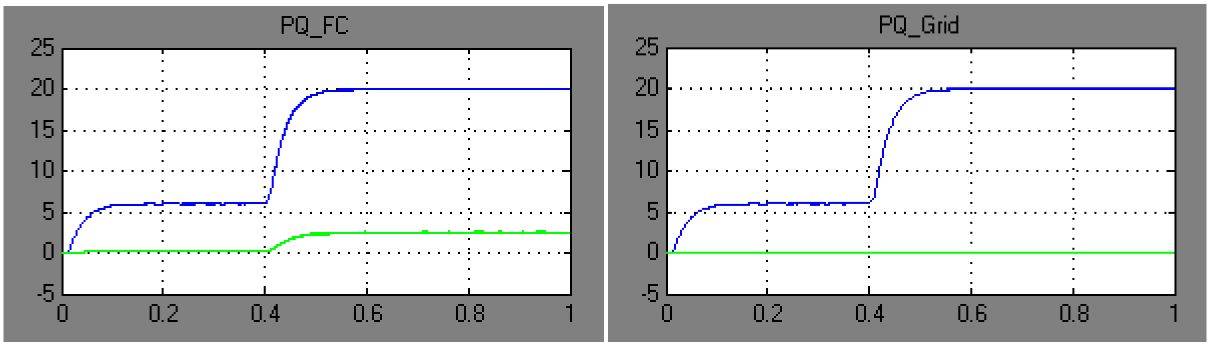
Table 4-2: Parameters of the SOFC block diagram

Parameter	Representation	Value
P_{rate}	Rated power	20 kW
P_{ref}	Real power reference	20 kW
T	Absolute temperature	1273 K
N_O	Number of cells in series	384
r	Ohmic loss	0.126 Ω
T_e	Electrical response time	0.8 s
r_{H_O}	Ratio of hydrogen to oxygen	1.145
PF	Power factor	1.0



(a) (b)

Fig. 4-14: (a) FC voltage (V); (b) FC current (A)



(a) (b)

Fig. 4-15: (a) FC active and reactive power (kW/kVar); (b) Grid active and reactive power (kW/kVar)

At $t = 0$ s, an active power reference (P_{ref}) of 0.3 pu is commanded. It can be observed that the reference is captured within 0.2 s. At $t = 0.4$ s, $P_{ref} = 1$ $pu$is commanded.

The model used for electrolyser is the same model illustrated for fuel cell, but with different efficiency.

4.3 Diesel generator

Another component used in the modeling of the microgrid was a diesel generator. For this research, a diesel generator witha 100 kW power rating was simulated. The block diagram of the system can be seen in Fig. 4-16, and the output waveforms are shown in Figs. 4-17 and 4-18. The simulation was performed for a step change from 50 kW to 60 kW at t=0.1 s.

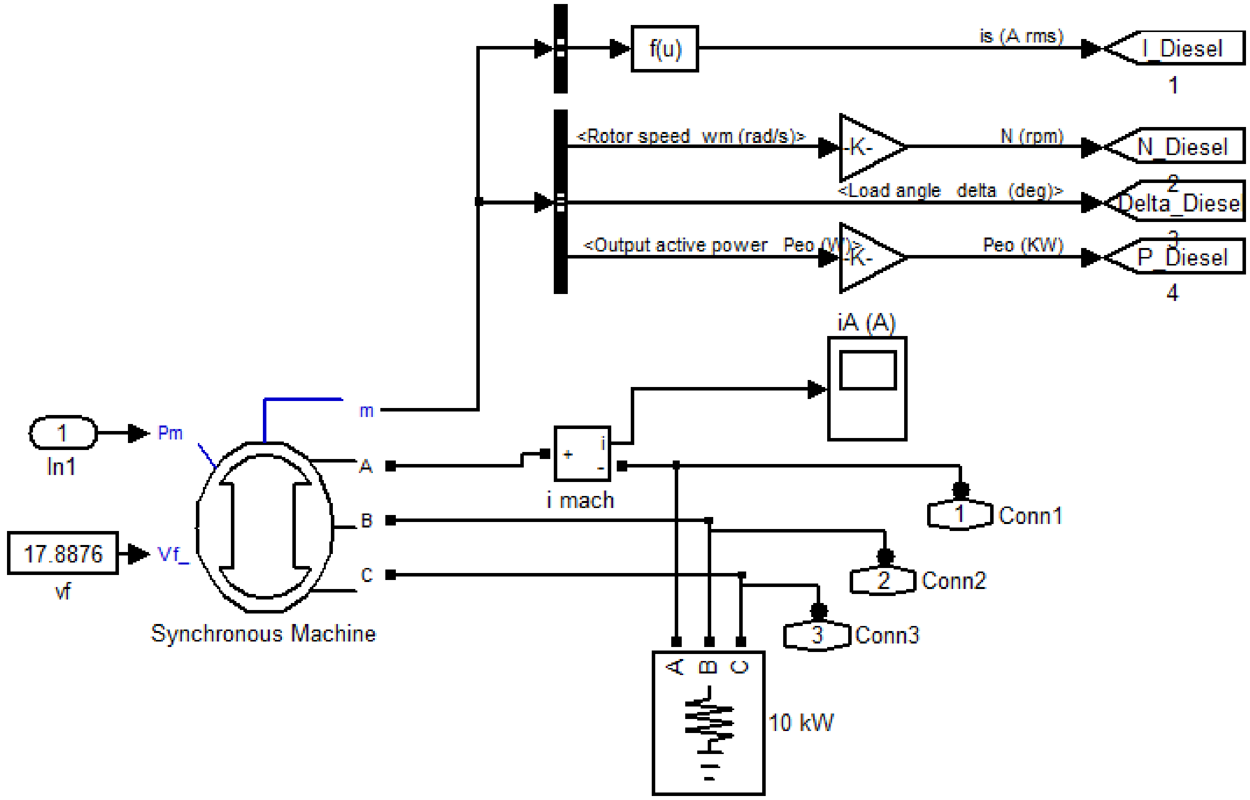
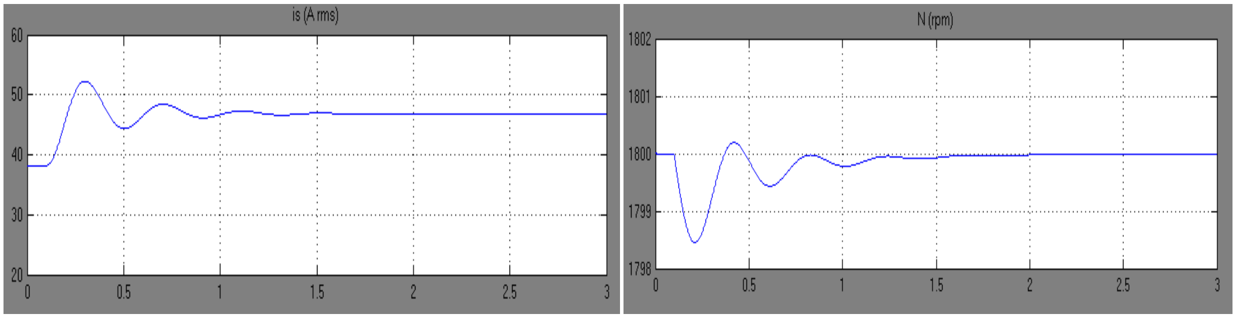
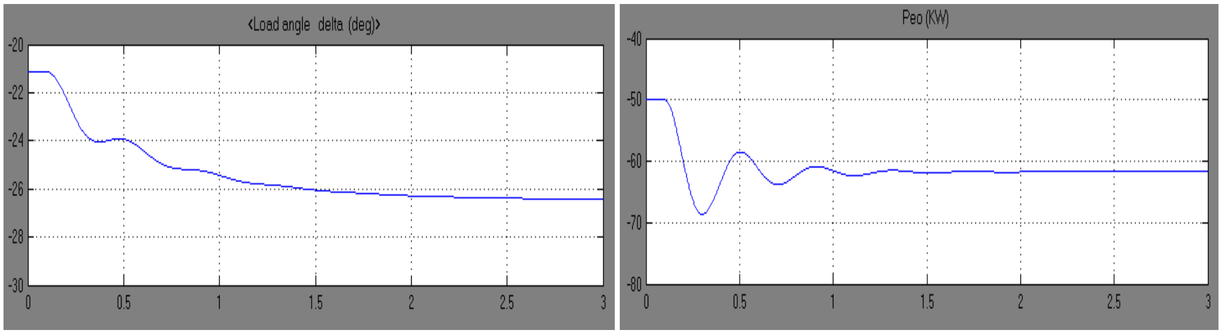


Fig. 4-16: Block diagram of the diesel generator



(a) (b)

Fig. 4-17: (a) Machine current (A); (b) Machine speed (rpm)



(a) (b)

Fig. 4-18: (a) Load angle (deg); (b) Machine output power (kW)

4.4 Three-phase controllable load

A controllable load was used as the load of the system. The active and reactive power levels of the load were adjustable and were controlled and adjusted for the values needed. The load profile of the area was used to determine the active and reactive power of the load.

