USING ELECTRIC WATER HEATERS (EWHS) FOR POWER BALANCING AND FREQUENCY CONTROL IN PV-DIESEL HYBRID MINI-GRIDS

Khalid Ibrahim Elamari

A Thesis

in

The Department

of

Electrical and Computer Engineering

Presented in Partial Fulfillment of the Requirements

For the degree of Master of Applied Science at

Concordia University

Montréal, Québec, Canada

August 2011

CONCORDIA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

This is to certify that the thesis prepared

By: Khalid Ibrahim Elamari

Entitled: "Using Electric Water Heaters (EWHs) for Power Balancing and Frequency Control in PV-Diesel Hybrid Mini-Grids

and submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science

Complies with the regulations of this University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

____ Chair
Dr. R. Raut

____ Examiner, External To the Program
Dr. M. Zaheeruddin (BCEE)

____ Examiner
Dr. P. Pillay

____ Supervisor
Dr. L. A. Lopes

Approved by: ____
Dr. W. E. Lynch, Chair
Department of Electrical and Computer Engineering

____________20_____ ____________________________________
Dr. Robin A. L. Drew
Dean, Faculty of Engineering and Computer Science

ABSTRACT

Using Electric Water Heaters (EWHs) for Power Balancing and Frequency

Control in PV-Diesel Hybrid Mini-Grids

Khalid Ibrahim Elamari

Electricity is usually supplied by diesel generators in remote communities at high costs. In such a case, renewable energy sources (RESs), such as wind and photovoltaics (PV), can be cost effective to meet part of the energy needs. However, the integration of RESs may lead to large power fluctuations and to the operation of the diesel genset under-loaded. Traditionally, energy storage devices have been used to provide power smoothing and frequency regulations, but this solution is quite costly.

In this thesis, electric water heaters (EWH) are used to assist with power balancing and frequency regulation and to prevent the diesel genset from operating under-loaded, in a PV-diesel hybrid mini-grid.

The characteristics of the diesel genset, PV, and the EWH are studied. An EWH is modeled using Matlab/SIMULINK. Approximate linear equations are derived and used for estimating the amount of power an EWH can take or drop, by varying the set point temperature T_d.

A review of methods used to control the EWH are then presented. A basic integrated control of the EWH, which varies the set point temperature (T_d), using the system frequency is studied. Issues using this control in a small power system are investigated, and a modified integrated control is proposed to solve them.

The effectiveness of basic and modified integrated controls is validated using a hybrid PV-diesel mini-grid benchmark implemented in PSCAD. Moreover, the impact of the PV on fuel consumption, and frequency variations is observed. Simulation results indicate that the modified integrated control is effective for frequency regulations, peak shavings, and for preventing genset operates under loaded.

ACKNOWLEDGMENTS

I would like to express my gratitude to my supervisor, *Prof Dr. Luiz Lopes* who was abundantly helpful and offered invaluable assistance, support and guidance. This work would not have been possible without his support and encouragement.

I would like also to thank my other distinguished professors, *Pragasen Pillay* and *Sheldon S. Williamson,* and my colleagues in the Power Electronics and Energy Research (PEER) group. A very special thank to my colleague, *Reinaldo Tonkoski*, for his motivation and encouragement during my study.

Last, but not least, I would like to express my love and gratitude to my beloved mother and father, *Fatima and Ibrahim* for endless giving. I wish also to express my gratitude to my brothers and sisters for their support. Finally, I would like to express gratitude to my wife for her understanding and patient through the duration of my study.

I cannot close without express my sincere gratitude to my close relative and friends for their steady support and encouragement.

TABLE OF CONTENTS

LIST OF FIGURES .... **XI**

LIST OF TABLES .... **XIV**

CHAPTER 1 .... **1**

INTRODUCTION **1**

1.1 Introduction 1

1.2 The Mini-Grid 1

1.3 Overview of Conventional Methods to Improve the Performance of Hybrid System 3

1.4 Demand Side Management (DSM) 5

1.4.1 Potential of Residential Loads for DSM 5

1.4.2 Electric Water Heater for DSM 6

1.4.3 Statement of DSM in the Mini-Grid 6

1.5 The Objective of the Thesis 6

1.6 Outline of the Thesis 7

CHAPTER 2 .... **9**

HYBRID-MINI-GRID SOURCES **9**

2.1 Introduction 9

2.2 Diesel Genset 9

2.2.1 Frequency and Voltage Droop Control 10

2.2.2 Fuel Consumption Characteristics 13

2.3 Renewable energy source (photovoltaic power) 16

CHAPTER 3 18

ELECTRIC WATER HEATER (EWH) 18

3.1 Introduction 18

3.2 Back Ground on the EWH 18

3.3 Electric Water Heater Model.. 19

3.3.1 The Parameters of the EWH Model:.. 21

3.3.2 EWH Model in Matlab/SIMULINK 25

3.3.3 Hot Water Temperature Variation for 24 H (One Day):.......................... 26

3.4 Mathematical Analysis 28

3.4.1 Conventional Equations 28

3.4.2 Proposed approximate linear equations: 29

3.4.3 Validating the Derived Liner Equations 31

3.4.4 Validating the Linear Equations for Different *Wd* Values: 32

3.5 Impact of Key Parameters of EWH on Its Operations 36

3.4.5 Impact of T_d and Δ on EWH 36

3.4.6 Identify the Sensitively of the P_{EWH} to Its Key Parameters: 41

3.6 Study the Impact of Changing T_d during Transient Condition 42

CHAPTER 4 46

CONTROL METHODS 46

4.1 Introduction 46

4.2 Back Ground of Control Methods for EWH in DSM 46

4.2.1 External Control 47

4.2.2 Integrated Control 47

4.3 Design Consideration of the Integrated Control Parameters 49

4.4 Design of the Integrated Control Parameters for RES-Diesel Hybrid Mini-Grid 51

4.4.1 Set Point Temperature at Base Case (T_{db}) 52

4.4.4 Coefficient of Frequency Change or Slope Factor (*m*) 53

4.5 Study the Impact of Using the Integrated Control 55

4.5.1 The Impact of Turning ON/OFF EWHs on the Mini Grid's System Frequency: 56

4.5.2 The Impact of Activation the Integrated Control on Multiple EWHs for Different Load Conditions 57

4.6 Solution to Improve the Results of Using the Integrated Control 62

4.6.1 The activation conditions of the modified integrated control 62

CHAPTER 5 65

HYBRID PV-DIESEL MINI GRID SYSTEM MODEL AND SIMULATION RESULTS 65

5.1 Introduction 65

5.2 Mini Grid Structure and Model 65
5.2.1 Diesel Genset Plant 66
5.2.2 Step-Down Transformer 67
5.2.3 Low Voltage Distribution Line (240V) 67
5.2.4 PV system 68
5.2.5 Ac loads 69
5.3 The Integrated Control of the EWH Model 73
5.4 Simulation Results........ 76
5.4.1 Simulation Time and Initial Values 76
5.5 Simulation Results for Different Operation Condition and Cases 76
5.6 Summary of the Results 93
CHAPTER 6 96
CONCLUSIONS AND FUTURE WORK 96
6.1 Summary 96
6.1 Future Work 99
6.2.1 The Impact of Using High Variable PV Power Profile on the Performance of the modified Integrated Control 99
6.2.2 Implement the Modified Integrated Control of EWHs in Wind-Diesel Hybrid 99

6.2.3 Develop control strategy to vary the input power of the EWH with the modified integrated control of EWH 100

REFERENCES.. 101

LIST OF FIGURES

Figure 1-1 Conventional mini-grid 2

Figure 1-2 Mini-grid with diesel and RES (hybrid mini-grid) 3

Figure 1-3 Hybrid mini-grid with energy storage devices 4

Figure 2-1 The block diagram of a diesel genset 11

Figure 2-2 (A) Frequency vs. active power droop (B) Voltage vs. reactive power droop 12

Figure 2-3 Frequency vs. power droop curve of the 95 kW diesel genset........................ 14

Figure 2-4 The fuel consumption characteristics of the 95kW diesel generator 17

Figure 2-5 A typical I-V curve of PV panel 19

Figure 3-1 EWH with one resistance element 24

Figure 3-2 Water draws profile during 24 hour (ASHRAE schedule water draws)........ 45

Figure 3-3 (A) Variation of TH (t), (B) The ASHRAE *Wd* , (C) The instantaneous power consumed by the EWH 27

Figure 3-4 t_{on} as function of *Wd* for three value of T_d 40

Figure 3-5 t_{off} as function of *Wd* for three value of T_d 40

Figure 4-1 T_d, $T_d + \Delta$, and $T_d - \Delta$, as function of the system frequency 55

Figure 5-1 The architecture of hybrid PV-diesel mini-grid 66

Figure 5-2 Sunny PV power profile 69

Figure 5-3 The community center load profile 69

Figure 5-4 The load profile of the uncontrollable loads 70

Figure 5-5 The average power consumption of a 4kW EWH at base case....................... 71

Figure 5-6 Electric circuit of the EWH 71

Figure 5-7 Real value of the input energy (Q) 71

Figure 5-8 EWH thermal model in PSCAD 73

Figure 5-9 The basic integrated control 74

Figure 5-10 The modified integrated control 75

Figure 5-11 The output power of the diesel genset for Case 1 77

Figure 5-12 The system frequency for Case 1. 77

Figure 5-13 The fuel consumption of the diesel genset for Case 1 78

Figure 5-14 Demand of 20 EWHs for Case 1 78

Figure 5-15 The set point temperature for Case 1 78

Figure 5-16 The hot water temperatures of 20 EWH for Case 1 79

Figure 5-17 The output power of the diesel genset for Case 2. 80

Figure 5-18 The system frequency for Case 2 80

Figure 5-19 PV power of 6 PV panels 81

Figure 5-20 The fuel consumption of the diesel genset for Case 2 81

Figure 5-21 Demand of 20 EWHs for Case 2 81

Figure 5-22 The output power of the diesel genset for Case 3 84

Figure 5-23 The system frequency for Case 3 84

Figure 5-24 The fuel consumption of the diesel genset for Case 3 84

Figure 5-25 Demand of 20 EWHs for Case 3 85

Figure 5-26 The set point temperatures of 20 EWHs for Case 3 85

Figure 5-27 The hot water temperatures of 20 EWH for Case 3 85

Figure 5-28 The output power of the diesel genset for Case 4 ... 87Figure 5-29 The system frequency for Case 4 87

Figure 5-30 The fuel consumption of the diesel genset for Case 4 87

Figure 5-31 Demand of 20 EWHs for Case 4 88

Figure 5-32 The set point temperatures of 20 EWHs for Case 4 88
Figure 5-33 The hot water temperatures of 20 EWH for Case 4 88
Figure 5-34 The output power of the diesel genset for Case 5 90
Figure 5-35 The system frequency for Case 5 90
Figure 5-36 The fuel consumption of the diesel genset for Case 5 91
Figure 5-37 Demand of 20 EWHs for Case 5 91
Figure 5-38 The set point temperatures of 20 EWHs for Case 5 91
Figure 5-39 The hot water temperatures of 20 EWH for Case 5 92
Figure 5-40 Total time that diesel genset being below 30% and above 80% for different simulation cases 95

LIST OF TABLES

Table 2-1 Parameters of the 95kW diesel genset 12

Table 3-1 Constant parameters of EWH model 26

Table 3-2 The maximum and minimum ton, toff, and ttotal of the EWH 28

Table3-3: Comparing the results of using linear equations with other methods at base case (considered (Tdb = 120°F, and Δ = 2.5°F)) and Wd=6gal/h 31

Table 3-4 t_{on}, t_{off}, *and* t_{total} for ASHREA *Wd* profile 33

Table 3-5 Decreasing rate ΔTH of TH (t). 35

Table 3-6 Impact of varying Td&Δ on EWH operation (t_{on}, t_{off}, *D*, P_{EWH}, *and EC*) 37

Table 3-7 Variation of P_{EWH} (pu) with *Wd* and T_d. 41

Table 3-8 $t_{on(TC)}$ for different values of initial T_d (T_{do}) with respect to $t_{on(SSC)}$, using the ASHRAE *Wd* schedule: (T_{do}=120°F, ΔT_d=20°F, Δt_{on}=4.5) and (T_{do}=100°F, ΔT_d= 40°F, Δt_{on}=8.5) 44

Table 5-1 Transformer's Simulation Parameters 67

Table 5-2 Single-phase lines parameters (per line conductor 68

Table 5-3 Summary of the main results obtained from the simulated cases 93

CHAPTER 1
INTRODUCTION

1.1 Introduction

Electricity is a key element in global economic and social development. In most parts of the world, the demand for electricity has increased rapidly. In the common highly interconnected electric power systems, electricity is produced using large power plants based on conventional energy sources such as hydro, coal, nuclear and gas/oil. These power plants are characterized by relatively low-cost but they create environmental issues and are located relatively long distances from main consumer centers that require extensive infrastructures for the transmission and distribution of electricity[1].

In remote rural areas with low population densities, electricity can be supplied by extending transmission networks from large plants to those areas. However, the implementation of grid extension is expensive and impractical in many locations due to geographical obstacles and high capital costs. Therefore, many isolated systems employ distributed generation for supplying electricity in a stand-alone configuration, also known as a mini-grid [2].

1.2 The Mini-Grid

Conventionally, the main source used to produce electricity in mini-grids is the diesel generator set (diesel genset). Diesel gensets operate by using diesel fuel which, like all fossil fuel types, is unsustainable and can harm the environment. Moreover, delivering diesel fuel to remote areas is difficult and may require one litre or gallon of diesel to deliver one litre or gallon of the fuel to certain rural areas. Therefore, the price of electricity can cost as much as 1.5 $ per kWh [3]. Figure 1-1 shows a simplified diagram of a conventional mini-grid.

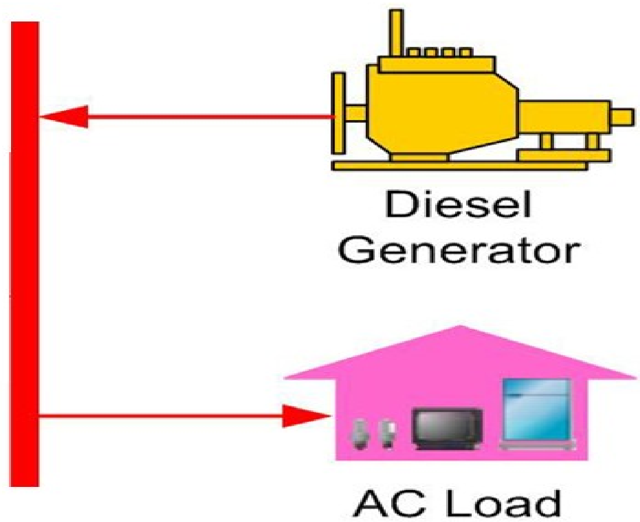

Figure 1-1: Conventional mini-grid

In such a case, renewable energy sources (RESs), such as wind and photovoltaic, can be cost effective to produce electricity in mini-grids. They are environmentally friendly, sustainable sources and are readily available. In principle, they can either replace or supplement diesel gensets in mini-grids. However, replacing a diesel genset is not practical, since RESs by themselves are considered to be uncontrollable. Therefore, RESs usually supplement the diesel genset(s) as shown in Figure 1-2 [4].

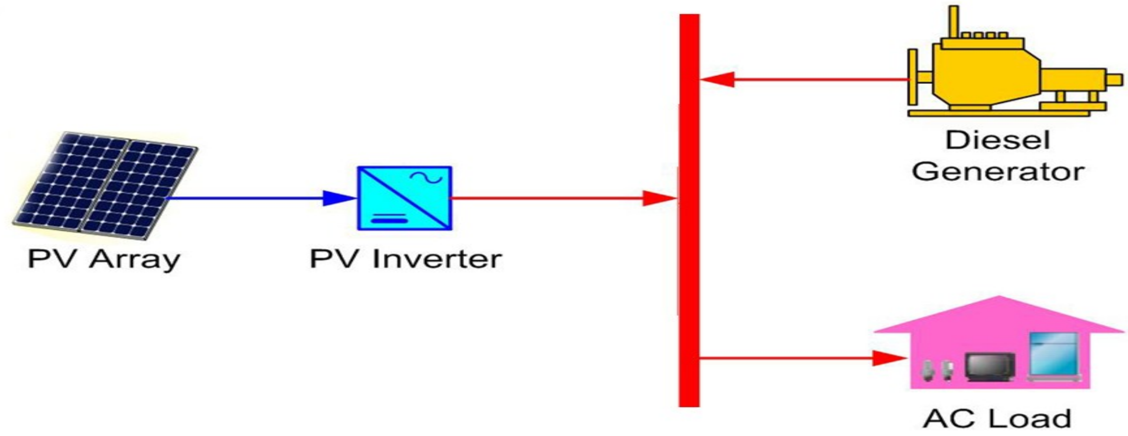

Figure 1-2: Mini-grid with diesel and RES (hybrid mini-grid)

RES-diesel-hybrid mini-grids reduce fuel consumption while producing power at low cost and with less pollution [5]. On the other hand, a reliable supply with the same power quality of a only diesel system is not easy to accomplish as reported in the literature [6]. One reason is that RESs are considered fluctuating and non-dispatchable sources that can cause disturbances in hybrid power systems leading to increases in frequency and voltage variations. Furthermore, balancing power generation with demand becomes an even bigger challenge since the demand in small communities varies significantly within a 24 hour period. The peak load can be as high as 5 to 10 times the average load [7].

1.3 Overview of Conventional Methods to Improve the Performance of Hybrid System

A common approach used to balance power generation with demand and to improve frequency regulation is the use of energy storage devices [8]. Examples of energy storage devices are battery banks, ultra-capacitors, and fly-wheels. These devices usually provide power smoothing in a hybrid system. They store the surplus power from RESs and supply it at peak load times. Commonly, battery banks are used for this purpose. However, conventional battery banks are the most expensive mini-grid component over its life-time[9]. Figure 1-3 illustrates a hybrid mini-grid with energy storage.

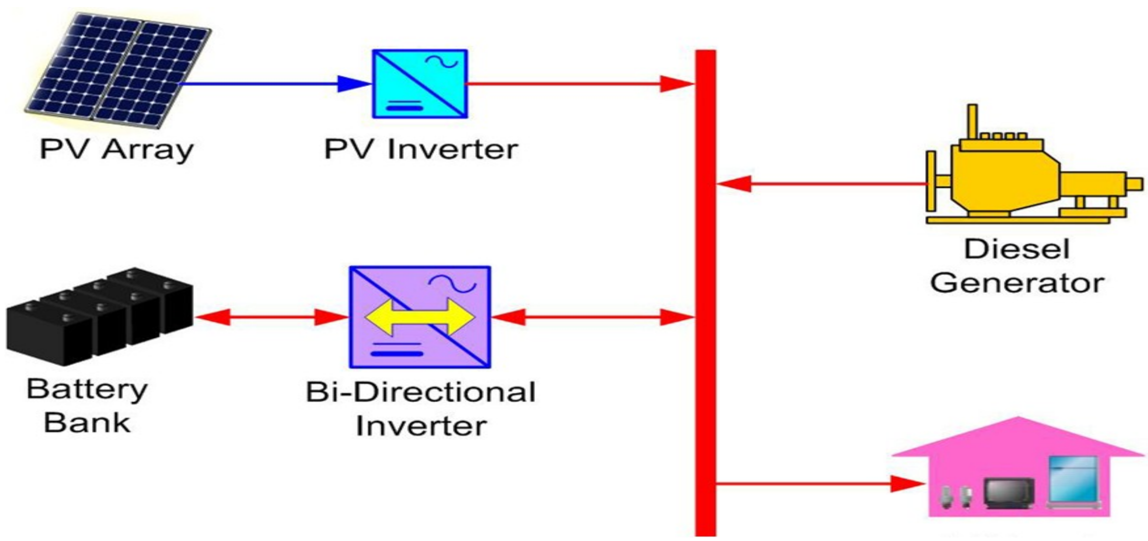

Figure 1-3: Hybrid mini-grid with energy storage devices

Dump loads are also used in a hybrid mini-grid, mostly in storage-less systems, to prevent diesel gensets from operating below a minimum output power level, which is typically 30% of their rated capacities, thus avoiding carbon build up in the diesel engine. Dump loads consume the surplus power from the diesel genset in case of light load conditions at night or when RESs provide surplus power and storage devices are either fully charged or not accessible (storage-less systems). Obviously, this method is wasteful and non-economic, especially in storages-less systems, and the reduction of fuel consumption is compromised [10].

An attractive method that has been investigated by many researchers is to use the power demand as part of the control of the power system. Some loads in the power system or the hybrid mini-grid behave like energy storage devices and can be controlled to consume the surplus power from RESs or genset like dump loads. Moreover, they can be controlled to not consume any power during periods of both shortage of RESs and peak consumption of uncontrollable loads. Since the loads already exist in the power system, fuel consumption due to dumping loads and the maintenance and replacement costs of battery banks can potentially be decreased.

1.4 Demand Side Management (DSM)

The general principle of DSM is to include the end-user loads as part of the electricity system control. DSM has commonly been used to encourage and influence customers to change their electricity use pattern in order to reshape the load profiles according to utility needs [11].

DSM is utilized to reduce the peak load and shift it to off-peak periods in order to defer building new power plants and transmission lines. DSM can reduce both energy consumption and electricity operation costs. DSM can also benefit consumers by reducing their energy bills and improving service. [12].

1.4.1 Potential of Residential Loads for DSM

Residential loads based on energy consumption rather than power consumption are preferable for DSM. The End-use Load and Consumer Assessment Program (ELCAP) [13] for residential electricity demand indicated that about 63% of total household electricity consumption is of energy based loads. Examples of these loads are electric water heaters, space heaters, air conditioners, and refrigerators/freezers. These loads can be used for DSM without significant impact on consumer comfort [14].

1.4.2 Electric Water Heater for DSM

One of the most common loads used in DSM are electric water heaters (EWHs). They are good candidates for DSM for many reasons. They are considered the second largest load in a house. In the winter time, the energy consumed by a EWH is about 30% of the total energy consumed in a house [15, 16].

In addition, they have long thermal time constants, so they are not affected by short term power interruptions. Finally, they are located in different sites throughout the electrical power system, which reduces the effect of the significant active power variation because of using EWHs as controllable loads in the voltage magnitude in a single bus or phase [17].

1.4.3 Statement of DSM in the Mini-Grid

DSM is commonly used in large electricity grids. On the other hand, little attention has been paid to DSM in mini-grids. This depicts the fact that DSM can have a significant impact on the economical operation of a mini-grid, especially when RES is incorporated. This is the main motivation of this thesis.

1.5 The Objective of the Thesis

The main objective of this thesis is to investigate a way to control EWHs to assist with power balancing and frequency regulation, achieve peak shaving of load demand, and make diesel genset work in more efficient operation region, in the PV-diesel hybrid mini-grid. This can be done by varying the set point temperatures of the EWHs and consequently their active power consumption as a function of the mini-grid frequency. Additional objectives of the thesis are the following:

1- Analyse and study the EWH parameters and implementation of a suitable model in Matlab/SIMULINK.
2- Design the parameters of the EWH controls to be used in a sample mini-grid based on local measurement frequency.
3- Modify the hybrid mini-grid benchmark used in [18] and use it to compare the performance of the PV-diesel hybrid mini-grid in different cases and validate the impact of the proposed control strategy of EWHs on frequency variation and fuel consumption.

1.6 Outline of the Thesis

Chapter 2 discusses the characteristics and behaviour of the hybrid mini-grid power sources. It gives details about the diesel genset and the droop control. It also defines the recommended operation region of a genset. Furthermore, Chapter 2 gives a brief explanation of PV power.

Chapter 3 studies the electric water heater characteristics and model. The EWH model was developed and implemented in SIMULINK/Matlab. The parameters of EWH are also discussed in this chapter. In addition, mathematical analysis is performed by deriving linear equations to find the impact of changing certain parameters of EWH on its operation and power consumption. Finally, the sensitivity of EWH to its parameters is observed.

Chapter 4 introduces the control methods that have been used when EWHs are employed as controllable loads in DSM programs. This chapter gives the background of these control methods and the design consideration of the proposed control strategy. It then discusses the issue of using the integrated control in the case of multiple EWHs and how the problem of multiple EWHs turning on and off at the same time can be mitigated.

Chapter 5 gives a brief description of the hybrid mini-grid that was implemented in PSCAD software. It provides detailed information about the mini-grid components: the diesel genset, transformers, and load profile. The implementation model of the controllable loads (EWHs) and their control are discussed. Moreover, this chapter presents the simulation parameters and initial values that should be determined at the beginning of the simulations. Lastly, this chapter discusses the simulation results for different cases.

Chapter 6 presents the conclusions and summary of this study in addition to proposed future research.

CHAPTER 2
HYBRID-MINI-GRID SOURCES

2.1 Introduction

In order to design the control scheme of a RES-diesel hybrid mini-grid to explore its potential as a DSM unit, the characteristics and behaviour of the generation side and controllable loads should be well understood. In this chapter, the generation side of the hybrid mini-grid system is studied in detail. The controllable load (EWH) will be discussed in the next two chapters.

The power sources used in this study are a diesel genset and photovoltaic panels (PV) as RES.

2.2 Diesel Genset

The term diesel genset refers to a diesel engine generator set. It is a common source of electricity employed in stand-alone systems, such as those used in remote communities. A diesel genset consists of two main parts: a diesel combustion engine and an alternator, usually a synchronous generator, coupled with the same shaft. The diesel engine provides the mechanical power that the synchronous generator converts to electrical power [19].

The speed of a diesel engine is controlled by the fuel intake. The fuel intake is controlled by the governor. In case of the mini-grid, the speed controller is mainly responsible for frequency control. The excitation system of the generator consists of a voltage regulator and an exciter that provides DC voltage to the field winding of the synchronous generator [20]. Figure 2-1 shows the block diagram of a diesel genset

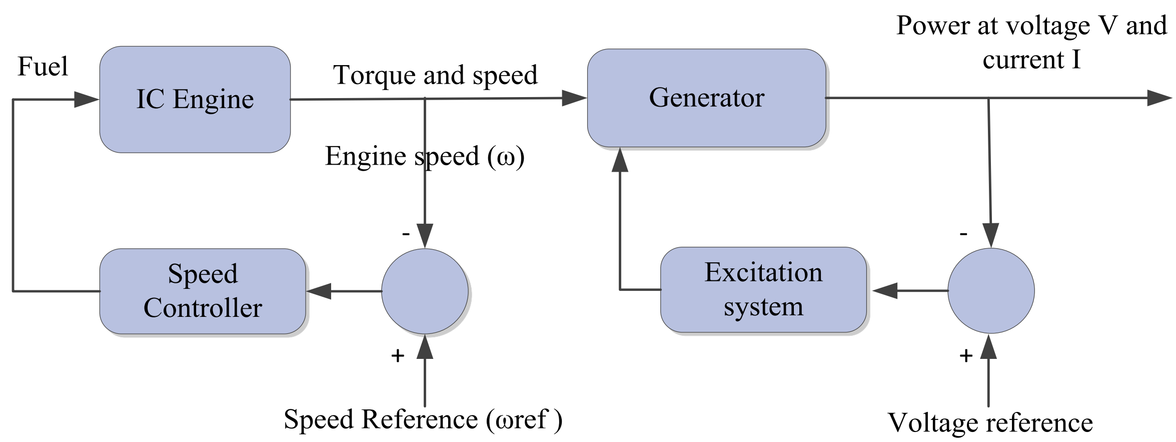

Figure 2-1: The block diagram of a diesel genset

2.2.1 Frequency and Voltage Droop Control

In an electric power system, the active and reactive power demands must be met by an equivalent amount of active and reactive power supply, which is not a problem when a single source is used. When multiple sources are used, the droop control technique is an effective way of sharing the active and reactive power demands among the sources, thus avoiding overloading any of them. As mentioned in the previous subsection, the frequency and the output voltage of gensets can be adjusted though the governor and exciter, respectively. The frequency is usually varied as a function of the active power with a drooped curve, while the voltage is adjusted according to the reactive power as shown in Figure 2-2 [21].

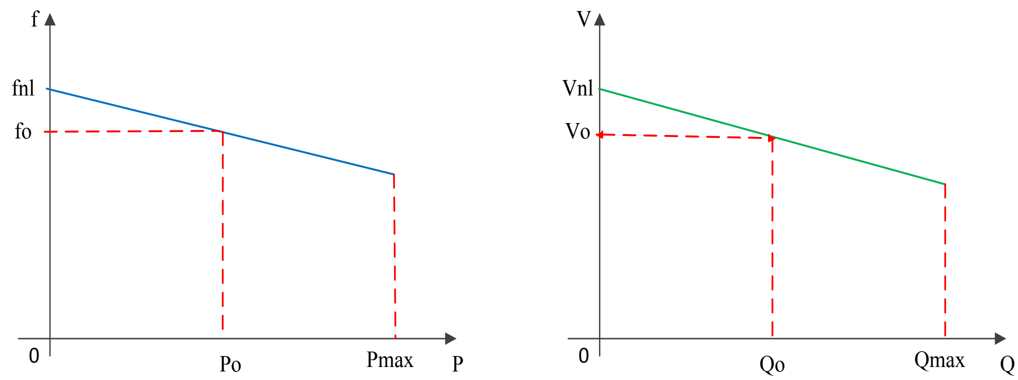

Figure 2-2: (A) Frequency vs. active power droop, (B) Voltage vs. reactive power droop

In Figure 2-2, P_0 and Q_0 are the temporary set points for the active and reactive power of the machine at the nominal frequency f_0 and voltage V_0 respectively, and f_{nl} and V_{nl} are the no load frequency and voltage,-respectively.

This study is concerned mostly with fuel consumption reduction and frequency regulation in RES-diesel hybrid mini-grids. Since reactive power control has no impact on either of these and since voltage regulation is not usually an issue in small mini-grids, there will be no further discussion on the latter.

2.2.1.1 Frequency Droop Control

The relationship between the system frequency and the output power of the diesel genset when using droop control can be described by

$$P_g = s_P \left(f_{nl} - f \right) \quad (2.1)$$

where P_g is the output power of the generator (kW); s_P is the slope of the droop curve (kW/Hz), f_{nl} is the no-load frequency of the generator (Hz) and f is the operating frequency of the system (Hz). The slope of the droop curve is usually selected so that the slope of the droop curve is between 2 and 5 % [22]. That is, the generator's frequency will vary by 2 to 5% of the no-load frequency as the power demanded from the genset varies from zero (no-load) to rated power.