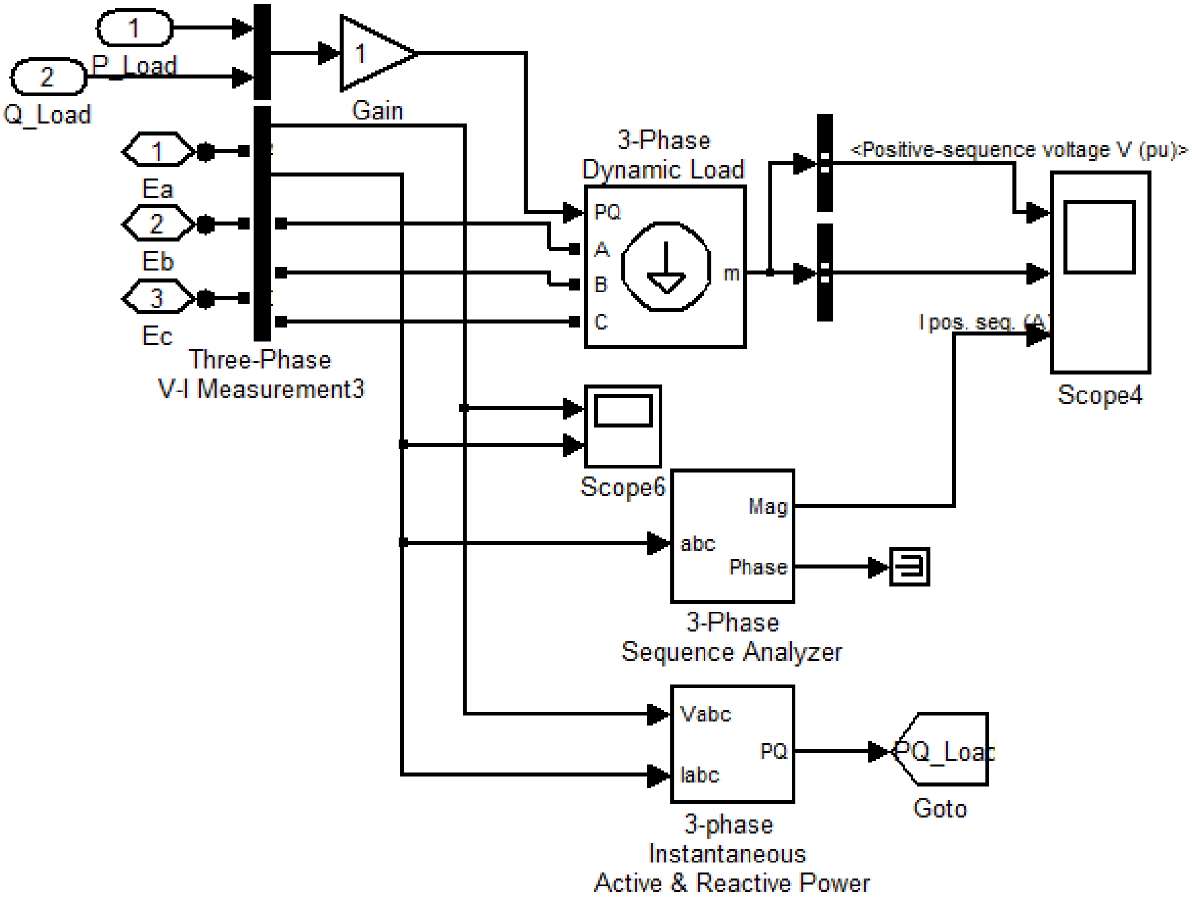


Fig. 4-19: Three-phase controllable load

4.5 Modeling of the microgrid

The overall model included the components whose models were described and illustrated in the previous subsections. The system was connected to a three-phase infinite bus for regulating the frequency and voltage. To manage the power flow between the components, a control unit based on the power flow strategy presented in Chapter 2 was modeled.

The control unit receives the available data from the load and from the generation of wind and diesel and then produces reference points for the fuel cell, the electrolyser, and the diesel generator. The control unit determines whether to dump the excess portion of the generation if it cannot be stored and also whether to use the grid to supply the portion of the load that cannot be supplied by the generation resources available. A controllable load mimics the load of the system. A grid was used as a frequency and voltage regulator.

The components of the system were connected to a three-phase balanced grid, and the model was used to verify the results of the optimization problem whose definition and solution were presented in Chapter 3. A block diagram of this system is shown in Fig. 4-20.

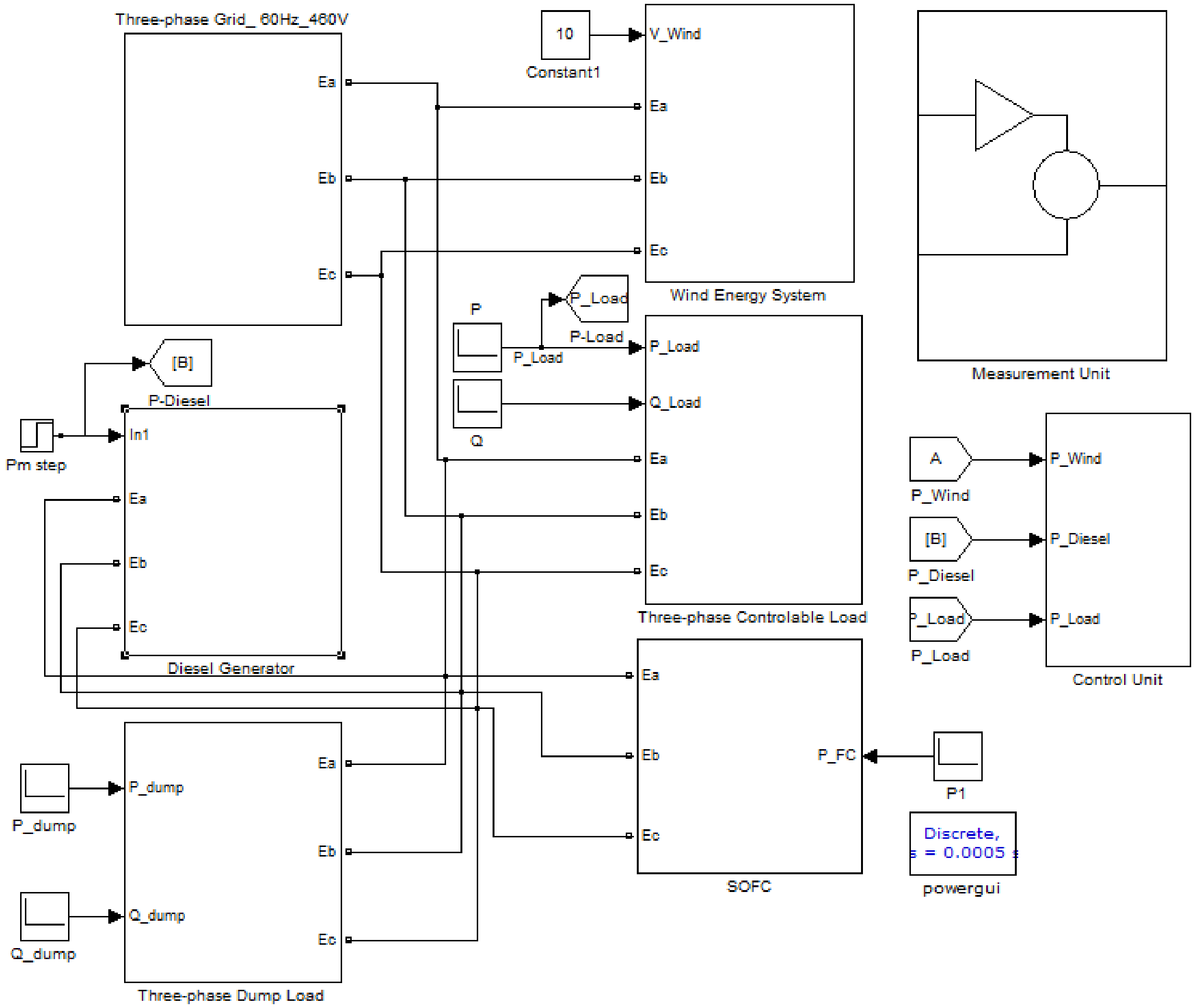


Fig. 4-20: Block diagram of the microgridin MATLAB

Information about the wind power, electrolyser, fuel cell, diesel generator, and load of the area were used to determine the command of the fuel cell, the electrolyser, and the diesel generator. The optimization outputs at two points were selected, and the power shares of the components were verified at these two points. The input for the wind turbine model was the wind speed, which establishes the wind turbine output power.

At $t = 16$ s, the wind turbine output power is 560 kWand the demand is 610 kW. To meet the demand, the fuel cell supplies the additional 49 kW required beyond the power supplied by the wind turbine. At this point, the output power of the diesel generator is zero (free running). At $t = 17$ s, the wind power drops, and the wind generation becomes zero. The demand is 648 kW, and since no wind power is available, the fuel cell and diesel generator should meet this demand. The fuel cell works at its rated maximum power (360 kW), and the remaining demand is met by the diesel generator. Fig. 4-21 shows the power flow in the system during a48-hour period. Table 4-3 lists the data for the two points mentioned.