Table 2-1 and Figure 2-3 show the main parameters and the frequency vs. active power droop curve of the 95k W diesel that is used in this study [23].

Table 2-1: Parameters of the 95kW diesel genset

Genset rated power	Slope factor (s_p)	No load frequency (f_{nl})
95 kW	29.4 kW/Hz	62.34Hz

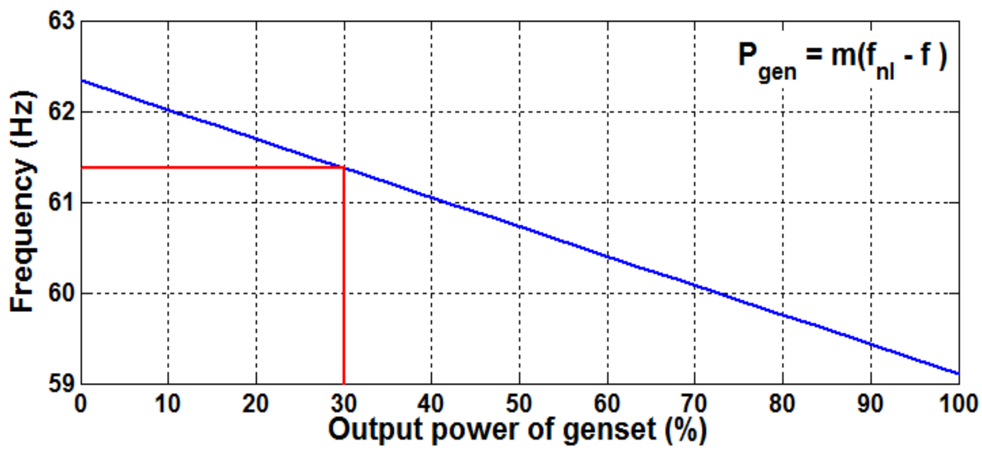

Figure 2-3: Frequency vs. power droop curve of the 95 kW diesel genset

Eq. (2-1) and Figure 2-3 demonstrate that any change in demand will cause frequency variation. If demand increases, the system frequency will decrease as more active power is produced to meet the demand. In the case of low demand or light load, the system frequency will increase as result of the production of less active power.

Regarding to operating constraints, a diesel genset should not operate below a certain percentage of its rated power. If the diesel genset operates at a low load, it will operate at low efficiency and the fuel (diesel) will be not burned properly. As a result, carbon buildup will increase inside the engine, which increases maintenance cost [24, 25].

The typical recommended minimum power for diesel gensets is between 30% and 40%, depending on the manufacturer.

2.2.2 Fuel Consumption Characteristics

The fuel consumption characteristics of the diesel engine can be represented by fuel consumption rate (L/h) and fuel efficiency curve (%) [4].

2.2.2.1 Fuel consumption rate

The fuel consumption rate indicates the amount of fuel needed to produce a certain amount of electricity (kW) during one hour. The fuel consumption rate is usually provided by the manufacturer of the diesel genset in a chart or in datasheet in certain percentages (25%, 50%. 75% and 100%) of its rated power [26].

For clarification, let us take the fuel consumption rate of the 95kW genset that is used in this study. From the data provided by the manufacturer, the fuel consumption rate is plotted in an excel file and then a polynomial equation is obtained to estimate the fuel consumption rate (F) at any output power value of the diesel genset (P_g) with a correlation (R^2) of 0.9995.

$$F = 0.0004 \times P_g^2 + 0.1646 \times P_g + 6.105 \qquad (2.2)$$

2.1.2.2 Fuel efficiency curve

The simple way to find the fuel efficiency curve is to divide the output power from the diesel genset by the input chemical power [27].

$$\eta_g = \frac{3.6 \times P_g}{m_{fuel} \times LHV_{fuel}} (\%) \qquad (2.3)$$

where m_{fuel} is the mass flow rate of the fuel in (kg/h), LHV_{fuel} is the lower heating value of the fuel in (MJ/kg), and 3.6 is the conversion factor from MJ to kWh. 1 kWh = 3.6 MJ.

The mass flow rate of the fuel is related to the generator's fuel consumption rate (F). If the fuel unit is litres, m_{fuel} is obtained as follows:

$$m_{fuel}=\rho_{fuel}\left(\frac{F}{1000}\right)=\frac{\rho_{fuel}(0.0004\times P_g^2+0.1646\times P_g+6.105}{1000} \tag{2.4}$$

where ρ_{fuel} is the fuel density in kg/m^3.

By substituting equation (2.4) into equation (2.3), fuel efficiency becomes:

$$\eta_g=\frac{3600\times P_g}{\rho_{fuel}(0.0004\times P_g^2+0.1646\times P_g+6.105)\times LHV_{fuel}} \tag{2.5}$$

For diesel fuel, the LHV_{fuel} = 43.2MJ/kg and $\rho_{fuel}=820kg/m^3$.

Eqs. (2.2) and (2.5) were used to obtain the fuel consumption characteristics of the 95 kW diesel genset as a function of the output power of the diesel genset as shown in Figure 2-4.

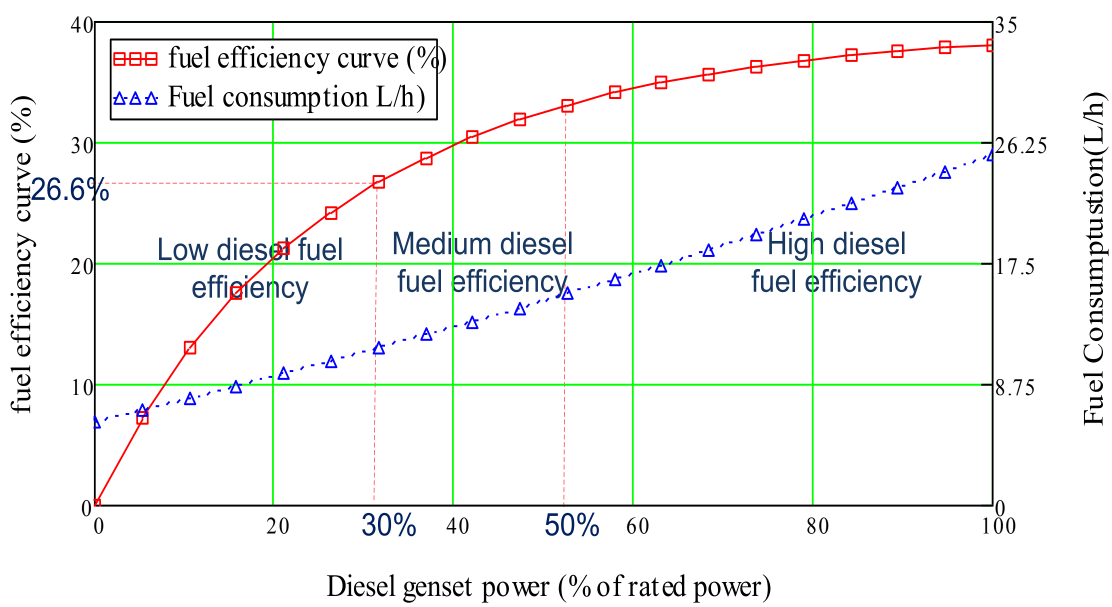

Figure 2-4: The fuel consumption characteristics of the 95kW diesel generator

Figure 2-4 shows that the fuel consumption rate increases almost linearly as the demand increases. However, one litre of diesel that is consumed when the diesel genset works at a high load condition produces more kW than when it operates at a low load condition.

This fact is reflected in the diesel fuel efficiency curve shown in Figure 2-4. The diesel fuel efficiency is very low when the diesel genset works at a light load condition. Figure 2-4, demonstrates that the efficiency does not exceed 26% when the genset works below 30% of its rated power (low fuel efficiency region). When the diesel genset operates above 30% of its rated power, the fuel efficiency increases and reaches almost 35% when it works at 50% of its rated power (medium fuel efficiency region). For operation above 50% of its rated power, the fuel efficiency will increase, but by a small rate. The maximum fuel efficiency is around 39% which is achieved when the diesel genset operates at full load. This region of operation is called the high fuel efficiency region. However, it is not highly recommended to operate the diesel genset at full load for long time. It should operate at 80-90% of its rated power in order to provide power in case of sudden increase of demand (spinning reserve). In this way, overloading of the diesel genset can be avoided.

This analysis and study of the fuel characteristics of a diesel genset shows clearly why it is recommended in the literature that diesel genset should operate at high or medium fuel efficiency regions (30% to 80% or 90%). However, the diesel genset cannot operate continually in this region, especially in the RES-diesel hybrid mini-grid. This is due to the demand in the mini-grid, which varies significantly over a 24-hour period. Moreover, the RESs produce fluctuating powers that cause further frequency variations.

The diesel genset in this case is mainly responsible to compensate for these variations and provide frequency control.

Nevertheless, if the diesel genset operates below the ideal region for a short time, it might not be a serious problem, especially when the diesel genset operates at a heavy load after a light load condition. Operating the diesel genset at high load condition will clean up the carbon build up. A serious problem will occur when the diesel genset operates for long time below the optimum operation region as mentioned in a previous section of this chapter.

2.3 Renewable energy source (photovoltaic power)

Renewable energy sources (RESs) have become an attractive alternative to produce electricity especially in remote areas. They are considered as clean energy sources and environmentally friendly. One of the most common sources of RESs is solar energy or photovoltaic (PV) energy. It is available everywhere and should not run out since the sun still rises every morning.

PV panels are used to convert solar irradiance into electrical power. The PV panel consists of PV cells connected in series and/or parallel to produce adequate voltage and current levels, respectively. The power obtained from these panels is direct current (DC). Therefore, an inverter has to be used to convert the DC power to AC power to supply AC loads [28].

A PV panel is usually described by its I-V and V-P curves plotted for various solar irradiance levels as shown in Figure 2-5 [29]. The PV cell also affects these curves, but solar irradiance is the dominant parameter. There one sees that as the output current of the PV panel increases, the output voltage tends to decrease, first slightly and then sharply, reaching zero at the short-circuit current (I_{SC}). The resulting output power of the PV panel can be computed by multiplying the current and voltage values at each point of the I-V curve. As shown in Figure 2-5, the point of maximum power occurs at the knee of the I-V curve, and it depends significantly on the solar irradiance levels. Moreover, as the solar irradiance levels change, the values of current and voltage that lead to maximum power production vary. Maximum power point tacking (MPPT) algorithms are frequently incorporated in the power electronic interfaces of PV panels to produce the maximum power possible in all solar irradiance conditions. [30].

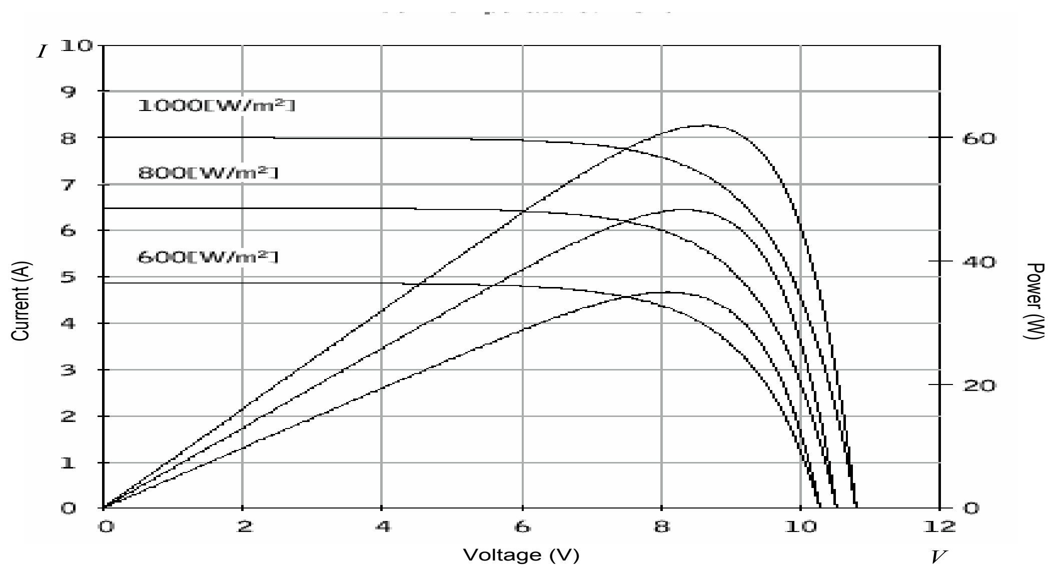

Figure **2-5:** Typical I-V and P-V curves of a PV panel

A detailed discussion on the MPPT techniques is beyond the scope of this work. However, it should be pointed out that the grid tie PV inverter model that is used in this work is based on MPPT control strategy. Usually, this kind of PV inverter is modeled by current source [31] and is assumed to behave as a non-controllable negative source. The power it injects into the mini-grid depends only on the solar irradiance and the task of balancing power generated; consumption will be delegated to the diesel genset alone.

CHAPTER 3
ELECTRIC WATER HEATER (EWH)

3.1 Introduction

Before investigating the benefits of using the EWH as controllable load, the basic operating principle of the EWH must be well understood and a suitable model of EWH should be created. This chapter discusses the design of a EWH model and investigates the impact of its main parameters on its ability to assist with power balance and frequency regulation. The control strategies developed to control the EWH are discussed in chapter 4.

3.2 Back Ground on the EWH

The electric water heaters under consideration supply hot water for domestic use. An EWH usually consists of a tank to store hot water, one or two electric resistance element(s) for heating water in the storage tank, a thermostat to regulate the temperature of water, an inlet pipe for cold water and an outlet pipe for supplying hot water to the consumer [32]. Figure 3-1 shows a EWH with one resistance element.

The rated power of the electric resistance element is typically between 3000 and 5500 W. It depends on how many element are used (one or two) and the size of the storage tank. The tank size is usually between 20 to 120 gallons (75.71 to 454.25 liter). EWHs with two elements are more common than one element in household use. Since the two elements are not allowed to operate or turn ON at the same time, for the sake of simplicity, a EWH with one element will be considered in this study.

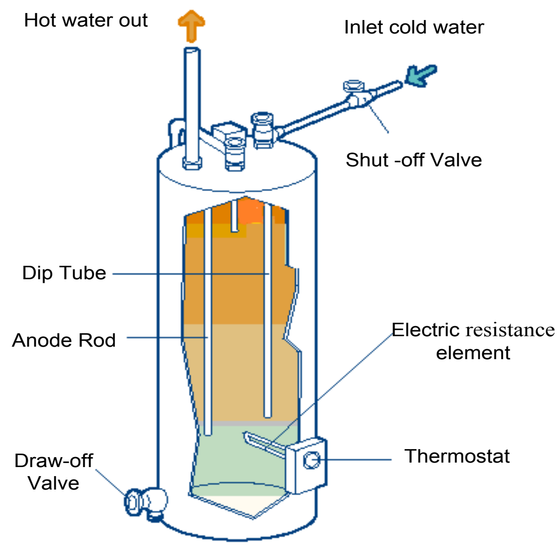

Figure 3-1: EWH with one resistance element [32]

The thermostat is a simple device used to control or regulate the hot water temperature in a certain range. The thermostat controls the flow of energy of the EWH by letting electric energy flow when the hot water temperature reaches the low temperature limit (T_{low}) and stops the energy flow when the hot water temperature reaches the high temperature limit (T_{high}).

3.3 Electric Water Heater Model

Many models of different types of EWHs have been introduced in the literature. The objectives of these models differ from one to another. For example, the Water Heater Analysis Model (WHAM) was designed to calculate the energy consumption per day [33]. Other models were designed to obtain the EWH demand in order to control it by means of DSM [34-36].

The EWH model discussed in this work was conceived to obtain the EWH electric power demand. It is based on the energy flow in the EWH. In general, the electric energy consumed by the EWH is used for two purposes: to heat the inlet cold water that replaces the hot water drawn from the tank and to compensate for the thermal losses from the EWH tank to the ambient [37, 38]. Based on these two purposes and knowing the parameters of the EWH, a model can be created as reported in [39].

A first-order differential equation (3.1), which represents the energy flow in the EWH, is used for this model. The hot water in this model is assumed to be fully mixed inside the storage tank. Therefore, the temperature is assumed the same in the entire tank and only one hot water temperature variable T_H (t) is used in this model, which is noted in Eq. (3.1) [40].

$$C\frac{dT_H}{dt} = U\,SA\,(T_a - T_H(t)) + Wd(t)\rho C_p\,(T_{in} - T_H(t)) + K(t)Q \tag{3.1}$$

where

$T_H(t)$ = temperature of hot water in tank (°F);

T_{in} = incoming inlet cold water temperature (°F);

T_a = ambient air temperature outside tank (°F);

C = thermal capacity of water in the tank (BTU/°F); $C=V\rho\, C_{p;}$

ρ = Density of water (lb/gal);

V= volume of tank (gal);

C_p = specific heat of the water (BTU/lb. °F);

$Wd(t)$ = average hot water draw per hour (gal/h);

SA = surface area of tank (ft^2);

U = stand-by heat loss coefficient (Btu/°F. h. ft^2);

Q = energy input rate (Btu/h); $Q= P_{rated}$ *3413;

$K(t)$ = thermostat binary state (1 for ON, 0 for OFF);

P_{rated} = power rated input of the heating resistance element (kW);

3413 = factor to change the unit of power from kW to Btu/h;

The left side of Eq. (3.1) represents the changing rate of the water temperature within the thermal capacity of water in the tank. The first part at the right side represents the heat losses to the ambient temperature. The second part represents the heat needed to heat the inlet cold water, and the last part is the input heat energy from the heating resistance element of the EWH.

3.3.1 The Parameters of the EWH Model:

The purpose of this section is to define the parameters of EWH in detail. Since Inch-Pound units (IP) are more common in this kind of application, all parameters used in this thesis for the EWH are represented in IP units.

3.3.1.1 Power rated of heating resistance element (P_{rated})

As previously mentioned, the heating resistance element heats up the water inside the tank and a control loop is used to keep it within a certain temperature range. Based on an extensive review of previous research, which are cited in this thesis, the power rated for the single heating element that is used for the EWH model is between (3-5.5kW). For this reason, a 4kW element is chosen in this research and considered to be constant.

The power values in kW are converted to Btu/h. Btu refers to British thermal unit. Recall that 1kW = 3413 Btu/h; thus, $Q = P_{rated}$ 3413. For this work, Q = 4*3413 = 13652 Btu/h.

3.3.1.2 Ambient temperature (T_a) and inlet water temperature (T_{in})

Obviously, the values of T_a and T_{in} vary seasonally, daily, and even hourly, thus, they are assumed to be constant in this study .The effect of these variations can be the focus of future work. According to the EnergyGuide test for electric water heaters, the ambient temperature can vary between 65°F to 70°F. In this work, T_a is assumed to be equal to the average of those two values, 67.5°F (19.72°C). For the inlet cold water temperature of the water supply, the temperature is assumed to be 60 °F (15.56°C) [41].

3.3.1.3 Stand-by heat loss coefficient (U) and surface area of tank (SA)

The amount of thermal loss from the EWH tank to the ambient temperature given in Eq. (3.1) is a function of the stand-by heat loss (U), surface area of the tank (SA), and the difference between T_H *(t)* and T_a. The heat loss will be transferred through the insulation of the EWH tank, which has a thermal resistance (R). U is equal to the inverse of R. The surface area of the tank (SA) is assumed to be equal to the cylinder surface area, $2\pi rh + 2\pi r2$. where r = the tank radius (ft), h is the tank height (ft). In some references, U and SA are represented by G, $G=U*SA$.

Due to the lack of information about the specifications of the tank, such as the height, radius and thermal resistance, the value of G is taken directly from reference [42]. The EWH tank volume (V) and G in this study are equal to 50 gallon (189.27L) and 3.6 Btu/°F. h, respectively.

3.3.1.4 The density of water (ρ) and specific heat of water (C_p)

The density of water changes slightly with the temperature. However, this variation has a very small effect in terms of the calculations and thus can be ignored. Thus, ρ=8.34

lb/gal (0.998kg/L). The specific heat is the amount of heat per unit mass required to raise the temperature by one degree. *Cp* of water is equal to 1Btu/lb °F (4.18 kJ/ (kg·°C).

3.3.1.5 Water draw (*Wd*)

Wd is the value of hot water that is drawn from the EWH tank due to domestic use such as showering, hand washing, dishwashing, and so on. Many water usage profiles have been suggested in the literature and used for analysis of EWHs. The majority of them give the hourly averaged value of *Wd* [43].

Recent research has developed water draw profiles that are based on usage events (e.g., showering, dishwashing, and hand washing) and used for analysis instead of unvarying averaged hourly water draws. These water profiles could give more accurate results since they consider small time intervals (e.g., 15 or 5 minutes). However, due to the lack of information available on these profiles, the hourly average *Wd* profile is used in this work. The 24-hour hot water draw (*Wd*) profile refers to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) shown in Figure 3-2 is used in this study[44].

It worthy mentioned, the hot water usage (*Wd*) can be different from place to other and this due to consumers behaviours and habits as well as the number of family members. Therefore, the hourly average *Wd* profile used in this study can be replaced by other hourly average *Wd* profiles.

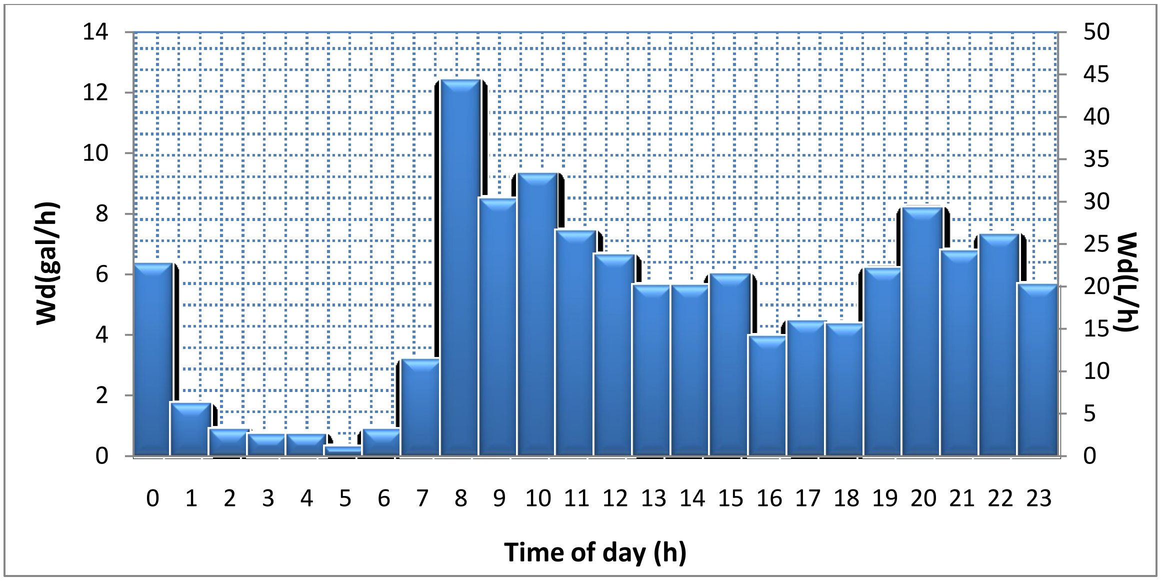

Figure 3-2: Water draws profile during a 24-hour period (ASHRAE schedule water draws)

Figure 3-2 shows that the peak demand of hot water occurs in the morning. In the early morning (from 1:00 am to 6:00 am), the demand for hot water is very small.

3.3.1.6 The set point temperature (T_d) and the dead band (Δ)

The value of $T_H(t)$ usually should be kept within certain limits. The main parameters that determine this value are the set point temperature (T_d) and the dead band (Δ) around which the hot water temperature is allowed to vary. T_d is the thermostat setting set by the consumer and it reflects his/her comfort. Usually, the standard adjustable temperature range of the thermostat is between 90°F and 150°F (32° to 66°C) [45]. However, the most common value of T_d is usually between 120°F and 140°F [42]. It is highly recommended that T_d does not exceed 140°F (60°C) to avoid any scalding effects [46]. Moreover, T_d should not set below certain temperature to avoid the effect of bacteria growth in the piping system. In this work, the acceptable range is considered between 100°F and 140°F (37.78°C to 60°C).

The hysteresis or dead band (Δ) around T_d is usually varied between ±2.5 to ±5°F (±1.38 to 2.77°C). The high limit temperature (T_{high}) and low limit temperature (T_{low}) in this case will be equal to ($T_d+\Delta$) and ($T_d-\Delta$), respectively.

3.3.2 EWH Model in Matlab/SIMULINK

The previous sections present the parameters of the EWH model. The next step is to implement this model in Matlab/SIMULINK. Given that $B(t)=Wd(t)\,\rho\,C_p$ and $G=U\,SA$, Eq. (3.1) becomes

$$C\frac{dT_H}{dt}=G(T_a+B(t)T_{in}-T_H(t)\big(G+B(t)\big)+K(t).Q \quad (3.2)$$

Dividing both sides by ($G+B$) and given that $R^{'}(t)=1/(G+B)$, Eq. (3.2) becomes

$$R^{'}(t)C\frac{dT_H}{dt}=R^{'}(t)GT_a+R^{'}(t)B(t)T_{in}+R^{'}(t).K(t).Q\text{-}T_H(t) \quad (3.3)$$

$R^{'}(t)C$ in this equation can be replaced by (τ), where τ is the time constant of the EWH.

By integrating both sides of the equation, one derives

$$T_H(t)=\frac{1}{\tau}\int(R^{'}(t)GT_a+R^{'}(t)B(t)T_{in}-T_H+R^{'}(t)\,K(t).Q)dt \quad (3.4)$$

Eq. (3.5) shows a logic control for the EWH:

$$\begin{cases} EWH\ ON,(K(t)=1):\ T_H(t)\leq Td\text{-}\Delta \quad or\ Td\text{-}\Delta<T_H(t)<Td+\Delta\ and\ \dfrac{dT_H}{dt}>0\ \ (T_H\uparrow) \\ EWH\ OFF,(K(t)=0):\ T_H(t)>Td+\Delta \quad or\ Td\text{-}\Delta<T_H(t)<Td+\Delta\ and\ \dfrac{dT_H}{dt}<0\ \ (T_H\downarrow) \end{cases} \quad (3.5)$$

Eqs. (3.4) and (3.5) are implemented in Matlab/SIMULINK to achieve the EWH model.

3.3.3 Hot Water Temperature Variation for 24 H (One Day):

Since all parameters of the EWH model are defined and the EWH model is implemented in SIMULINK, one can observe the variation of the temperature of the hot water in the tank T_H (t) for 24 h and how the EWH operates to heat up water. Let us consider the base case. T_d for the base case (T_{db}) is set at 120 °F (48.89°C) with Δ equal to 2.5 °F (1.38°C). The *Wd* profile shown in Figure 3-2 is used. The other parameters of the EWH model, already mentioned, are shown in Table 3-1.

Table 3-1: Constant parameters of the EWH model

P_{rated} *(kW)*	*Q(Btu/h)*	ρ(lb/gal)	*V (gal.)*	*C* (Btu/°F)	T_a (°F)	*Tin*(°F)	*G*(Btu/°F. h)
4	*13652*	*8.34*	*50*	*417*	*67.5*	*60*	*3.6*

The initial hot water temperature, T_H *(to)* is assumed to be equal to T_d - Δ.The variation of T_H *(t)* for one day is shown in Figure 3-3 (A), the ASHRAE *Wd* schedule is shown in Figure 3-3 (B) and the instantaneous power consumed by the EWH is shown in Figure 3-3 (C). The simulation (time) step is 0.0001h.

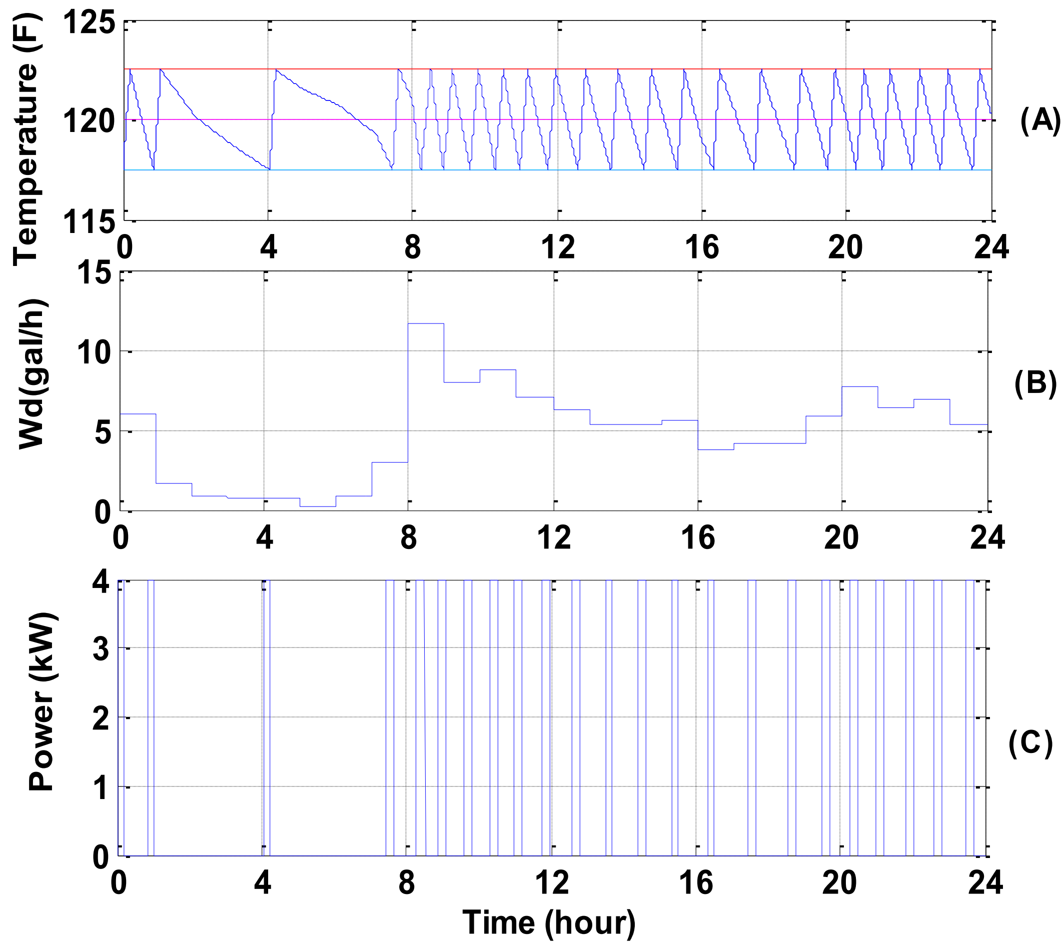

Figure 3-3: (A) variation of $T_H (t)$, (B) the ASHRAE *Wd*, (C) the instantaneous power consumed by the EWH

Figure 3-3 shows that the heating element of the EWH is turned ON and OFF in order to keep $T_H (t)$ within a tolerance band (+/- Δ) of T_d. When the heating element is ON, $T_H(t)$ rises until it reaches (T_d+Δ), which is equal to 122.5°F(50.28°C). When the heating element is turned OFF, $T_H(t)$ decreases until it reaches T_d-Δ, which is equal to 117.5°F (47.5°C). The heating element then is turned ON again.