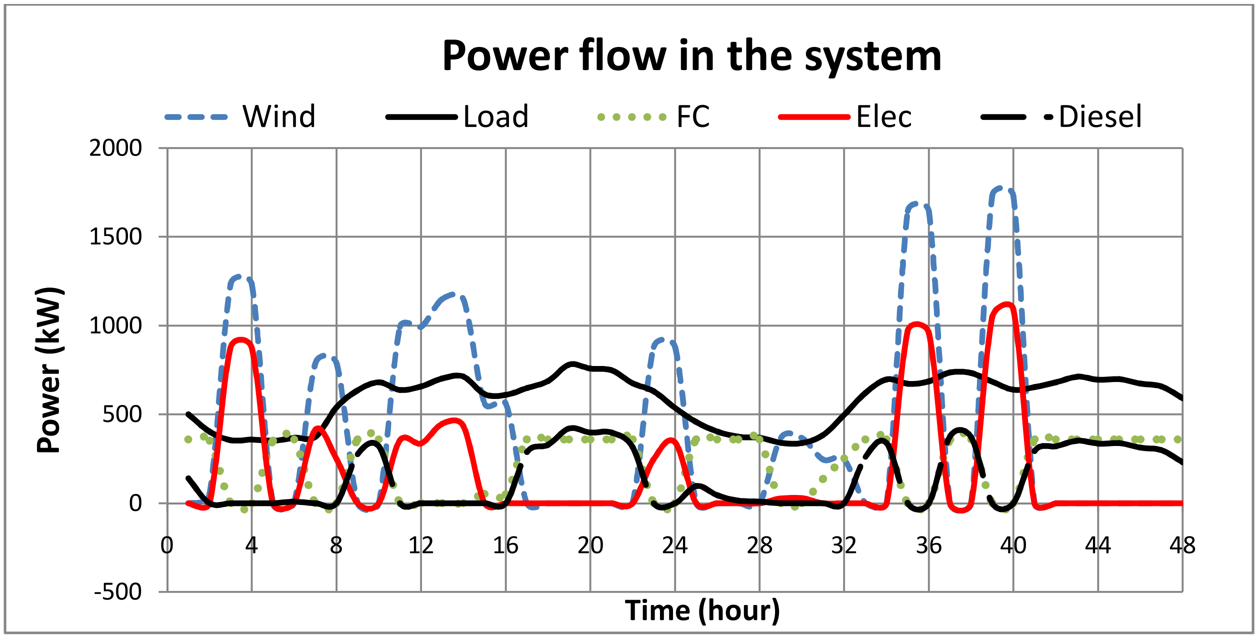
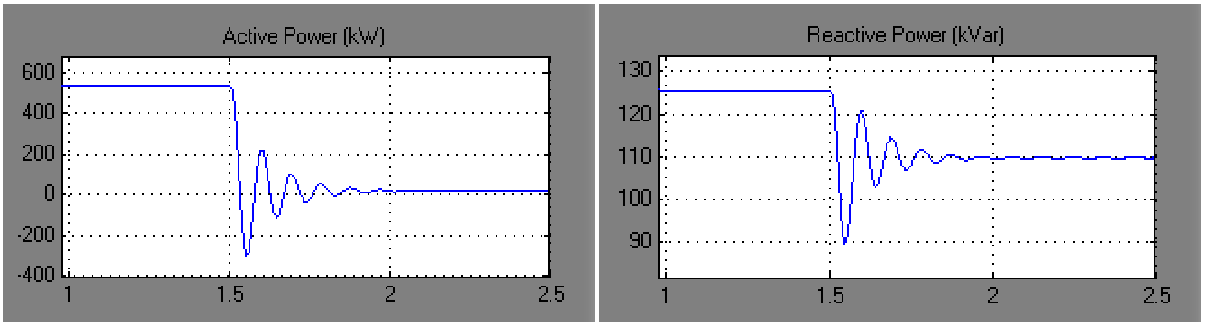


Fig. 4-21: Power flow in the system during a 48-hour period

Table 4-3: Sample points in the power flow of the system (kW)

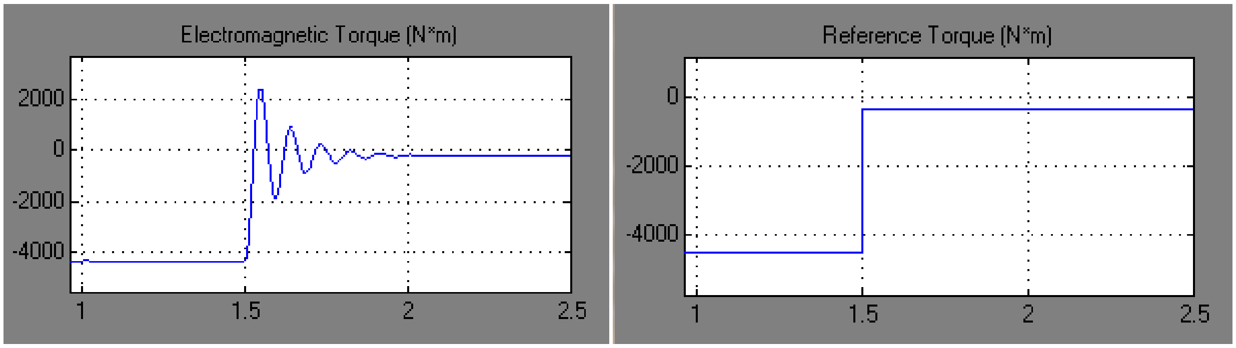
Time (s)	Wind	Load	FC	Elec	Diesel
16	560.65	610	49.34	0	0
17	0	648	360	0	288

The response and the active and reactive power levels of each component in the microgrid are shown in Fig. 4-22 to Fig. 4-28. The step change was applied at $t = 1.5$ s. The active power of the wind turbine drops from 560 kW to near zero. The reactive power is about 125 kVar, but after the step change in active power, this value is reduced to 110 kW. The electromagnetic torque of the induction generator and the output torque of the wind turbine are shown in Fig. 4-23. The voltage and rotor speed of the induction generator are shown in Fig. 4-24. The voltage is reduced by about 2 V, and the speed of the generator drops to 188.5 rad/s.



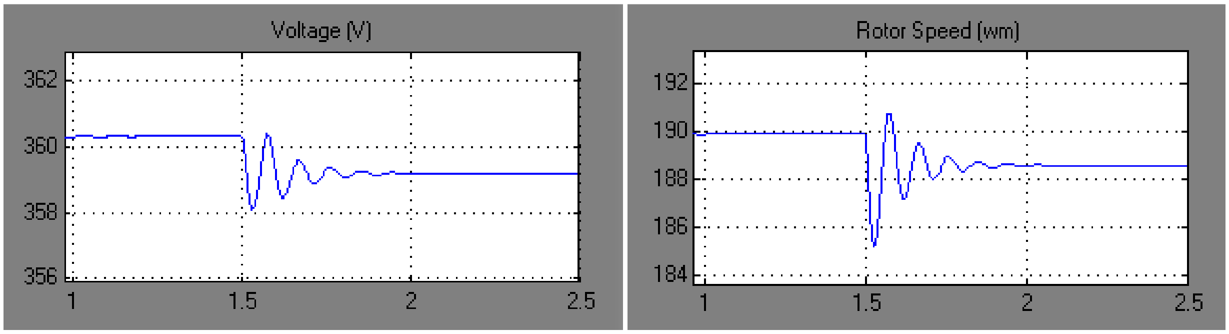
(a) (b)

Fig. 4-22: (a) Active power (kW); (b) Reactive power (kVar)



(a) (b)

Fig. 4-23: (a) Electromagnetic torque of the induction generator (Nm); (b) Output torque of the wind turbine (Nm)



(a) (b)

Fig. 4-24: (a) Voltage of the induction generator (V); (b) Speed of the induction generator (rpm)

The response of the fuel cell unit is shown in Figs. 4-25 and 4-26. Before the step change in wind power is applied to the system, the output power of the fuel cell is 50 kW, and the reactive power that the fuel cell unit absorbs from the grid is near zero. The next level of active power is the rated power of the fuel cell unit, which is 360 kW. The reactive power level increases to 45 kVar. The voltage and current are shown in Fig. 4-26.

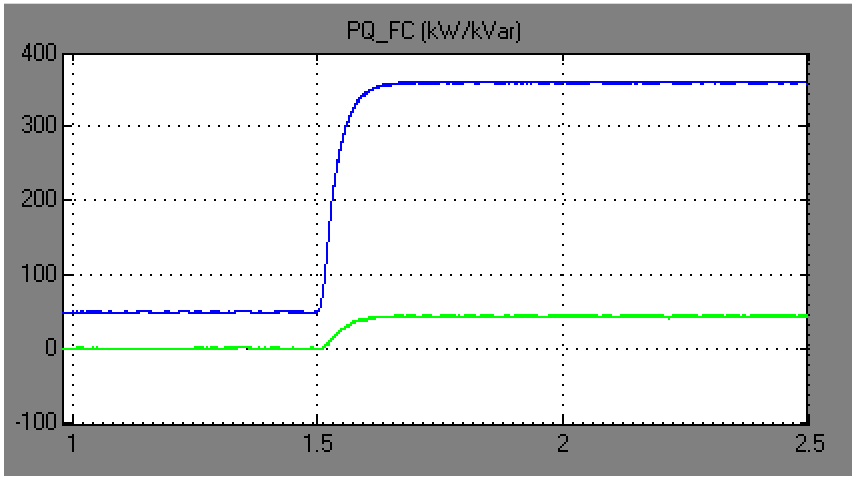
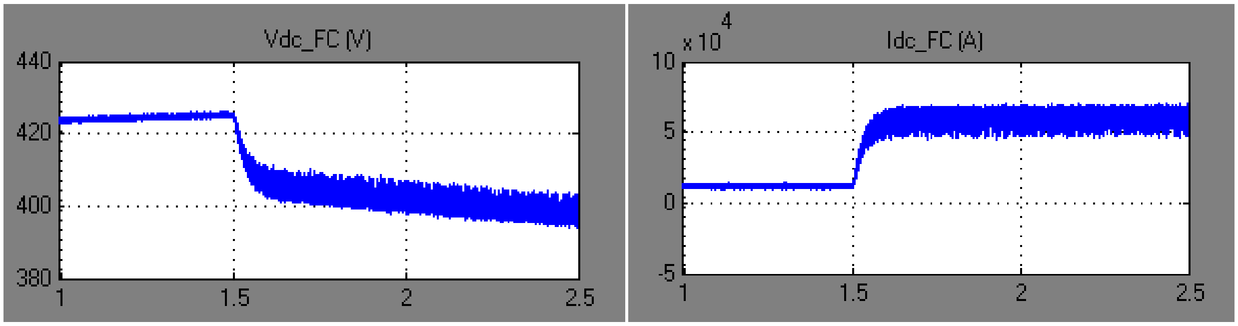


Fig. 4-25: Fuel cell active and reactive power (kW/kVar)

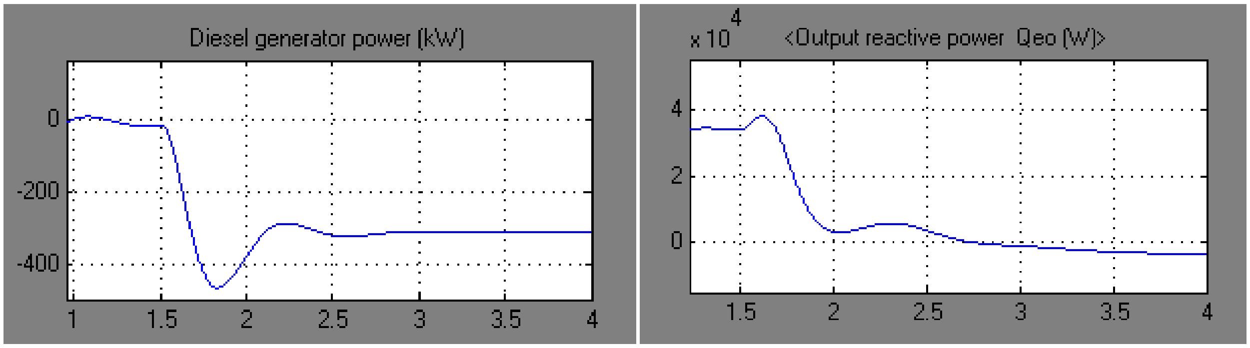


(a) (b)

Fig. 4-26: (a) Fuel cell voltage (V); (b) Fuel cell current (A)

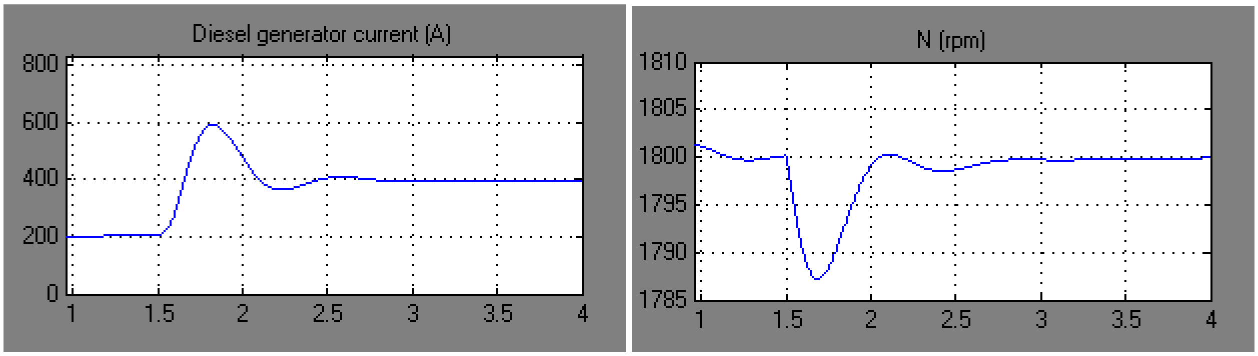
The active and reactive power levels of the diesel generator are shown in Fig. 4-27. The active power level is zero, and the generator is free running. A command for power equal to 288 kW is sent to the diesel generator at *t* = 1.5 s. The active power level goes up and reaches 313 kW at steady state. The reactive power level is about zero at steady state.

The generator current at zero active power is 200 A to supply the reactive power needed to run the generator at no-load. This level shows that it is not efficient to run the diesel generator at low power levels. In this case, the minimum level of the diesel generator was not considered. In other cases, a minimum power level of operation is set for the diesel generator below which it cannot operate. After a frequency drop of about 0.4 Hz, the speed of the machine returns to a synchronous speed.



(a) (b)

Fig. 4-27 (a) Active power of the diesel generator (kW); (b) Reactive power of the diesel generator (kVar)



(a) (b)

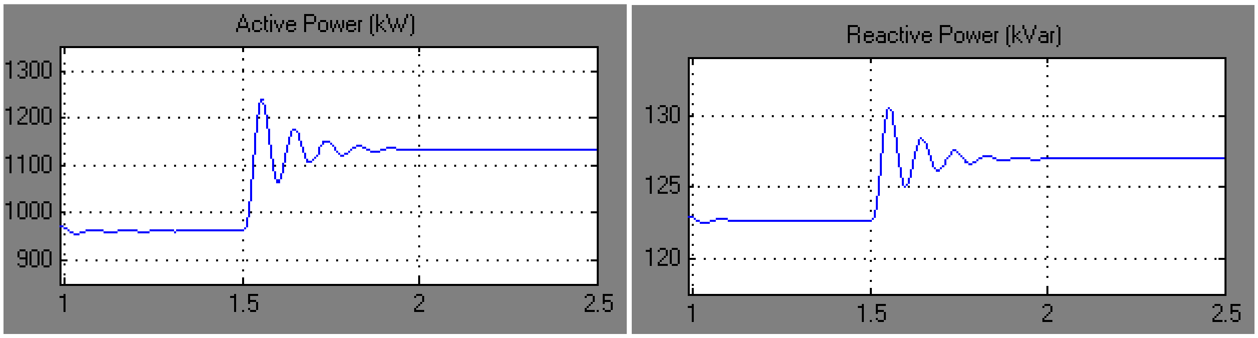
Fig. 4-28: (a) Current of the diesel generator (A); (b) Speed of the diesel generator (rpm)

Another simulation shows the power share between components when there is excess power and the electrolyser unit runs. Table 4-4 lists the data for the two points that are used for this simulation. At $t = 12$ sthe wind turbine output power is 993 kWand the demand is 657 kW. The electrolyser unit absorbs the excess power that equals to 336 kW. At this point, the output power of the diesel generator is zero. At $t = 13$ s, the wind power goes up, and the wind generation becomes 1149 kW. The demand is 702 kW, and the excess power is 447 kW that is absorbed by electrolyser.

Table 4-4: Sample points in the power flow of the system (kW)

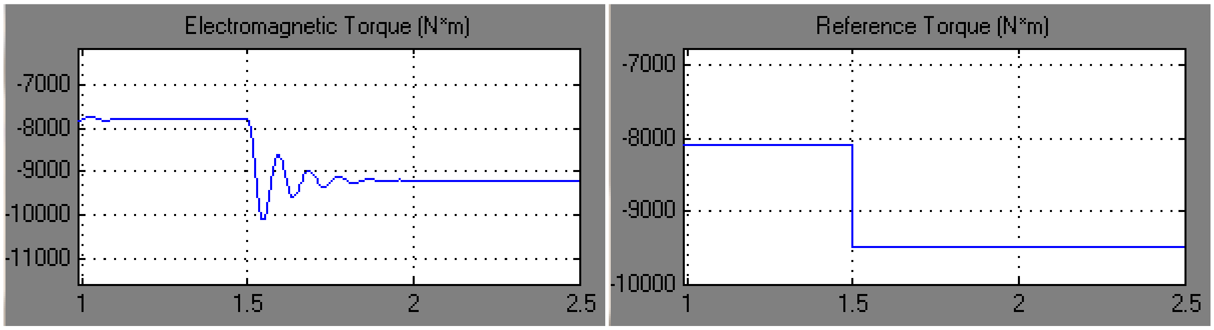
Time (s)	Wind	Load	FC	Elec	Diesel
12	993.64	657	0	336.64	0
13	1149.53	702	0	447.53	0

The response and the active and reactive power levels of each component in the microgrid are shown in Fig. 4-29 to Fig. 4-33. The step change for wind power and demand was applied at $t = 1.5$ s. The active power of the wind turbine goes up from 993 kW to 1149 kW. The electromagnetic torque of the induction generator and the output torque of the wind turbine are shown in Fig. 4-30. The voltage and rotor speed of the induction generator are shown in Fig. 4-31.



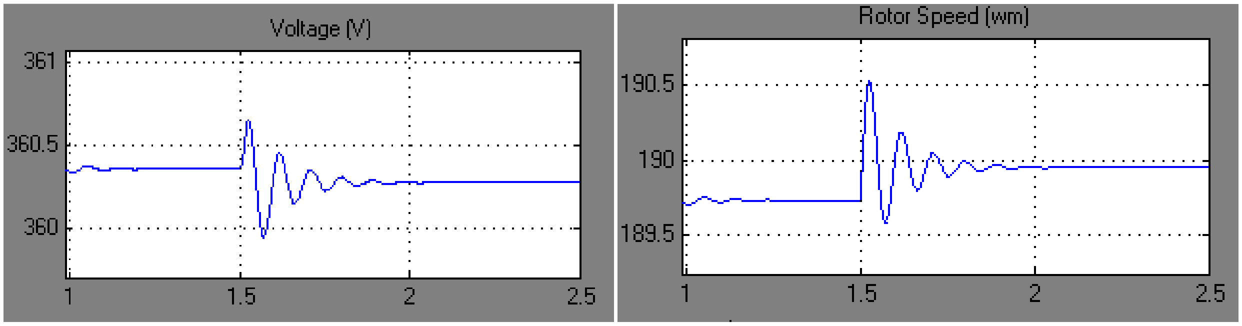
(a) (b)

Fig. 4-29: (a) Active power (kW); (b) Reactive power (kVar)



(a) (b)

Fig. 4-30: (a) Electromagnetic torque of the induction generator (Nm); (b) Output torque of the wind turbine (Nm)



(a) (b)

Fig. 4-31: (a) Voltage of the induction generator (V); (b) Speed of the induction generator (rpm)

The response of the electrolyser unit is shown in Figs. 4-32 and 4-33. Before the step change in wind power is applied to the system, the output power of the electrolyser is 336 kW, and the reactive power that the electrolyser unit absorbs from the grid is near zero. The next level of active power is 447 kW. The reactive power level increases to 45 kVar. The voltage and current profiles are shown in Fig. 4-33.