Figure 3-3 also shows that t_{on} and t_{off} and the operation period ($t_{total} = t_{on} + t_{off}$) of the EWH during the day are not constant. In particular, t_{off} varies significantly with *Wd*.

Table 3-2 shows the maximum and minimum values of t_{on}, t_{off} and t_{total} during a 24 hour period.

Table 3-2: The maximum and minimum t_{on}, t_{off}, and t_{total} of the EWH.

$t_{on-\max}$ (h)	$t_{on-\min}$ (h)	$t_{off-\max}$ (h)	$t_{off-\min}$ (h)	$t_{total-\max}$ (h)	$t_{total-\min}$ (h)
0.1639	0.1143	3.6571	0.3453	3.7714	0.5092

Table 3-2 shows that the difference between t_{on-max} and t_{on-min} is small, while the difference between $t_{off-max}$ and $t_{off-min}$ is very large. This is due to the impact of Q for the t_{on} case and the impact of Wd for the t_{off} case. More details of the impact of Q and Wd and other EWH parameters on t_{on} and t_{off} are provided in the next sections.

3.4 Mathematical Analysis

The main purpose of this section is to develop simple mathematical equations that represent the affect of varying some EWH parameters on its operation cycle, power, and energy consumption. This can be achieved by deriving equations to obtain $T_{H(t)}$, t_{on}, t_{off}, duty cycle (D), and average power consumed by EWH (P_{EWH}) from the energy flow Eq.(3.1).

3.4.1 Conventional Equations

In the literature, the equation to obtain $T_H(t)$ at any time was obtained by solving the step response of the first order Eq. (3.1) that is given in section 3.3 [38] .

$$T_H(t)=T_H(t_o)e^{-\left(\frac{1}{R'C}\right)(t-t_o)}+\left[R'(t)GT_a+R'(t)B(t)T_{in}+R'(t)K(t)Q\right]\times\left[1-e^{-\left(\frac{1}{R'C}\right)(t-t_o)}\right] \quad (3.6)$$

With the appropriate modifications, it can be used for obtaining expressions to calculate t_{on} and t_{off}.

For t_{on}, $K(t)=1$,

$$t_{on}=\tau\, ln\left[\frac{\left(GT_a\, R^{'}(t)+R^{'}(t).B(t)T_{in}+R^{'}(t)Q\right)-T_H(t_o)}{\left(GT_a(t)+R^{'}(t).B(t)T_{in}+R^{'}(t)Q\right)-T_d+\Delta}\right] \tag{3.7}$$

For t_{off}, $K(t)=0$,

$$t_{off}=\tau\, ln\left[\frac{T_H(t_o)\text{-}\left(GT_a\, R^{'}(t)+R^{'}(t)B(t)T_{in}\right)}{(T_d-\Delta)\text{-}\left(GT_a\, R^{'}(t)+R^{'}B(t)T_{in}\right)}\right] \tag{3.8}$$

where t_o is the initial time and $T_H\ (t_o)$ is the initial hot water temperature. The values of t_o and $T_H(t_o)$ must be updated if any changes in $B(t)$ or $K(t)$ occur at any time. For this reason, the above equations are very complicated for the required calculations. Furthermore, exponential equations are not very convenient to use.

3.4.2 Proposed approximate linear equations

In this work, approximate linear equations are derived to obtain t_{on}, t_{off}, D, P_{EWH}. This achieved by doing the following steps:

Step 1. Derive equation for t_{on}.

Replace dT_H by T_{high}-T_{low} and dt by t_{on} when EWH is ON in Eq. (3.1). In addition, $T_H(t)$ is assumed to be equal to T_d in order to calculate the average heat losses to the ambient and due to inlet cold water replacing the water drawn from the tank. Finally, by replacing $K(t)$ by 1 once obtains t_{on}.

$$\frac{\left(T_{high}\text{-}T_{low}\right)}{t_{on}}=U\,SA(T_a-T_d)+Wd(t)\rho C_p(T_{in}-T_d)+1\times Q$$

$$t_{on}=\frac{C\left(T_{high}-T_{low}\right)}{G(T_a-T_d)+Wd(t)\,\rho C_p(T_{in}-T_d)+Q} \tag{3.9}$$

Step 2. Derive equation for t_{off}

When the EWH is OFF, dT_H is replaced by T_{low} - T_{high} and dt is replaced by t_{off} in Eq. (3.1) and $K(t)$ is replaced by 0. Variable $T_H(t)$ is replaced by T_d in the case of t_{on}.

$$\frac{(T_{high}\text{-}T_{low})}{t_{off}}=U\,SA(T_a-T_d)+Wd(t)\rho C_p(T_{in}-T_d)+0\times Q$$

$$t_{off}=\frac{C(T_{high}-T_{low})}{G(T_d-T_a)+Wd(t)\rho\, C_p(T_d-T_{in})} \tag{3.10}$$

Step 3. Use the equations obtained from step 1 and 2 to obtain t_{total}, D and P_{EWH}.

Recall that

$$t_{total}=t_{on}+t_{off}$$

$$D=\frac{t_{on}}{T}$$

$$P_{EWH}=P_{rated}\times D$$

By substituting (3.8) and (3.9) in the above equations one gets

$$t_{total}=\frac{C(T_{high}-T_{low})Q}{G(T_a-T_d)+Wd(t)\rho C_p(T_{in}-T_d)+Q\,G(T_d-T_a)+Wd(t)\ \rho\, C_p(T_d-T_{in})} \tag{3.11}$$

$$=\frac{G(T_d-T_a)+Wd(t)\,\rho C_p(T_d\text{-}T_{in})}{Q} \tag{3.12}$$

$$P_{EWH}=\frac{G(T_d-T_a)+Wd\rho C_p(T_d-T_{in})}{3413} \tag{3.13}$$

Eq. (3.13) shows the relation between P_{EWH} and T_d. It is worth mentioning that Eqs. (3.12) and (3.13) are only valid in terms of calculations for changing any parameters of EWHs during steady state conditions. As for t_{on}, t_{off}, t_{total}, they can be used for transient conditions with a proper modification.

$T_H(t)$ can be obtained by replacing the first derivative $\frac{dT_H}{dt}$ in Eq. (3.3) with the finite difference $(T_H(t+1) - T_H(t))/\Delta t$ [47].

So, the equation (3.1) becomes

$$T_H(t)=T_H(t\text{-}\Delta t)\times\left(\frac{\tau}{\tau+\Delta t}\right)+\frac{\Delta t}{\tau+\Delta t}\times\left[R'(t)GT_a+R'(t)B(t)T_{in}+R'(t).K(t).Q\right] \quad (3.14)$$

where Δt is the time step.

3.4.3 Validating the Derived Liner Equations

In order to use the above derived equations for calculation and analysis, the potential effect of using EWH as a controllable load, they first should be validated by comparing the calculation results of those equations with both the exponential equations and the simulation results from the EWH model.

For these verifications, the base case will be considered (T_{db} = 120°F, and Δ = 2.5°F). *Wd* is assumed to be constant (6gal/h). Table 3-3 shows the results obtained from linear equations, exponential equations, and the simulation of the EWH model.

Table 3- 3: Comparison of the results of using linear equations with other methods in the base case (considered (T_{db} = 120°F (48.89°C) and Δ = 2.5°F (1.38°C)) and *Wd*=6gal/h (22.71L/h).

Methods	t_{on}(h)	t_{off}(h)	t_{total}(h)	D	P_{EWH}(kW)
Linear equations	0.1993	0.6533	0.8526	0.2338	0.9351
Exponential equations	0.1993	0.6537	0.8530	0.2337	0.9347
Simulation results	0.1993	0.6540	0.8533	0.2336	0.9343

Table 3.3 shows that the results obtained from linear equations are almost the same as the results obtained from exponential equations (Exp.) and the results obtained

from the simulations of EWH model (Simu.). In fact, the error is very small. The error is zero in the case of t_{on} and 0.07 % in the case of t_{off}.

3.4.4 Validating the Linear Equations for Different *Wd* Values:

When the linear equations are used for different values of *Wd,* such as the ASHREA *Wd* profile for one day, one should consider the total operation cycle of the EWH (t_{on} and t_{off}). Generally, the linear equations are valid when the total operation cycle ($t_{on}+t_{off}$) occurred within the specific time interval (hour of day). This means that the duration of t_{on} and t_{off} should fall within this time interval. For example, at the beginning of the day, if the EWH is turned on and turned off within the time period (00:00 am to 1:00 am), the linear equations in this period are valid.

Table 3-4 shows the values of t_{on}, t_{off}, and t_{total} for the 24 h ASHREA *Wd* profile. This table gives the baseline of the value of *Wd* by which one can use these linear equations.

Table 3-4: t_{on}, t_{off}, *and* t_{total} for ASHREA *Wd* profile

Time of day (h)	*Wd*(gal/h)	T_d(F)	t_{on}(h)	t_{off}(h)	t_{total} (h)	Linear equation validation
0:00	6	120	0.1993	0.6533	0.8526	Valid
1:00	1.6	120	0.1647	2.1068	2.2715	Not valid
2:00	0.8	120	0.1596	3.5380	3.6976	Not valid
3:00	0.66	120	0.1588	4.0153	4.1741	Not valid
4:00	0.66	120	0.1588	4.0153	4.1741	Not valid
5:00	0.26	120	0.1564	6.5339	6.6903	Not valid
6:00	0.8	120	0.1596	3.5380	3.6976	Not valid
7:00	3	120	0.1743	1.2336	1.4079	Not valid
8:00	11.7	120	0.2740	0.3450	0.6190	Valid
9:00	8	120	0.2204	0.4974	0.7178	Valid
10:00	8.8	120	0.2301	0.4540	0.6841	Valid
11:00	7	120	0.2093	0.5648	0.7741	Valid
12:00	6.25	120	0.2017	0.6287	0.8304	Valid
13:00	5.3	120	0.1929	0.7339	0.9267	Valid
14:00	5.3	120	0.1929	0.7339	0.9267	Valid
15:00	5.65	120	0.1960	0.6913	0.8873	Valid
16:00	3.7	120	0.1796	1.0218	1.2014	Not valid
17:00	4.2	120	0.1835	0.9102	1.0937	Not valid
18:00	4.1	120	0.1827	0.9305	1.1133	Not valid
19:00	5.85	120	0.1979	0.6691	0.8670	Valid
20:00	7.73	120	0.2173	0.5139	0.7312	Valid
21:00	6.38	120	0.2030	0.6166	0.8196	Valid
22:00	6.9	120	0.2083	0.5725	0.7808	Valid
23:00	5.33	120	0.1931	0.7300	0.9231	Valid

Table 3-4, shows that for the case that T_{high}-T_{low}=2Δ and with Δ = 2.5 °F, t_{on} is always smaller than 1h, which allows the use of the linear equation for t_{on} for the hourly ASHRAE *Wd* schedule.

It can also be noted that t_{on} changes as *Wd* changes, but it does not vary significantly with *Wd* since *Q* is the dominant element in the denominator of equation (3.9).

On the other hand, t_{off} varies more with *Wd* and can be larger than 1 h, usually for low values of *Wd*. In this case, an average value for *Wd* value for that duration should be considered.

Regarding Eqs. (3.1) and (3.10), the main reason that t_{off} varies more with *Wd* is because of the effect of *Wd* on the amount of the energy needed to heat up the inlet cold water. If *Wd* is large, the energy needed to heat water will be large as well. Since no input energy will compensate for the energy needed in this case, because EWH is OFF, $T_H(t)$ will decrease rapidly. Conversely, when *Wd* is small, the energy needed to heat the inlet cold water will be small as well, which causes $T_H(t)$ to decrease slowly.

Based on the results shown in Table 3-4 and previous explanations, Eq. (3.10) is not valid for all *Wd* profile values. Nevertheless, Eq. (3.10) can be useful for another purpose, such as finding the decreasing rate of T_H *(t)* per every *Wd* value per hour. This knowledge can be quite useful for using EWHs for DSM when the *Wd* profile is already known, as in this case.

The decreasing rate ΔT_H of T_H *(t)* can be obtained by replacing $(T_{hig}$-$T_{low})$ by ΔT_H and t_{off} by the time interval, which is equal to one hour in this study. Eq. (3.10) becomes

$$\Delta T_H = \frac{G(T_d - T_a) + Wd(t)\rho C_p(T_d - T_{in})}{C} \quad (3.15)$$

Table 3-5 shows the number of degrees Fahrenheit that $T_H(t)$ decreased when using the ASHREA Wd profile.

Table 3-5: Decreasing rate ΔT_H *of* $T_H(t)$

Time of day (h)	Wd(gal/h)	T_d(F)	T_H at the beginning of time period	T_H at the end of the time period	ΔT_H
0:00	6	120	122.5	114.8468	7.6532
1:00	1.6	120	122.5	120.1268	2.3732
2:00	0.8	120	122.5	121.0868	1.4132
3:00	0.66	120	122.5	121.2548	1.2452
4:00	0.66	120	122.5	121.2548	1.2452
5:00	0.26	120	122.5	121.7348	0.7652
6:00	0.8	120	122.5	121.0868	1.4132
7:00	3	120	122.5	118.4468	4.0532
8:00	11.7	120	122.5	108.0068	14.4932
9:00	8	120	122.5	112.4468	10.0532
10:00	8.8	120	122.5	111.4868	11.0132
11:00	7	120	122.5	113.6468	8.8532
12:00	6.25	120	122.5	114.5468	7.9532
13:00	5.3	120	122.5	115.6868	6.8132
14:00	5.3	120	122.5	115.6868	6.8132
15:00	5.65	120	122.5	115.2668	7.2332
16:00	3.7	120	122.5	117.6068	4.8932
17:00	4.2	120	122.5	117.0068	5.4932
18:00	4.1	120	122.5	117.1268	5.3732
19:00	5.85	120	122.5	115.0268	7.4732
20:00	7.73	120	122.5	112.7708	9.7292
21:00	6.38	120	122.5	114.3908	8.1092
22:00	6.9	120	122.5	113.7668	8.7332
23:00	5.33	120	122.5	115.6508	7.6532

Table 3-5 shows that ΔT_H varies significantly with Wd. When $dT_H > (2\Delta)$, Wd is large (Wd>4 gal/h in this case). This means that the EWH will be less than one hour off, assuming that the initial hot water temperature is T_{high}. When $dT_H < (2\Delta)$, Wd is small (Wd<4 gal/h in this case). In this case, the EWH will be more than one hour off, under the assumption that the initial hot water temperature is T_{high}.

3.5 Impact of Key Parameters of Electric Water Heart (EWH) on Its Operations

The key parameters of the EWH considered here are *Wd, Td,* and *Δ*. As previously mentioned, Wd is a variable parameter. It cannot be controlled since it depends on consumer behaviour. Therefore, it is considered a disturbed parameter. $T_H(t)$ is a quantity that varies with the time. $T_H(t)$ can be controlled by controlling T_d and *Δ*. Consequently, T_d and *Δ* can be considered controllable parameters since they can be changed within a certain range (see section 3.3.1.6).

3.4.5 Impact of T_d and Δ on Electric Water Heart (EWH)

Since the impact of *Wd* has already been noted in the above tables, and it cannot be controlled, only the impact of T_d and Δ on EWH operation (t_{on}, t_{off}, D, P_{EWH}, and EC) are considered here. *EC* is the energy consumption of the EWH per hour (kWh). It is equal to $t_{on} * P_{rated}$.

In this section, three values of T_d, two values of Δ, and three values of Wd are used as shown in Table 3-6. The main reason for using three values of *Wd*, despite the fact that the impact of *Wd* is already known, is to observe the impact of varying T_d or Δ for different values of *Wd*. The value of *Wd* is assumed to be constant for the operation cycle of EWH even it is rises above 1 h.

Table 3-6: Impact of varying T_d and Δ on EWH operation *(t_{on}, t_{off}, D, P_{EWH},* and *EC)*

Wd(gal/)	T_d(°F)	Δ(°F)	t_{on}(h)	t_{off}(h)	t_{total}(h)	*D*	P_{EWH}(kW)	*EC*(kWh)
0.25	100	2.5	0.1550	10.4042	10.5592	0.0147	0.0587	0.62
		5	0.3100	20.8084	21.1184	0.0147	0.0587	1.2400
	120	2.5	0.1563	6.6380	6.7943	0.023	0.0920	0.6252
		5	0.3126	13.2760	13.5887	0.0230	0.0920	1.2504
	140	2.5	0.1577	4.8738	5.0314	0.0313	0.1253	0.6308
		5	0.3153	9.7475	10.0629	0.0313	0.1253	1.2612
6	100	2.5	0.1808	0.9841	1.1649	0.1552	0.6207	0.7232
		5	0.3616	1.9683	2.3298	0.1552	0.6207	1.4464
	120	2.5	0.1993	0.6533	0.8526	0.2338	0.9351	0.7972
		5	0.3986	1.3066	1.7053	0.2338	0.9351	1.5944
	140	2.5	0.2221	0.4890	0.7111	0.3123	1.2494	0.8884
		5	0.4442	0.9779	1.4221	0.3123	1.2494	1.7768
12	100	2.5	0.2187	0.5060	0.7248	0.3018	1.2072	0.8748
		5	0.4375	1.0121	1.4496	0.3018	1.2072	1.75
	120	2.5	0.2796	0.3366	0.6162	0.4537	1.8148	1.1184
		5	0.5591	0.6733	1.2324	0.4537	1.8148	2.2364
	140	2.5	0.3872	0.2522	0.6394	0.6056	2.4223	1.5488
		5	0.7744	0.5044	1.2788	0.6056	2.4223	3.0975

3.4.5.1 The impact of changing the hysteresis band (Δ)

A. t_{on} increases linearly with Δ**.** Table 3-6 shows that the EWH will take more time (almost two times) to heat the water by 10°F (5.56°C) when Δ = 5°F (2.77°C) than to heat the water by 5°F (2.78°C) when Δ = 2.5 °F (1.38°C).

B. t_{off} increases linearly with Δ**.** Table 3-6 shows that EWH will take more time (almost two times) to lose 10°F (5.56°C) when Δ = 5°F (2.78°C) than to lose 5°F (2.78°C) when Δ = 2.5°F (1.38)°C.

C. Duty cycle (*D*) will be the same at any value of Δ as shown in Table 3-6. This is due to the increasing or decreasing rate of t_{off} and $t_{on,}$, which are almost the same when Δ is varied.

D. Energy consumption per operation cycle (*EC*) will increase as Δ is increased. However, the overall energy per day will be almost the same.

In conclusion, one can say that varying Δ can be useful to control the values of t_{on} or t_{off}. On the other hand, varying Δ will not have any effect on *D* and P_{EWH}. Therefore, varying Δ will only be useful for a short term effect (add/drop the instant power of EWH), which can be useful for a transient operation. However, the main limitation is that some commercial units of EWHs do not offer the option to change Δ. Therefore, in the next section, only the impact of T_d is considered.

3.4.5.2 The impact of changing set point temperature (Td).

A. t_{on} increases as T_d increases. Table 3-6 shows that t_{on} will increase almost two times when T_d increases from 100 °F to 140 °F (37.78°C to 60°C). The reason that the relation is not exactly as linear as that in the Δ case is due to the effects of the energy needed and the energy losses. However, this effect is very limited since *Q* is large (see section 3.4.4).

B. t_{off} will decrease as T_d increases as shown in Table 3-6. This is due to the heat needed and heat lost, which increases as T_d increases.

C. Duty cycle (D) will increase as T_d increases. Table 3-6 shows that D increases by two times when T_d increases from 100°F to 140°F (37.78°C to 60°C).

The power consumed by EWH (P_{EWH}) is proportional to T_d as in the case of D.

D. EC will also increase as T_d increases. The overall energy consumption of one day will be not the same as in the case of Δ.

In summary, varying T_d can be useful to control the t_{on}, t_{off}, and P_{EWH}. This means that varying T_d will be useful for both a short term effect (add/drop the instant power of EWH) and a long term effect (increase of decrease P_{EWH}). However, the main limitation is that T_d should vary within a certain narrow range (see section 3.3.1.6).

3.4.5.3 The impact of T_d on Electric Water Heater (EWH) at different value of *Wd*:

As explained in section 3.4.4, *Wd* has a noticeable impact, particularly on t_{off}. Therefore, *Wd* may limit the benefits of using T_d as controllable parameters in the EWH. Let us compare the values of t_{on}, t_{off} at different *Wd* and T_d. Table 3-6 shows that t_{on} changes significantly when T_d varies in cases when *Wd* is large, and t_{on} changes slightly when T_d varies in cases when *Wd* is small. On the other hand, t_{off} changes slightly when T_d varies in cases when *Wd* is large, and t_{off} changes significantly when T_d varies in cases when *Wd* is small. Figures 3-12 and 3-13 illustrate these results.

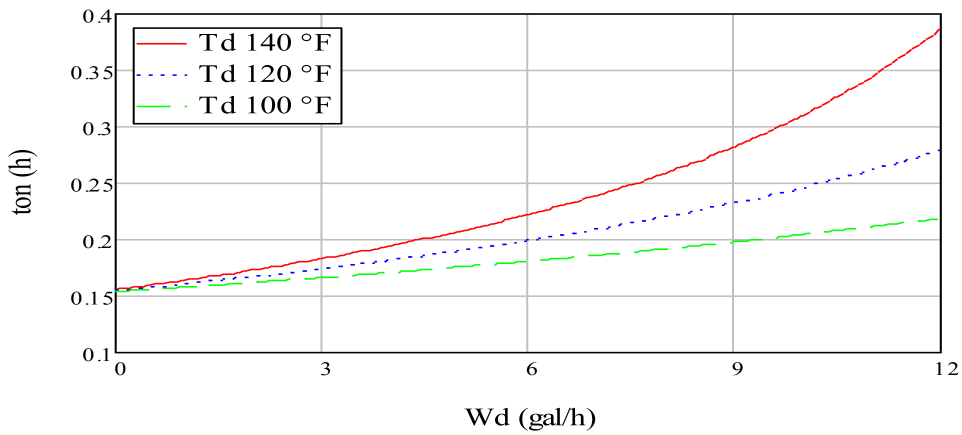

Figure 3-4: t_{on} as function of *Wd* for three value of T_d

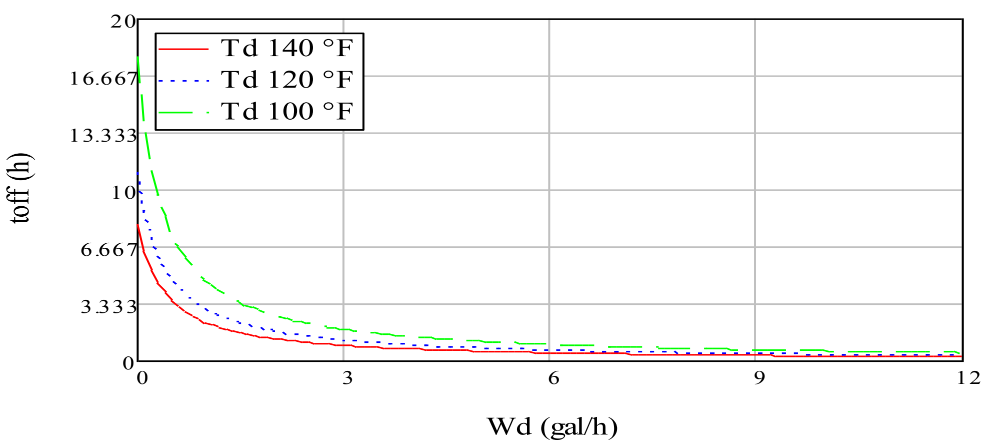

Figure 3-5: t_{off} as function of *Wd* for three value of T_d

These figures show that *Wd* limits the impact of varying T_d in the case of a short term effect. If there is no *Wd*, increasing T_d has a very small impact on t_{on}. If *Wd* is large, decreasing T_d has a small impact on extending t_{off}. For the effect of T_d on *D*, P_{EWH} is also considered. The values of *D* are obtained from Eq. (3.13), which are equivalent to P_{EWH} in pu. Table 3-7 shows the different values of *Wd* and T_d.

Table 3-7: Variation of P_{EWH} (pu) with Wd and T_d.

Wd(gal/h) / T_d(°F)	0.25	0.75	1.5	3	6	9	12
100	0.0107	0.0196	0.0329	0.0595	0.1129	0.1662	0.2195
108	0.0131	0.0238	0.0398	0.0717	0.1357	0.1997	0.2637
116	0.0155	0.028	0.0466	0.0839	0.1586	0.2332	0.3079
124	0.0179	0.0322	0.0535	0.0961	0.1814	0.2667	0.3521
132	0.0204	0.0364	0.0604	0.1083	0.2043	0.3003	0.3962
140	0.0228	0.0406	0.0672	0.1205	0.2272	0.3338	0.4404

Table 3-7 shows that operation at low values of Wd significantly limits the variation of P_{EWH} obtained by varying T_d. Thus, in these cases, the EWH will be less effective as a means of balancing active power in the electric system

3.4.6 Identify the Sensitively of the P_{EWH} to Its Key Parameters:

One important aspect when designing the control scheme of a given system is to identify the sensitivity of a quantity of interest to variations in some of its key parameters. This is done by means of partial derivatives. For D, and consequently P_{EWH}, these key parameters are T_d, taken here as the control parameter, and Wd, assumed as a disturbance in the system.

Since $P_{EWH}=D\times P_{rated}$ and P_{rated} is equal to 1pu, the value of D is equivalent to P_{EWH} in pu. Therefore, only Eq. (3.12) is used for this analysis. The partial derivatives for Eq. (3.12) are as follows:

$$\Delta P_{EWH}(pu) = \Delta D = \frac{\partial D}{\partial T_d}\Delta T_d + \frac{\partial D}{\partial Wd}\Delta Wd = \frac{G+Wd\rho C_p}{Q}\Delta T_d + \frac{\rho C_p(T_d - T_{in})}{Q}\Delta Wd \quad (3.16)$$

For the case under consideration, assuming that *Wd* is constant and using the simulation parameters,

$$\Delta P_{EWH}\ (pu) = \Delta D = \frac{3.6+8.34Wd}{13652}\Delta T_d \qquad (3.17)$$

Eq. (3.17) is very useful to compute by how much T_d, should change for EWH operating with a given value of *Wd*, in order to change P_{EWH} by a certain value in steady state.

For the case under consideration, assume that T_d is constant and use the simulation parameters.

$$\Delta P_{EWH}=\Delta D= \frac{8.34T_d-500.4}{13652}\Delta Wd \qquad (3.18)$$

Eq. (3.18) is very useful to determine by how much P_{EWH} will change if *Wd* changes by a certain value with a given value of T_d.

In addition, assuming one wants to keep P_{EWH} is constant at a certain value and that *Wd* is uncertain, one can see by how much T_d has to change to compensate for a certain ΔWd .

3.6 Study the Impact of Changing T_d during Transient Condition

Another important aspect of the operation of a EWH for active power balancing is the amount of power it can drop or take under transient conditions when T_d is changed. Since the EWH operates in an ON/OFF mode, its instantaneous power consumption is either rated or zero. This cannot be changed in many cases. However, during transient conditions, values for t_{on} and t_{off} can be obtained, which are significantly larger than those obtained for steady-state conditions. This will help in the short term control on the mini-grid.

Let us consider first the case in which the EWH takes an additional load. Figure 3- 4 (A) shows that T_H increases almost linearly when the EWH is ON and t_{on} is the time required for T_H to increase by 2Δ, 5 °F (2.78°C) when T_d remains constant. As shown in Eq. (3.9), t_{on} increases as Wd increases, but it does not vary significantly with Wd since Q is the dominant element in the denominator of Eq. (3.9) as reported in previous sections. If T_d is suddenly increased by a value larger than the tolerance band ($\Delta T_d > 2\Delta$), the EWH will be turned ON immediately and remain ON until the value of T_H increases by at least ΔT_d. Hence, one can estimate the increase in t_{on} during transient conditions (TC), with respect to the previous value in steady state condition (SSC), for a given ΔT_d on average for $T_H = T_d$..

Since $T_{high}=T_d+\Delta$ *and* $T_{low} = T_d-\Delta$, $(T_{high}- T_{low})$ in Eq. (3.9) can be replaced by 2Δ. Thus,

$$t_{on(SSC)}=\frac{C\times 2\Delta}{G(T_a - T_d)+Wd(t)\rho C_p(T_{in} - T_d)+Q} \tag{3.19}$$

For t_{on} in transient condition (t_{onTC}) with the assumption that the initial value of T_H is equal to T_d, and that T_d will increase by ΔT, $T_H(t)$ will increase from T_d to $T_{high}+\Delta T$, meaning that $T_H(t)$ will increase by $(\Delta+\Delta T)$. As result t_{onTC} will become

$$t_{on(TC)}=\frac{C(\Delta T+\Delta)}{G(T_a-T_d)+Wd(t)\rho C_p(T_{in}-T_d)+Q} \tag{3.20}$$

By dividing $t_{on(SSC)}$ and $t_{on(TC)}$ one gets:

$$\Delta t_{on} = \frac{\Delta + \Delta T_d}{\Delta} \tag{3.21}$$

Eq. (3.21) yields by how many times t_{on} will increase with respect to $t_{on(SSC)}$.