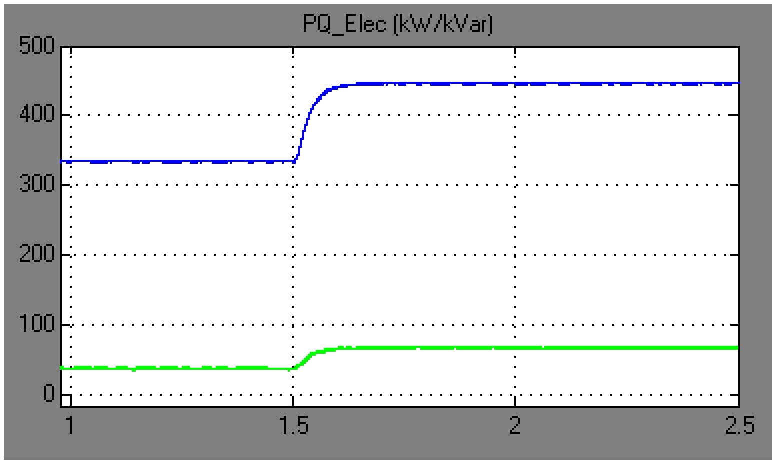
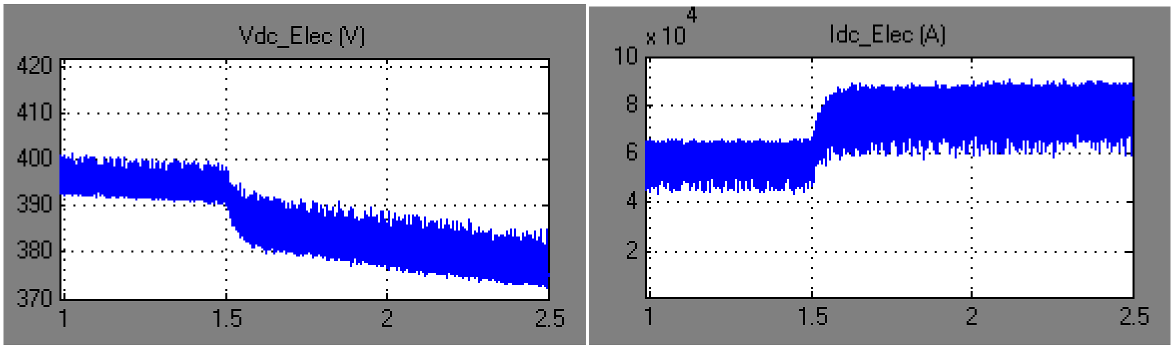


Fig. 4-32: Electrolyser active and reactive power (kW/kVar)



(a) (b)

Fig. 4-33: (a) Electrolyser voltage (V); (b) Electrolyser current (A)

4.6 Conclusion

The microgrid components, including a wind turbine, a fuel cell, a diesel generator, a three-phase controllable load, and a three-phase dump load were integrated into the overall system model. The power balance at steady state for all components was investigated, and the results were compared with the results presented in Chapter 3.

To manage the power flow between the components, a control unit based on the power flow strategy described in Chapter 2 was modeled. This control unit receives the available data from the load, wind turbine generation and diesel generator, and produces reference points for the fuel cell, the electrolyser, and the diesel generator.

Chapter 5

Conclusions

5.1 Summary and conclusions

For this thesis, a microgrid system was proposed, and the optimal sizing of its components was investigated. The microgrid system consists of the diesel generators that traditionally operate in the system, wind energy conversion systems connected through an induction generator to the system, an electrolyser that can store excess energy in the form of Hydrogen, a solid-oxide fuel cell system connected through an IGBT inverter to the grid, a three-phase balanced load that mimics the behaviour of the load in the system, and a dump load that is used in cases when excess energy cannot be stored.

Chapter 2 is dedicated to a historical background and a literature survey. The current state of microgrid research and applications was investigated, with a focus on wind-diesel hybrid systems for remote areas. For the purposes of this research, a microgrid is defined as operating based on a simple control algorithm that is used to balance the power flow in the system. The system uses a wind turbine as the main source of energy, an electrolyser to absorb the excess power from the wind source, a hydrogen tank to store the hydrogen generated by the electrolyser, a fuel cell to supply the power deficit when the wind is inadequate for meeting the demand, and a diesel generator as a backup and as a frequency and voltage regulator.

Chapter 3 presents an overall model of the microgrid along with an optimization problem for sizing the components of the system in order to obtain electricity at the minimum cost. The modeling and formulation of the optimization problem as well as the economical modeling of the problem in order to conduct optimal unit-sizing for the components of the hybrid system are discussed in this chapter. Three scenarios were used for the purpose of unit-sizing: (i) diesel-only operation, which is the traditional operating mode; (ii) all renewable so that the entire demand is met by renewable energy resources with the diesel generator acting as backup; and (iii) parallel operation, in which the diesel generator supplies the load in parallel with renewable sources.

The optimization problem was formulated in a GAMS environment. To define a cost function, the system was operated during an entire year. The results of the simulation of the power generation, the demand, the diesel generator, the fuel cell, the electrolyser, and the state of the charge of hydrogen tank are shown and discussed.

The output of the optimization problem was verified using a MATLAB simulation based on the whole possible area sweeping method. The same ratings, economical parameters, load and wind profiles, and power dispatch algorithm that were adopted in GAMS optimization problem were used for this simulation. The results are totally compatible with the results obtained from the GAMS model.

An analysis of the results for the optimization problem show that the lowest cost of the system results from an all-renewable scenario. The parallel operation scenario is the next most economical scenario: two diesel units operate in parallel with the wind turbine in order to supply the demand. Depending on the average load required, one of the diesel units runs at its optimum operating point and the other is used to supply any power deficit. The diesel-only case includes no wind turbines, and the entire demand of the community is supplied by traditionally operated diesel units. As expected, the annual fuel cost of the system is the highest with the diesel-only system, largely because of the cost of the fuel.

The carbon emissions are lowest with the fully renewable scenario and very high for the diesel-operated approach. The capital cost is very high for the fully renewable system, with the majority of the cost resulting from the installation of a vast wind turbine farm in the community. The results show that using renewable resources combined with diesel units is both economical and environmentally beneficial.

Chapter 4 verifies the results obtained from solving the optimization problem. The wind turbine model, the fuel cell model, and the electrolyser model were simulated. A wind turbine model based on an aerodynamic model of a turbine was developed. The fuel cell system consists of an

SOFC connected to a three-phase infinite bus through an IGBT inverter. The diesel generator used is a synchronous machine operating at 60 Hz and receiving the reference power command as input.

The components were then integrated into overall system model. To manage the power flow between the components, a control unit based on the power flow strategy presented in Chapter 2 was modeled. This control unit receives the available data from the load and the generation of wind and diesel and then produces reference points for the fuel cell, the electrolyser, and the diesel generator. The power balance at steady state for all components was investigated.

5.2 Contributions

The focus of this research was on three main areas:

- Developing a microgrid model and deriving the optimal sizing for the components in order to minimize the cost of electricity;
- Defining a variety of operational scenarios for the microgrid, investigating the parameter sizing, and determining the advantages and disadvantages of each scenario; and
- Developing a microgrid and designing the components in order to study the dynamic behaviour of microgrid.

The use of a renewable resource in combination with a diesel generator for the microgrid developed in this research, the real load profile of a remote community in northern Canada, a hydrogen-based energy storage, long-term analysis of the data, and consideration of the environmental impact all contribute to the significant impact of this thesis compared to other studies in the field of unit-sizing for hybrid systems.

The contributions of this research can be outlined as follows:

1. An optimal method of unit-sizing has been created for the microgrid. To obtain electricity at the minimum cost, the optimal size of the fuel cell, the electrolyser, and the hydrogen tank have been determined.

2. Three practical scenarios have been defined, and the sizing of the system for each scenario has been calculated. The advantages and disadvantages of each system have been presented.

3. A microgrid model has been developed in a MATLAB environment for the purposes of studying the dynamic behaviour of microgrid.

3.3 Suggestions for future work

The continuation and completion of the work presented in this thesis could include a focus on the following specific areas:

- **Multiple Renewable Resources**

  Solar energy, biomass, hydropower, geothermal energy, and other renewable resources need to be studied; some of them are economically viable for implementation in remote communities.

- **Optimal Operating Scenarios**

  Studies could examine the algorithms for operating the microgrid with the goal of optimizing the system both economically and environmentally. Operating the diesel units for different time periods and at different power levels can have a considerable effect on the efficiency and cost of operation. Many storage algorithms could be applied with respect to the production and consumption of hydrogen.

- **Control of the Microgrid**

  To examine the dynamic behaviour of the microgrid, the system control algorithms could be studied. The power flow analysis, the voltage and frequency stability analysis, the islanding operating mode, and the response of the system when faults occur are all challenging issues.

- **Experimental Testing**

  A laboratory prototype of the proposed microgrid system could be built and tested in order to verify the validity of the developed and optimized model.

Appendix

A. Capacity factor calculations

The definition of the CF is as:

$$CF = \frac{E_a}{P_{rated} * 8760} \tag{1}$$

P_{rated} is known, so we just need to calculate the E_a to put in this equation. The E_a will be calculated by this equation:

$$E_a = 8760 \times \sum_{v_1}^{v_2} f(v) P(v) \tag{2}$$

Where v_1 and v_2 are cut-in and cut-out speed, respectively;

$p(v)$ is the power at speed v, and $f(v)$ is Rayleigh PDF value at v.

Weibull probability density function is the most popular way to formulate the density function of wind speed. The Weibull probability is as below:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{3}$$

Based on the information (10) in Northern community:

$k = 2.13$, and $c = 6.89$, so:

$$f(v) = 0.31\left(\frac{v}{6.89}\right)^{1.13} \exp\left(-\left(\frac{v}{6.89}\right)^{2.13}\right) \tag{4}$$

The density function can be seen in Fig. A-1. The quantization of this density function is as Fig. A-2.