In this case, $t_{on(TC)}$ can be calculated by using Eqs. (3.19) and (3.21).

$$t_{on(TC)} = \Delta t_{on} \times t_{on(SSC)} \tag{3.22}$$

Table 3-8 shows the maximum values of $t_{on\,(TC)}$ at each time of the day, assuming the ASHRAE *Wd* schedule, that T_d is changed from an initial value, either 120 °F (48.89°C) or 100°F (37.78°C), to 140 °F (60°C). The base case is T_{db} =120 °F (48.89°C), when one does not expect the need to take or drop power during the next few hours. However, if it is known that there will be a need to take as much load as possible, due to a typical increase in production of PV power or due to a decrease in the regular electric load in the system, then operate with T_d = 100 °F (37.78°C).

Table 3-8: $t_{on(TC)}$ for different values of initial T_d (T_{do}) with respect to $t_{on(SSC)}$, using the ASHRAE *Wd* schedule: (T_{do}=120°F, ΔT_d=20°F, Δt_{on}=4.5) and (T_{do}=100°F, ΔT_d= 40°F, Δt_{on}=8.5).

Time of day (h)	*Wd*(gal/h)	$t_{on(SSC)}$ (T_d=140°F)	$t_{on(TC)}$ (T_{do}=120°F)	$t_{on(TC)}$ (T_{do}=100°F)
0:00	6	0.2221	0.9994	1.8878
1:00	1.6	0.1692	0.7614	1.4381
2:00	0.8	0.1622	0.7297	1.3784
3:00	0.66	0.1610	0.7245	1.3685
4:00	0.66	0.1610	0.7245	1.3685
5:00	0.26	0.1577	0.7099	1.3408
6:00	0.8	0.1622	0.7297	1.3784

7:00	3	0.1831	0.8238	1.5561
8:00	11.7	0.3733	1.6800	3.1734
9:00	8	0.2589	1.1650	2.2006
10:00	8.8	0.2773	1.2477	2.3568
11:00	7	0.2391	1.0759	2.0323
12:00	6.25	0.2261	1.0175	1.9220
13:00	5.3	0.2116	0.9521	1.7984
14:00	5.3	0.2116	0.9521	1.7984
15:00	5.65	0.2167	0.9752	1.8420
16:00	3.7	0.1909	0.8590	1.6226
17:00	4.2	0.1969	0.8861	1.6737
18:00	4.1	0.1957	0.8805	1.6632
19:00	5.85	0.2198	0.9889	1.8679
20:00	7.73	0.2532	1.1395	2.1525
21:00	6.38	0.2283	1.0272	1.9402
22:00	6.9	0.2373	1.0677	2.0168
23:00	5.33	0.2120	0.9540	1.8020

The results of Eqs. (3.23) and (3.24) are validated with the simulation results. The error varies between 0.125% when *Wd* = 0.26gal/h (6.048L/h) and 6.8% when *Wd* = 11.7gal/h (44.29 L/h). Although the error is slightly high when *Wd* is large, Eqs. (3.23) and (3.24) are good to estimate the t_{on} time.

A useful expression for Δt_{off} cannot be obtained in a similar way because the decreasing curve for T_H(t) does not resemble a straight line and because of the impact of *Wd* in the next time period (see sections 3.4.4). Nonetheless, one knows that t_{off} is usually long enough for the power balancing operation, particularly when *Wd* is very small. Therefore, in this case, one can define the worst case conditions (*Wd* =11.7 gal/h) for which t_{off_min}= 2.3337 (4.4081) h when T_d = 120(140) °F.

CHAPTER 4
Control methods:

4.1 Introduction

In this chapter, a brief review of the control methods that have been used to control EWHs with various objectives is presented. This chapter also discusses the design consideration of the control strategy that is used to vary the set point temperature (T_d) of EWHs in order to assist frequency regulation and power balancing.

4.2 Back Ground of Control Methods for EWH in DSM

EWH has been a subject of many studies on power balancing and frequency control. Many control strategies have been developed to manage and control the power consumed by EWHs, both individually and in groups. According to [45], two main approaches have been used for control the power consumed by EWHs. The first one is the consumer side control approach, which is intended to reduce the energy consumption of a single EWH. Different strategies have been used for this type of control. For examples, interrupting power for a certain time and changing the set point temperature (T_d) by using a double period setback timer, digital thermostat, or price sensitive thermostat [48].

The second one is the utility side control approach, which is aimed to control aggregate EWHs loads to compensate for frequency deviations and provide power system stability. Interrupting power and changing T_d have been used in this type of approach. However, the former one is more common in utility side control.

Since the consumer can save money when he/she participates in utility side control, both control strategies can be coordinated to achieve consumer and utility goals.

The demand as frequency controlled reverse (DFR) approach considers controlling the load in response to system frequency deviations. DFR can be classified according to where the control is implemented, either outside the load (external control box) or integrated control within the load (integrated control) [49, 50].

4.2.1 External Control

This type of control is used to cut off the power from the load (EWH) directly when the frequency goes below a certain set point frequency and turn it on again when the frequency recovers to the normal range.

One of the biggest advantages of this control is its guarantee that all loads (EWHs) will be turned off when the control becomes active. However, this type of control has aslo disadvantages. One of which is that this control approach may lead to loss of consumer comfort if the load (EWH) is turned off for long and the hot water temperature falls below certain values. Furthermore, an external control can only provide frequency regulation in case of under frequency operation conditions [51]. In other words, it is used only to reduce the load (peak shaving of load demand) to increase the system frequency.

4.2.2 Integrated Control

This kind of control is conceived mainly for thermostatically controlled loads such as EWH, refrigerators, air conditioners, and so on. In contrast to the external control, the integrated control is used to indirectly switch the load (EWH) by varying the set point temperature (T_d). Varying the set point temperature by the integrated control can be achieved by using a linear relation between the system frequency and the set point temperatures (T_d). This relation was introduced by dynamic demand program in the UK, when the set point temperature of a refrigerator in a busy office was varied by using the equations below [52].

$$\acute{T}_{high} = T_{high} - k\,\Delta f \tag{4.1}$$

$$\acute{T}_{low} = T_{low} - k\,\Delta f \tag{4.2}$$

where k is the coefficient of frequency change (Hz/°F (°C)) and Δf is frequency deviation, which is equal to the difference between the system frequency (f) and the nominal frequency (50 Hz or 60 Hz). T_{high} and T_{low} are the high and low set point temperatures, respectively .$\acute{T}_{high}$ and $\acute{T}_{low}$ are the new high and low set point temperatures, respectively.

These equations can be modified to be used for heating loads such as EWHs and space heaters by replacing the minus sign with a plus sign in Eqs. (4.1) and (4.2).

In Chapter 3, the dead band (+/-Δ) of the set point temperature (T_d) is used; therefore, only one equation instead of two can be used for the integrated control.

$$T_d = T_{db} + m(f - f_o) \tag{4.3}$$

One of the interesting features of the integrated control is its flexibility in over- and under-frequency events. It can shift power and achieve peak shaving in cases of low-frequency events, and it can add power and achieve valley load filling in cases of high-frequency events. The latter aspect of integrated control is very desirable, particularly for a power system with a high penetration of fluctuating sources such as PV or wind power.

Moreover, the hot water temperature inside the tank will not cause consumer discomfort since the set point temperature is set with certain limits. In other words, the integrated control is less disturbing to consumers since the EWH will extend its ON/OFF time for a certain time until $T_H(t)$ reaches T_d+/-Δ.

The external control will not be considered in this work since many studies have developed this control type. This study will consider only the potential of developing the integrated control of EWHs in mini-grids.

4.3 Design Consideration of the Integrated Control Parameters

As mentioned in the introduction of this thesis, using EWHs for DSM or demand as a frequency controlled reserve is common in large utility grids. Therefore, in the literature, the design of the integrated control parameters considers only large grids. For that reason, a design for the integrated control parameters has to be considered for the mini-grids.

Generally, the control parameters should be designed based on three main factors:

1- Consumers' comfort level. Consumers need hot water at a temperature that satisfies them. If they are not satisfied with this temperature, they will not be motivated to participate or continue to participate in DSM programs.

2- The load (EWH) itself. It is very important to consider and study the effect of the control strategy on the EWH. The EWH should not turn ON/OFF frequently in order to avoid reducing the lifetime of EWH switches.

3- Power system requirements. The purpose of using controllable loads in the power system is essentially to regulate it and reduce the frequency or voltage variations.

Unlike the first two factors, power system requirements can be different from one power system to another. Referring to the integrated control of EWHs, T_d varies as a function of the system frequency. Therefore, the power system requirement that will be considered is the system frequency.

The acceptable frequency range in the large utility grid can be different from the acceptable frequency range in the mini-grid, although they might have the same nominal value of system frequency (50 Hz or 60Hz).

Much effort has been made in frequency control for large grid systems to allow power flow from multiple sources. An imbalance between generation and demand will lead to increased frequency deviation, destabilize the system, and may even cause blackouts. Therefore, it is highly recommended that system frequency does not exceed (±1%) of its nominal frequency (50 or 60Hz) under normal operation conditions [53].

Not only is the frequency range of the mini-grid different than the large grid but also the way the frequency is controlled. For example, in a mini grid with a diesel genset as a main power source and without a supervisory controller, the system frequency variations are highly dependent on the parameters of the droop controllers of the gensets. The droop control (see Chapter 2) allows decreasing the speed of governor (the system frequency) from no load speed (no load frequency) to full load speed (full load frequency) by a certain percentage (~3-5%) [54].

The load in the mini-grid during the day is highly variable, which causes the system frequency to vary as well. Moreover, a mini-grid with renewable energy sources produces fluctuating power, and the frequency variations can potentially increase. In this case, the diesel generator is the main element responsible for frequency control.

As a result, the frequency deviation or variation in the mini-grid under normal operation conditions varies more with any change in the load or renewable output power than in the large utility grids.

Regarding the power system used in this work, the PV-diesel hybrid mini-grid, and with reference to the diesel genset parameters explained in Chapter 2, the system frequency can be dropped by 3.4% from the no-load frequency [23]. For normal operation conditions, which should be within the desired operation region of the diesel genset (30-80%), the system frequency varies by 2.7 %. These percentages are quite large compared with those of large grids, particularly for normal operation conditions.

4.4 Design of the Integrated Control Parameters for RES-Diesel Hybrid Mini-Grid

The previous section has considered the design consideration of the integrated control. The next step is the design of its parameters. With reference to Eq. (4.3), three parameters should be chosen according to the design consideration factors: set point temperature at the base case (T_{db}), the nominal frequency (f_o) and finally the coefficient of frequency change or slop factor (m).

4.4.1 Set Point Temperature at Base Case (T_{db})

T_{db} is the set point temperature when the integrated control is not active (T_d is not affected by the system frequency). The value of T_{db} is defined in Chapter 3 as equal to 120°F.

4.4.2 The System Frequency (f)

The system frequency is the main input parameter for the integrated control. The integrated control of the EWH is used to help controlling this frequency within a certain limit or range. This range depends on the optimum operation range of the diesel genset, which is defined in Chapter 2 (30%-80%). Thus, the system frequency range should between $f_{(0.3pu)}$ and $f_{(0.8pu)}$:

$$f_{(0.3pu)} = f_{max} = f_{nl} - \frac{P_{g(0.3pu)}}{s_p} \tag{4.4}$$

$$f_{(0.8pu)} = f_{min} = f_{nl} - \frac{P_{g(0.8pu)}}{s_p} \tag{4.5}$$

Recall that f_{nl} is the no load frequency, and P_g is the output power of the diesel genset.

4.4.3 Nominal System Frequency Value (f_o)

The nominal frequency value is a fixed value. In North America, f_o= 60 Hz.

Due to power source characteristics and load variation behavior in the mini-grid, droop control cannot keep the system frequency value within a small range of its nominal value. If the nominal frequency value is used in Eq. (4.3), T_d changes (ΔT_d) because the integrated control will be different in case of over- and under-frequency operation conditions. In order to make ΔT_d equal in both conditions, it is proposed in this work to replace the nominal frequency in Eq. (4.3) by the center frequency (f_c).

The center frequency is determined by the average of the maximum system frequency $f_{(0.3pu)}$ and minimum system frequency $f_{(0.8pu)}$.

By using Eqs. (4.4) and (4.5):

$$f_c = \frac{f_{max} + f_{min}}{2} \tag{4.6}$$

By replacing f_o *by* f_c ,equation (4.3) becomes:

$$T_d = T_{db} + m(f - f_c) \tag{4.7}$$

By using the parameters of the 95 kW genset presented in Chapter 2 and using Eqs. (4.4), (4.5) and (4.6), f_{max}, f_{min}, and f_c can easily be obtained as follows:

$$f_{(0.3pu)} = f_{max} = f_{nl} -- \frac{P_{g(0.3pu)}}{s_p} = 62.34 - \frac{0.3 \times 95}{29.4} = 61.37Hz$$

$$f_{(0.8pu)} = f_{min} = f_{nl} - \frac{P_{g(0.8pu)}}{s_p} = 62.34 - \frac{0.8 \times 95}{29.4} = 59.755Hz$$

$$f_c = \frac{f_{max} + f_{min}}{2} = \frac{61.37 + 59.755}{2} = 60.5625Hz$$

4.4.4 Coefficient of Frequency Change or Slope Factor (*m*)

The design of *m* is very important due to its effect on ΔT_d. If *m* is too large, T_d will increase or decrease by large amounts, which may lead to decreased consumer comfort levels and make the EWH turn ON/OFF frequently. If *m* is very small, the integrated control may not have a noticeable effect on the reduction of frequency deviations. Therefore, all the design considerations mentioned in section 4.3 should be considered when designing *m*.

The value of m should be designed to keep T_d within an acceptable range (T_{dmin} - T_{dmax}), which is (100-140°F), as shown in section 3.3.1.6. In addition, m should be designed to keep the frequency between (f_{min} – f_{max}). As a result, the value of m can be selected by using either the under-frequency operation condition (f_{min} and T_{dmin}) or the over-frequency operation condition (f_{max} and T_{dmax}). In both cases m should be same.

Let us consider the under-frequency operation condition. When the system frequency decreases from f_c to f_{min} (in this case the genset output power is equal to 0.8 pu), the integrated control should decrease T_d to the lowest possible value (T_{dmin}).

$$T_{dmin} = T_{db} + m\left(f_{min} - f_c\right) \tag{4.8}$$

$$m = \frac{T_{dmin} - T_{db}}{f_{min} - f_c} \tag{4.9}$$

In the case of the over-frequency operation condition, the system frequency increases from f_c to f_{max} (in this case the genset output power is equal to 0.3 pu), and the integrated control should increase from T_d to the highest possible value (T_{dmax}).

$$T_{dmax} = T_{db} + m\left(f_{max} - f_c\right) \tag{4.10}$$

$$m = \frac{T_{dmax} - T_{db}}{f_{max} - f_c} \tag{4.11}$$

Since the parameters in Eqs. (3.9) and (3.11) are known, m can easily be found:

$$m = \frac{T_{dmin} - T_{db}}{f_{min} - f_c} = \frac{100\text{-}120}{59.75\text{-}60.56} = 24.7\ \text{°F/Hz}$$

or

$$m = \frac{T_{dmax} - T_{db}}{f_{max} - f_c} = \frac{140\text{-}120}{61.37\text{-}60.56} = 24.7\ \text{°F/Hz}$$

After defining all the integrated control parameters, the droop curve of temperature versus system frequency can be plotted as shown in Figure 4-2.