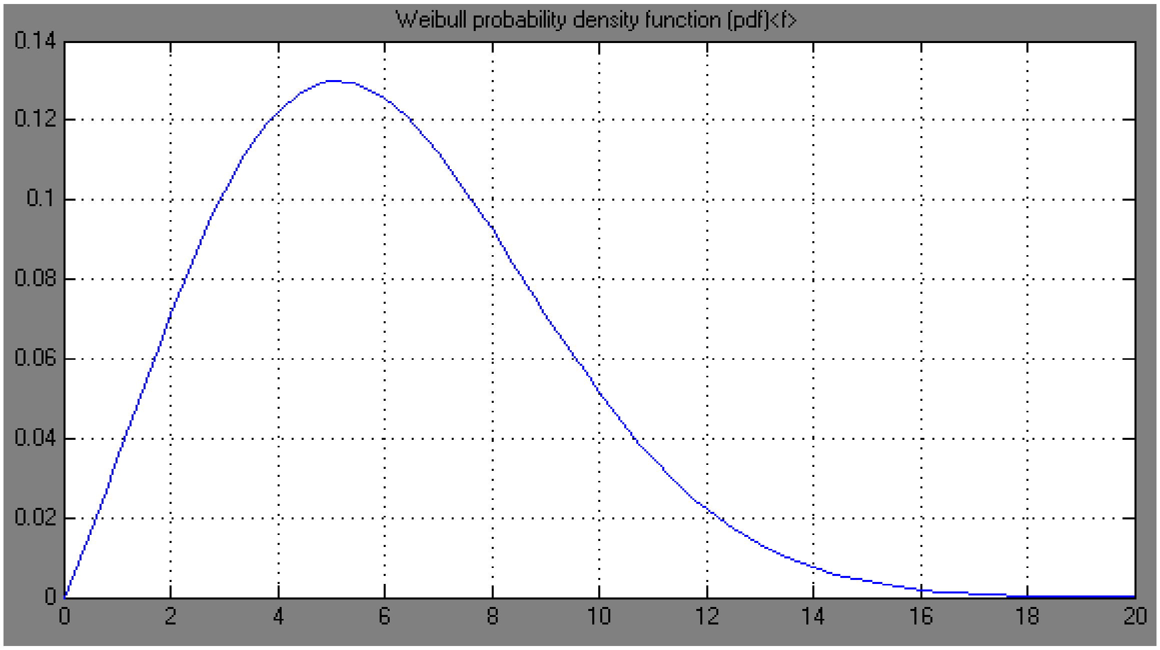


Fig. A-1: Wiebull density function for Northern teritory

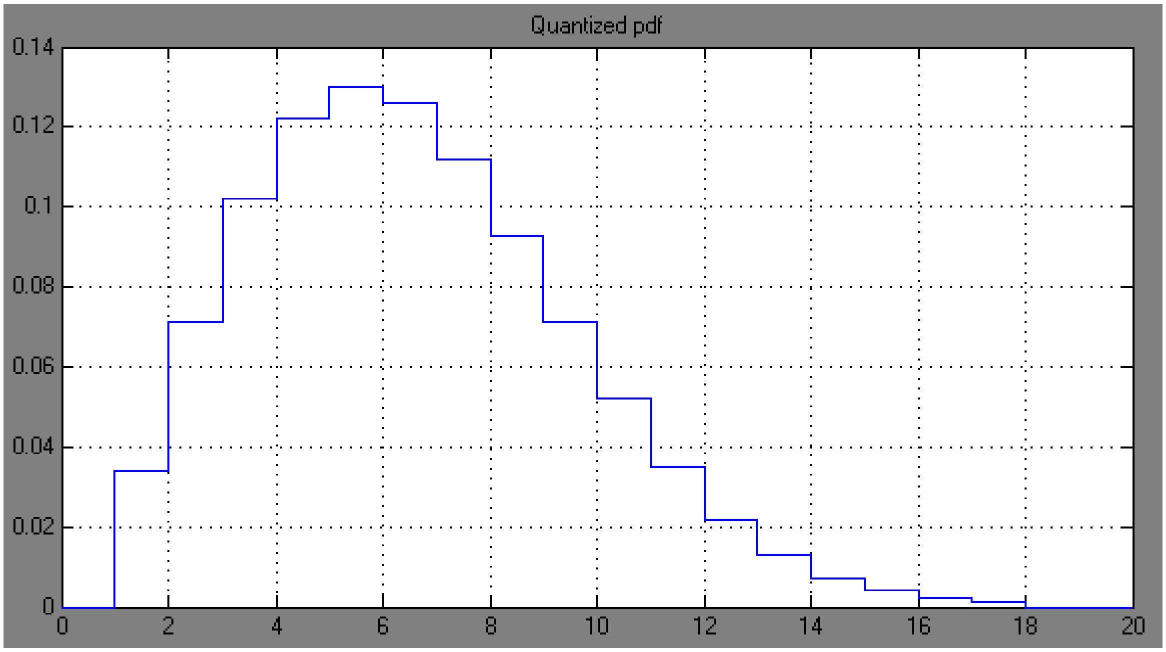


Fig. A-2: Quantized density function (quantization period is $1m/s$)

For $25kW$ wind turbine considered in this study, wind turbine power curve is as shown in Fig. A-3.

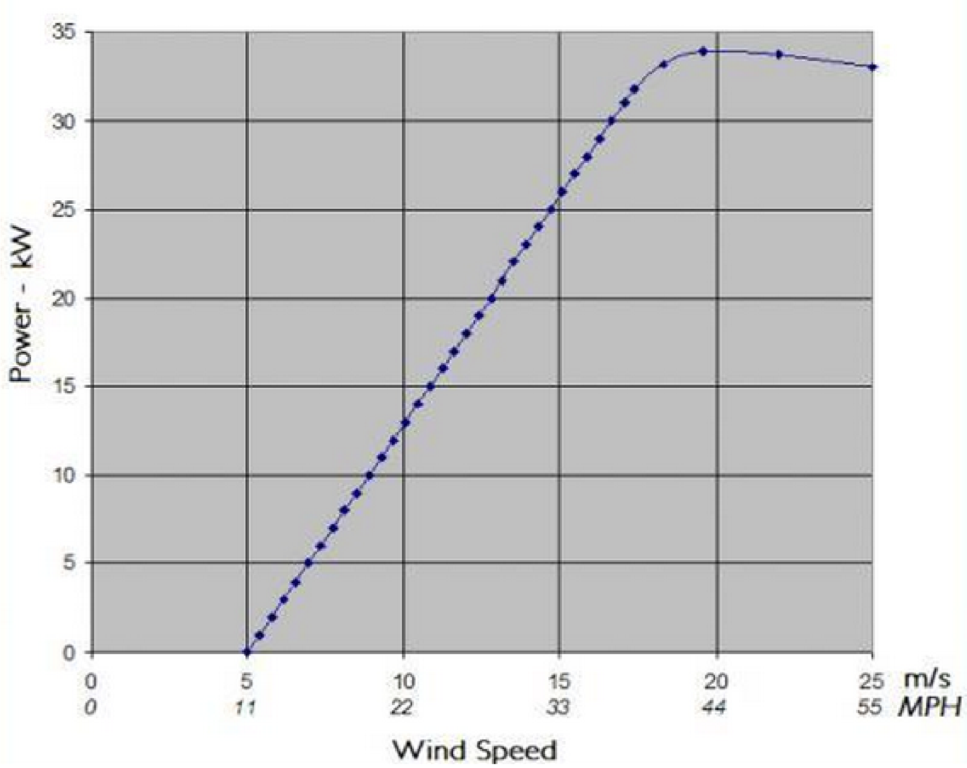


Fig. A-3: Wind turbine power curve

Based on power curve of wind turbine, and probabilty density function for the area under study, the energy production of wind turbine in a typical day is calculated as in Table. A-1.

Thable. A-1 Energy production of wind turbine in a typical day

Wind speed (m/s)	**Power (kW)**	**Probability of (V<v<V+1)**	**Number of Hours for this speed**	**Energy produced in any speed (kWh)**
0	0	0	0	0
1	0	0.034	0.816	0
2	0	0.071	1.704	0
3	0	0.102	2.448	0
4	0	0.122	2.928	0
5	0	0.13	3.12	0
6	2.5	0.126	3.024	7.56
7	5	0.112	2.688	13.44
8	7.5	0.093	2.232	16.74
9	10	0.071	1.704	17.04

10	12.5	0.052	1.248	15.6
11	15	0.035	0.84	12.6
12	17.5	0.022	0.528	9.24
13	20	0.013	0.312	6.24
14	22.5	0.007	0.168	3.78
15	25	0.004	0.096	2.4
16	27.5	0.002	0.048	1.32
17	30	0.001	0.024	0.72
18	32.5	0.0004	0.0096	0.312
19	34	0.0001	0.0024	0.0816
20	34	0	0	0
21	33.5	0	0	0
22	33.5	0	0	0
23	33	0	0	0
24	33	0	0	0
25	33	0	0	0
Energy production in a typical day				**107.0736 kWh**

The energy production in a typical day for wind turbine is $107.0736\ kWh$. Based on equation (1):

$$C_p = \frac{107.0736}{35*24} = 0.1275 \qquad (5)$$

$$C_p = 0.1275\% \qquad (6)$$

B. Carbon tax

A carbon tax is a policy instrument that sets a per-unit charge on emissions. Typically the system involves a tax on fuels that emit carbon dioxide when burned and on other greenhouse gas emissions. A schedule for future tax rates would be established, sending a long-range price signal to the economy. The tax thus provides price certainty but leaves the annual level of emissions reductions uncertain.

Fig. B-1 shows the price that should be put for CO_2 to cut the emissions level in the perspective of Canada government by 2050.

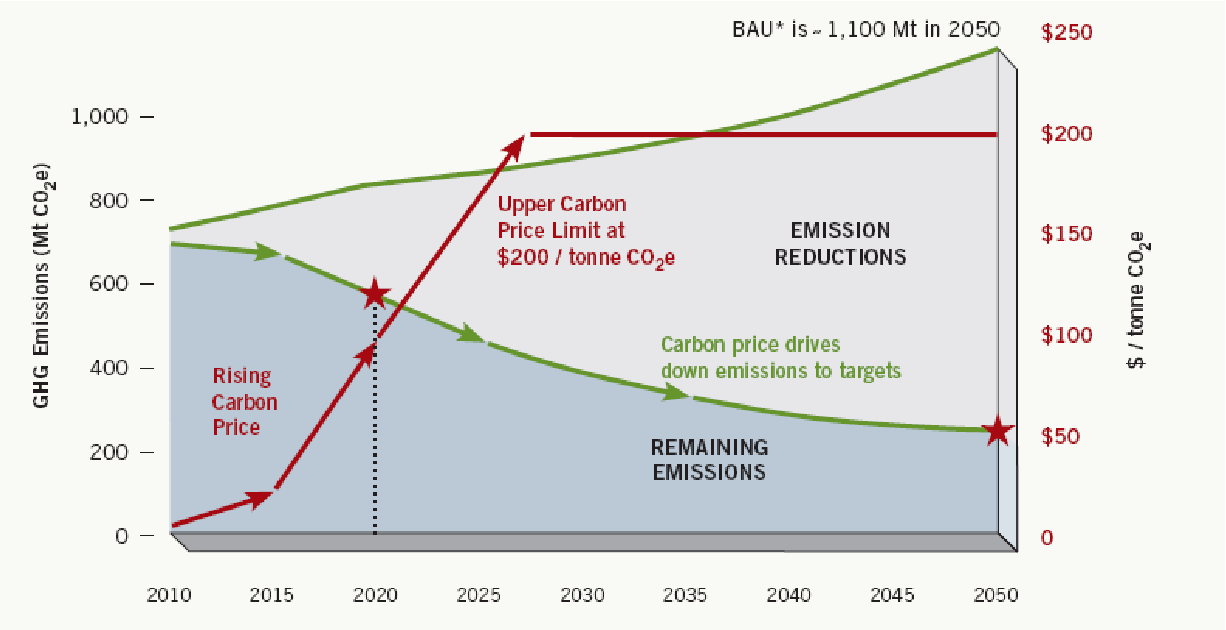


Fig. B-1: Government of Canada emission reductions target in 2020 and 2050

Emitters can initially meet 70% of their targets through contributions to the Technology Fund at the rate of 15 $\$/tonne CO_2$; the price rises to a maximum of about 23 $\$/tonne$ in 2017, and the fund is to be phased out by 2018. The prices are used in different scenarios in this thesis.

C. Diesel units switching

Logic cycling diagram for two diesel units is shown in Fig. C-1. The operation states of the diesel power plant units are shown in Table C-1. There is same algorithm for three diesel units as for two units.

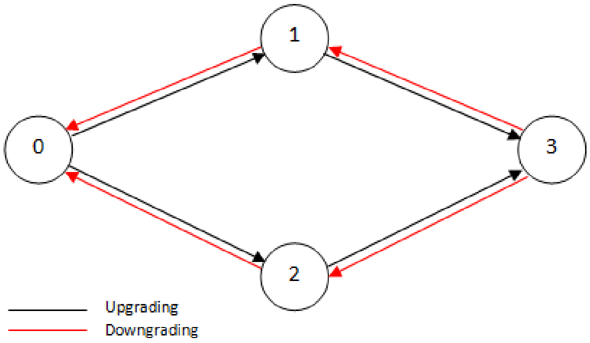


Fig. C-1: Logic cycling diagram for two diesel units

Table C-1: Operation states of the diesel power plant units

Logical State	**Diesel 1**	**Diesel 2**	**Upgrading states**		**Downgrading states**	
0	Off	Off	1	2	1	1
1	On	Off	4	4	1	1
2	Off	On	4	4	1	1
3	On	On	4	4	2	3

The logic used for operation of the diesel units is as below:

$$\left\{\begin{array}{cl} P_d < P_1 & \rightarrow St.0 \\ P_1 < P_d < P_2 & \rightarrow St.1 \\ P_2 < P_d < P_1 + P_2 & \rightarrow St.2 \\ P_d > P_1 + P_2 & \rightarrow St.3 \end{array}\right\}$$

where P_1, P_2 are the power of $Unit$ 1, and $Unit$ 2 that they operate in most efficient point, and P_d is demand of the system.

D. MATLAB Program

```
%*****************************************************************%
%**********************%Microgrid Unit-Sizing*********************%
%*************************%by Mehdi Vafaei************************%
%*****************************************************************%

format long;
clear all;
close all;
clc;

%*****************************************************************%
%**********************%Parameters Definition*********************%
%*****************************************************************%

% A is the vector for Load information in a week, and the samples
%are in an hour. the values are in kW.
A=[];
%The B is the vector for wind turbines generation in a week
% and the samples are in an hour
B1=[];
B2=[];
W=176;
W1=176;
Bm=0.1*(W/W1)*B1;
%disp('A=');
%disp(A);
%disp('B=');
%disp(B);
H2=4000;
%H2 Tank capacity that is 20000kWh
%Elec=560;
%Electrolyser capacity that is 600kW
%FC=280;
%FC capacity that is 500kW
%There are 176 units of 25kW wind turbines
PV=0;
% There are 6250 units of 120W PV panels.
Diesel_R=1200;
%Diesel generator rating
W_C=5000;
%25kW wind turbine is 100,000$, and 20 years life time, 100000/20
FC_C=100;
%FC stacks are 20000$ for 20 years lifetime
%and Stacks are 3kW, so 20000/20/3 = 333
Elec_C=100;
%Electrolysers are 20000$ for 20 years lifetime
%and units are 3kW, so 20000/20/3 = 333
PV_C=50;
%120W units of PV are 1000$ per unit, and their lifetime is 20 years
%their efficiency are 16%, we have 120kW PV panels in the system, so total cost
of the
%system is 1000/0.16=6250 panels, 6250*1000=6,250,000$, and the annual cost
%is 6,250,000/20=312,500$, so the annual cost is 50 $/Unit
```

```
Diesel_C=1.5;
%120 L/hour is fuel burn of diesels for a 400kW unit
%, so 120/400 L/kWh, so 0.3 L/kWh, and any litre of fuel is 0.5$, so
% 0.15 $/kWh is electricity price of diesels, I put the price more for
% better results
CO2_C=0.010485;
%Carbon tax is 15 $/tonne, and co2 emissions for diesel unit is
% 0.699 kg/kWh. So the CO2_C = 0.699*15*0.001 = 0.010485 $/kWh
CO2_E=0.699;
%Co2 emission is 0.669 kg/kwh
Dump_C=1;
%Dump load cost is 1 $/kW
Dump_E_C=0.1;
%Electricity price in the area is 0.1 $/kWh
H2_C=1.5;
%Hydrogen tank price is supposed 30 $/kWh, so 600000/20 $/year,
% so 30000/20000 = 1.5$


%*******************************************************************%
%**********************%ECONOMICAL PARAMETERS********************%
%*******************************************************************%


%***********************Annual Capital Cost*********************%
i_loan=0.05;
%loan rate
f=0.02;
%inflation rate
i=(i_loan-f)/(1+f);
%annual interest rate
n1=20;
%lifetime of the project
CRF1=(i*(1+i)^n1)/((1+i)^n1-1);
%Capital recovery factor

n2=5;
%lifetime of the project
CRF2=(i*(1+i)^n2)/((1+i)^n2-1);
%Capital recovery factor

ACC_wind=4000*CRF1;
%100,000/25kW=4000 $/kW
ACC_FC=(20000/3)*CRF2;
%Each 3kW unit of FC is 20000$
ACC_Elec=(20000/3)*CRF2;
%Each 3kW unit of Elec is 20000$
ACC_H2=30*CRF1;
%H2 tank is 30 $/kWh and 20 yrs lifetime

%************************Annual replacement cost******************%

SFF=i/((1+i)^n2-1);
%sinking fund factor
ARC_FC=(1400/3)*SFF;
```

```
%Annual replacement cost of FC units, 1400 for 3kW units
ARC_Elec=(1400/3)*SFF;
%Annual replacement cost of Elec units, 1400 for 3kW units

%**********************Annual fuel cost****************************%

%   AFC=T_fc*CRF1;
%Annual fuel cost
%T-fc is total fuel consumption for lifetime of the project
%T_fc is 20*6*Diesel_E(59)

%*********************Annual operation and maintenance cost**********%

AOC_wind=(100/25)*(1+f)^n1
%for 25kW Wind units the operation cost for a years is 100$
AOC_FC=(15/3)*(1+f)^n1
%for 3kW FC units the operation cost for a years is 15$
AOC_Elec=(15/3)*(1+f)^n1
%for 3kW Elec units the operation cost for a years is 15$
AOC_Diesel=6*(1+f)^n1

%*********************************************************************%

[x,y]=meshgrid(1:1:20,1:1:20);
% x is presenting number of Electrolyser Units, and y is presenting number
% of FC units

z=[];
%z=x^2-y^2;
surf(x,y,z);
r=20*1;
%Elec Units
q=20*1;
%FC Units
j=q;
%The units are composed of 100kW units

u=1;

while(u<=10)

while(j<=10*q)

    p=r;

while(p<=10*r)

    FC=j;
Elec=p;
    B=u*Bm;

Excess=B-A;
Extra=A-B;
```

```
%Extra demand power is (Demand - Wind Power), but negative values should put
zero

F=[0
   0];
%Summation of Extra load, and its total extra demand in the period of
%time, and since time period is one hour so it doesnt need any scaling

%difference of stored power in any time in H2 tank, there is 20000kWh save
%energy in H2 before start to work

i=0;
while(i<=719)
    i=i+1;
if(Excess(i)>=0)
if (F(i)<=H2-Elec)
if(Excess(i)<=Elec)
                Excess(i)=Excess(i);
else
                Excess(i)=Elec;
end
else
            Excess(i)=0;
end
else
        Excess(i)=0;
end


if(Excess(i)>=0)
if (Excess(i)<=Elec)
if(F(i)<=H2)
                Excess(i)=Excess(i);
else
                Excess(i)=0;
end
elseif(F(i)<=H2)
            Excess(i)=Elec;
else
            Excess(i)=0;
end
else
        Excess(i)=0;
end


if(Extra(i)>=0)
if (Extra(i)<=FC)
if(F(i)>=Extra(i))
                Extra(i)=Extra(i);
else
                Extra(i)=0;
end
elseif(F(i)>=Extra(i))
            Extra(i)=FC;
```

```
else
            Extra(i)=0;
end
else
        Extra(i)=0;
end


if(Excess(i)>0)
        F(i+1)=F(i)+Excess(i);
elseif(Extra(i)>0)
        F(i+1)=F(i)-Extra(i);
else
        F(i+1)=F(i);
end

end



%If excess power is more than capacity of Electrolyser, it should be put
%equal to Electrolyser rated power

%If extra demand is more than capacity of FC, it should be put
%equal to FC rated power

%figure,plot(Extra);

Dump=B-A;
% we just make this vector to get dumped power

i=0;
while(i<=719)
    i=i+1;
if(Dump(i)>=0)
       Dump(i)=Dump(i)-Excess(i);
%dumped power in any time period is ((B-A)-Excess)
else
       Dump(i)=0;
end
end

%figure,plot(Dump);

%disp('Dump=');
%disp(Dump);

Max_Dump=max(Dump.');
%disp('Max_Dump=');
%disp(Max_Dump);


Dump_E=cumsum(Dump);
```

```
%Summation of dumoped power in the scale of time is dumped energy, 52 weeks
%in a year

Diesel=A-B;
% we just make this vector to get extra demand

i=0;
while(i<=719)
    i=i+1;
if(Diesel(i)>=0)
       Diesel(i)=Diesel(i)-Extra(i);
%Extra demand in any time period is ((A-B)-Extra)
else
       Diesel(i)=0;
end
end


%disp('Diesel=');
%disp(Diesel);

%figure,plot(Diesel);

Diesel_E=cumsum(Diesel);
%Summation of extra demand in the scale of time is extra energy in the
%system that should be supplied by diesel generators, 52 weeks in a year

n=j/q;
m=p/r;
% n change from 1,2,3,..,20


ACC_T=W*25*ACC_wind+Elec*ACC_Elec+FC*ACC_FC+H2*ACC_H2;
%Total ACC: W number of wind turbiens 25kW, Elect number of elec units r
%kW, FC number of Fc units with q kW, H2 capacity of tank in kWh

ARC_T=Elec*ARC_Elec+FC*ARC_FC;
%Elec number of elec units r kW, FC number of Fc units with q kW

ACO2_C=CO2_C*20*6*(Diesel_E(720)+400*720)*CRF1;
%CO2 Annual cost
AFC_T=Diesel_C*20*6*(Diesel_E(720)+400*720)*CRF1+ACO2_C;
%fuel consumption in 59 days so 6 cause a year is 12 month, and 20 is
%lifetime of project;

AOC_T=W*25*AOC_wind+Elec*AOC_Elec+FC*AOC_FC+Diesel_R*AOC_Diesel;
%Total AOC: W number of wind turbiens 25kW, Elect number of elec units r
%kW, FC number of Fc units with q kW, H2 capacity of tank in kWh

Cost(u,n,m)=ACC_T+ARC_T+AFC_T+AOC_T;


%Cost(n,m)=W*W_C+Elec*Elec_C+FC*FC_C+PV*PV_C+Diesel_E(48)*Diesel_C+Diesel_E(48)
*CO2_C+Max_Dump*Dump_C+H2*H2_C;
```

```
Load_E=cumsum(A);
%Energy Consumed as Load in 2 months

Wind_E=cumsum(B1);
%Energy produced by wind in 2 months

Total_Dump_Energy=6*Dump_E(720);
%Total dumped energy in a year

Total_Dump=20*6*Dump_E(720)*Dump_E_C*CRF1;
%Total dump cost in a year

Total_Load=6*Load_E(720);
%Energy cosumed in a year

Total_Wind=6*Wind_E(720);
%Wind energy produced in a year

Hybrid_Electricity_cost=Cost/Total_Load;
%Electricity cost in the case of optimum design

Only_D_Cost=Diesel_C*20*Total_Load*CRF1;
%Annual Cost of system if it operates in diesel mode only

Only_D_Electricity_Cost=Only_D_Cost/Total_Load;
%Cost of electtricity in diesel only cost

CO2_only_Diesel=CO2_E*Total_Load;
%CO2 emissions in a year for only diesel case (kg)
CO2_Hybrid=6*CO2_E*(Diesel_E(720)+400*720);
%CO2 emissions in a year for hybrid system (kg)

%Cost includes wind turbines capital cots
%Electrolyser capital cost
%FC stacks capital cost
%energy supplied by diesel units
%Dump energy cost
% and H2 tank capital cost

    p=p+r;

end

    j=j+q;

end

u=u+1;

end
```

E. GAMS Program

```
$title Optimal Unit-Sizing of a Wind-Hydrogen-Diesel Microgrid
$Ontext
  Optimal Unit-Sizing of a Wind-Hydrogen-Diesel Microgrid

$Offtext

set
  t period  /T1*T29/

alias(t,tt);

Sets
       i   nameinput   / name for input /

*parameter p_load(t) demand at any time t in kW

*/T1 350, T2 400, T3 450, T4 550, T5 600, T6 650, T7 700, T8 650,
* T9 600, T10 550, T11 400, T12 300/;

*parameter p_wind(t) wind power at any time t in kW

*/T1 500, T2 400, T3 800, T4 500, T5 300, T6 100, T7 200, T8 500,
* T9 800, T10 1000, T11 900, T12 600/;


$call gdxxrw.exe ploadwind.xlsx par=p_windrng=sheet1!a1:a29 Rdim=1 Cdim=0

*=== Now import data from GDX
Parameter p_wind(t);
$GDXIN ploadwind.gdx
$LOAD p_wind
$GDXIN


*=== First unload to GDX file (occurs during compilation phase)
$call gdxxrw.exe ploadwind.xlsx par=p_loadrng=sheet2!a1:a29 Rdim=1 Cdim=0

*=== Now import data from GDX
Parameter p_load(t);
$GDXIN ploadwind.gdx
$LOAD p_load
$GDXIN

display p_load,p_wind

*scalar fc_c fuel cell cost per unit /100/;
*scalar elec_c electrolyser cell cost per unit /100/;
scalar diesel_c diesel fuel cost per unit /0.5/ ;
scalar H2 hydrogen tank size /1000/;
scalar p_fcb fuel cell rated power /20/;
scalar p_elecb Electrolyser rated power /20/;

positive variables
```

```
p_diesel(t)      Diesel generator power at any time k
p_fc(t)  FC power at any time k
p_elec(t)        Electrolyser power at any time k
;

variable cost     cost of system;

integer variables
afc      integer varible for fc size
aelec    integer variable for elec size
awind integer variable for wind size
;

*Cost=ACC_T+ARC_T+AFC_T+AOC_T;

*ACC_T=W*25*ACC_wind+Elec*ACC_Elec+FC*ACC_FC+H2*ACC_H2;
*ACC_T=176*25*267.4+1453.3*Elec+1453.3*FC+2.0055*H2;

*ARC_T=Elec*ARC_Elec+FC*ARC_FC;
*ARC_T=88.0022*Elec+88.0022*FC;

*AFC_T=Diesel_C*20*6*Diesel_E(720)*CRF1;
*AFC_T=0.0669*Diesel_C*20*6*Diesel_E(720);

*AOC_T=W*25*AOC_wind+Elec*AOC_Elec+FC*AOC_FC;
*AOC_T=176*25*5.99438+7.4297*FC+7.4297*Elec;

*Cost=1202935.27+1548.7*Elec+1548.7*FC+2.0055*H2+8.028*Diesel_C*Diesel_E(720);


equations
costfn   cost function
flowfn(t)   power flow function
elecmaxfn(t)        electrolyser rating function
fcmaxfn(t)  fuel cell rating function
elecfn(t)   electrolyser power function
fcfn(t)     fuel cell power function
h2tankminfn(t)      hydrogen tank minimum function
h2tankmaxfn(t)      hydrogen tank maximum function ;



costfn.. 8.028*diesel_c*sum(t, p_diesel(t)) + 1548.7*aelec*p_elecb +
1548.7*afc*P_fcb + 2.0055*H2 + 1202935.27 - cost =e= 0;

flowfn(t).. awind*p_wind(t) + p_diesel(t) + p_fc(t) =e= p_elec(t) + p_load(t);

elecmaxfn(t).. aelec*p_elecb =g= awind*p_wind(t) + p_diesel(t) - p_load(t);

fcmaxfn(t).. afc*p_fcb =g= p_load(t) - awind*p_wind(t) + p_diesel(t);

elecfn(t).. aelec*p_elecb =g= p_elec(t);

fcfn(t).. afc*p_fcb =g= p_fc(t);

h2tankminfn(t).. sum(tt$(ord(tt)<ord(t)), p_elec(tt)) =g=
sum(tt$(ord(tt)<ord(t)), p_fc(tt));
```

```
h2tankmaxfn(t).. sum(tt$(ord(tt)<ord(t)), p_fc(tt)) + H2 =g=
sum(tt$(ord(tt)<ord(t)), p_elec(tt));

Model Unit_sizing         /costfn
flowfn
elecmaxfn
fcmaxfn
elecfn
fcfn
                          h2tankminfn
                          h2tankmaxfn
/;


Solve Unit_sizing minimizing cost using MIP;
```

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