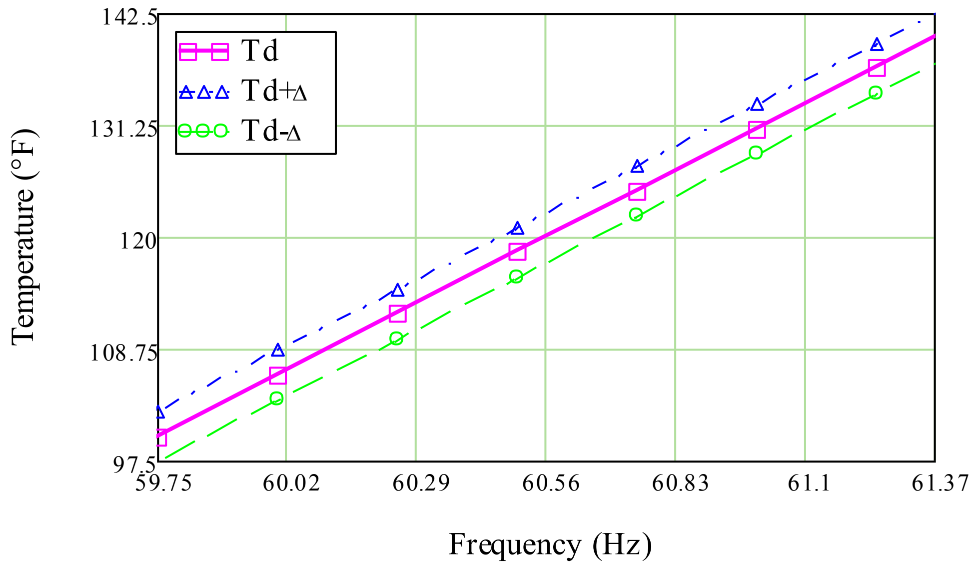

Figure 4-1: T_d, $T_d + \Delta$, and $T_d - \Delta$, as function of the system frequency

Figure 4-1 shows that T_d, $T_d + \Delta$, and $T_d - \Delta$ change linearly with the system frequency. T_d reaches the maximum value (140°F) when the frequency is equal to 61.37Hz, and T_d reaches the lowest value (100°F) when the system frequency is equal to 59.75Hz.

Notably, when the frequency goes above 61.37 Hz or below 59.75 Hz, T_d must be equal to 140°F (60°C) or 100°F (37.78°C), respectively. Therefore, a limiter should be used to keep T_d within this range.

4.5 Study the Impact of Using the Integrated Control

As explained in Chapter 3, changing T_d will affect the EWH in terms of its operation cycle and its power consumption. The method of varying T_d is defined by the integrated control as explained in previous sections. Next, the impact of varying T_d (using the integrated control) on the mini-grid in case of using multiple EWHs should be identified. This can be achieved first by calculating by how many Hz the system frequency will change if one EWH is turned ON/OFF without the integrated control. The impact of using the integrated control (varying T_d as function of the system frequency) is then observed for multiple EWHs and for different load conditions. For example, a power oscillation might occur due to the activation of the integrated controls for multiple EWHs. Thus, one can identify the problems in using the integrated controls and develop or modify the integrated control scheme to be useful in mini-grid systems containing multiple EWHs.

4.5.1 The Impact of Turning ON/OFF EWHs on the Mini Grid's System Frequency:

Let us assume that the frequency of the mini-grid is equal to the center frequency, $f = f_c$=60.56Hz.

The output power of diesel genset in this case with reference to Eq. (2.1) in Chapter 2 is as follow:

$$P_g = s_p\left(f_{nl} - f\right) = 29.4((62.34 - 60.56) = 52.332kW = \frac{52.332}{95} = 0.55pu$$

This value will be considered as the base load value.

If only 4kW EWH in the mini-gird is turned ON because the hot water temperature reached the low limit, the output power of the genset will increase by 4kW.

$$P_g = P_{g(fc)} + P_{EWH(rated)} = 52.332+4 = 56.332kW$$

In this case, the system frequency and frequency deviation Δf will be

$$f = 62.34 - \left(\frac{P_g}{29.4}\right) = 60.424Hz, \quad \Delta f = 60.56 - 60.424 = 0.136Hz$$

This calculation shows that turning one EWH ON or even OFF will make the system frequency change by ±0.136Hz. This frequency change value is quite large. This can induce T_d of other EHWs to vary and change their states (ON/OFF).

When the mini-grid has multiple EWHs, the case will be even worse. If 5 EWHs change their operation mode at the same time, the system frequency will change by ± 0.68 Hz (5*±0.136Hz).

This may be a disadvantage of using high power rated elements of EWH in small systems, especially when a group of EWH turns ON/OFF at the same time.

4.5.2 The Impact of Activation the Integrated Control on Multiple EWHs for Different Load Conditions

It is very important to analyze the impact of the integrated control on the mini-grid in the case of multiple EWHs to determine how many EWHs would change their operation mode in the same way and at the same time.

With reference to the previous sections, the frequency of a small mini-grid is very sensitive to demand variations, particularly EWHs demand and RESs power fluctuation. RESs will be considered as a negative passive load. The load demand from the diesel genset can be categorized into two categories with respect to the base load or base case. The first category is a light load demand condition from the diesel genset. In this case, the demand from the diesel genset is small; consequently, the system frequency is high. This case is most likely to occur at night and at high PV generation periods (afternoon). The second category is a high load demand conditions from the diesel genset. In this case, the demand from the diesel genset is high; consequently the system frequency is low. This case is most likely to occur in the evening. Both cases can be sub-categorized in term of how much the demand will vary, by small or large value, with respect to the base load (P_g=$P_{g(o.55pu)}$).

The integrated control will act according to these load demand conditions from the diesel genset. If the load demand condition from the diesel genset is high or low, the integrated control acts to return the frequency, if possible, to the base case.

Significantly, the effect of the integrated control will depend on the frequency variation, which in turns depends on the load conditions from the diesel genset. If the frequency variation is small, the integrated control effect may be low or high depending on other parameters of the EWHs, such as the dead band (2*Δ), the hot water temperature in EWH tank ($T_H(t)$), and the operation mode of EWH (ON or OFF). If the frequency variation is high, the control will change T_d by a high value, greater than 2*Δ, that makes all EWHs ON or OFF depend on the load demand condition from the diesel genset.

To clarify, let us consider all load demand conditions from the diesel genset.

4.5.2.1 Light load demand condition from the diesel genset (*f* >*fc*).

Case A. The system frequency increases by small value

If the system frequency increases from f_c by a small value, the integrated control will make T_d increase by ΔTd. If $\Delta Td < 2 * \Delta$, the action of EWH will depend on its $T_H(t)$ and its operation mode, ($K(t)$, (1 for ON, 0 for OFF)):

Case 1- $T_H > (T_d - \Delta)$, and EWH operation mode is OFF, $K(t)$ =0. EWH will remain OFF, but for less time.

Case 2− $T_H \leq (T_d - \Delta)$, and EWH operation mode is OFF, $K(t)$ =0. EWH will be turned *ON* immediately.

Case 3- $T_H > (T_d\text{-}\Delta)$, and EWH operation mode is ON, $K\ (t)$ =1. EWH will remain ON.

Case 4- $T_H \le (T_d\text{-}\Delta)$, and EWH operation mode is ON, $K\ (t)$ =1. EWH will remain ON for more time than in Case 3.

where $\Delta T_d = m\ (f\text{-}f_c)$ and $T_d\text{-}\Delta = T_{low}$.

Returning to the previous cases in this section, only EWHs with $T_H < T_{low}$ and $K\ (t)$ =0 will be turned ON immediately because of the integrated control. The effect of the integrated control for other EWHs is to extend the t_{on} for EWHs with $K\ (t)$ =1, and make EWHs with $T_H > T_{low}$ and $K\ (t)$ =0 turn ON sooner.

Case B. The system frequency increases by a large value

If the system frequency increases from f_c by a large value, the integrated control will make T_d increase by a large value. If $\Delta T_d \ge 2 * \Delta$, the EWHs with $K\ (t)$ =0 will be turned ON immediately.

Case 1-$T_H \le (T_d\text{-}\Delta)$, and EWH operation mode is OFF, $K\ (t) = 0$. EWH will be turned ON immediately.

Case 2- $T_H \le (T_d\text{-}\Delta)$, and EWH operation mode is ON, $K\ (t)$ =1. EWH will remain *ON*.

For this case, the integrated control will make all EWHs with $T_H \le (T_d - \Delta)$ and $K\ (t) = 0$ turning ON immediately. The integrated control will extend the t_{on} for EWHs with $K\ (t)$ =1.

The problem with this case (the system frequency increases by large value) is that all EWHs with OFF state, $K\ (t) = 0)$ will be turned ON together. This leads to a large reduction of system frequency, particularly when a small power system is considered, as in our case. If there are 10 EWH OFF before activation of the control, they will become ON after activation of the integrated control. As a result, the frequency will decrease by 1.36 Hz (0.136*10) (see section 4.5.1).

4.5.2.2 High load demand condition from the diesel genset ($f < f_c$)

Case C. The system frequency decreases by small value

If the system frequency decreases from f_c by a small value, the integrated control will make T_d decrease by ΔTd. If $\Delta T_d > -2\Delta$, the action of the EWH will depend on its $T_H(t)$ and its operation mode $K(t)$, similarly to Case A.

Case 1- $T_H < (T_d+\Delta)$, and EWH operation mode is ON, $K(t)=1$. EWH will remain ON but for less time.

Case 2- $T_H \geq (T_d+\Delta)$, and EWH operation mode is ON, $K(t)=1$. EWH will be turned OFF immediately

Case 3- $T_H < (T_d+\Delta)$, and EWH operation mode is OFF, $K(t)=0$. EWH will remain OFF.

Case 4-$T_H \geq (T_d+\Delta)$, and EWH operation mode is OFF, $K(t)=0$. EWH will remain OFF. EWH will remain *ON* for more time than in Case 3.

The effect of the integrated control in this case is similar to the effect of the control in the case where the system frequency decreases by a small value. However, in the opposite, only EWHs with $T_H > (T_d+\Delta)$, and $K(t)=1$ will be turned OFF immediately because of the integrated control. The effect of the integrated control for other EWHs is to extend the t_{off} for EWHs with $K(t)=0$ and make EWHs with $T_H < (T_d+\Delta)$, and $K(t)=1$, turn OFF sooner. For this type of change, the integrated control will help to increase the system frequency without causing issues.

Case D. The system frequency decreases by large value

If the system frequency decreases from f_c by a large value, the integrated control will make T_d decrease by a large value. If $\Delta T_d \leq -2\,\Delta$, the EWHs with $K(t)=1$ will be OFF immediately.

Case 1- $T_H \geq (T_d+\Delta)$, and $K(t)=1$. EWH will be turned OFF immediately.

Case 2- $T_H \geq (T_d+\Delta)$, and $K(t)=0$. EWH will remain OFF.

The effect of the integrated control in this case is similar to the effect of the control in the case where the system frequency increases by a large value (case B). However, in contrast, EWHs with $T_H \geq (T_d+\Delta)$, and $K(t)=1$ will be turned OFF immediately because of the integrated control. The integrated control will extend the t_{off} for EWHs with $K(t)=0$.

In general, Case D has the same problem as Case B, however in the opposite side. All EWHs with ON state $K(t)=1$ will be turned OFF together. This leads to large increase in the system frequency, particularly when a small power system is considered.

4.5.3 Summary of the impact of the integrated control on the system frequency

According to the previous analysis, using the integrated control for multiple EWHs can be useful to assist frequency regulation in the case of a small increase or decrease in the system frequency (Case A and Case C). Variations in the frequency will be reduced in those cases by using the integrated control. However, the integrated control for multiple EWHs may not be useful in the case of a large increase or decrease in the system frequency (Case B and Case D). The system frequency will vary more, which occurs when many EWHs in the power system are turned ON or OFF at the same time.

Regarding load and RES variations in the mini-grid when the rated power of the EWH element is high, Case B and Case D will be more likely to happen. Therefore, the basic integrated control will not be enough to get good results for the RES-Diesel bybrid mini-grid. A modified integrated control should be designed carefully considering the large system frequency variation (Case B and Case D).

4.6 Solution to Improve the Results of Using the Integrated Control

This study proposes a solution to solve the issues caused by the basic control when a large system frequency variation occurs due to other EWHs are turned ON/OFF or because of PV varies a lot in the mini-grid. The principle of this solution is to modify the basic integrated control of each EWH by adding activation conditions that can control the state of the integrated control (enable or disable). Thus, the number of EWHs that are turned ON or OFF due to effect of the integrated control can be reduced. In this case, the basic integrated control with additional activation conditions can be named as the modified integrated control.

4.6.1 The activation conditions of the modified integrated control

The activation conditions of modified integrated are defined based on the hot water temperature in the tank (T_H) and the operation mode of the EWH.

1- **A large increase of the system frequency (Case B).** In Case B (see section 4.5.2.1), $\Delta T_d > 2\Delta$ $(T_H \leq Td - \Delta)$, and the EWH is either ON or OFF.

The problem that needs to be solved in this case is to decrease the number of EWHs that will be turned ON at a certain time because of the grid frequency value. Therefore, only EWHs in the OFF operation mode will be considered for activation conditions.

The activation conditions of the integrated control of EWHs in the OFF operation mode are based on the hot water temperature of the EWH. If T_H is below the old set point temperature, the modified integrated control should be enabled. If T_H is above or equal to the old set point temperature, the modified integrated control should be disabled. The logic control of the activation conditions are as follows:

If $T_H < T_{d\,(old)}$ and $K(t) = 0$, enable the modified integrated control.

Where $T_{d\,(old)}$ is the previous set point temperature.

If $T_H > T_{d\,(old)}$ and $K(t) = 0$, disable the modified integrated control.

For $K(t)$=1, for any value of T_H, enable the control.

The initial value of $T_{d\,(old)}$ is T_{db} when the control is just activated.

2- **A large decrease of the system frequency (Case D).** In Case D (see section 4.5.2.1), $\Delta T_d \leq -2\Delta$ $(T_H > Td + \Delta)$. EWH is either ON or OFF.

The problem that needs to be solved in this case is the opposite of that in Case B. The number of EWHs that are turned OFF at the same time because of the integrated control should be decreased. Therefore, only EWHs in the ON operation mode will be considered for activation conditions. The EWHs in the

OFF operation mode will not be considered. If T_H is above the old set point temperature, the integrated control should be enabled. If T_H is below or equal to the old set point temperature, the integrated control should be disabled. The logic of activation condition is as follows:

If $T_H > T_{d\,(old)}$ and $K(t) = 1$, enable the modified integrated control.

If $T_H < T_{d\,(old)}$ and $K(t) = 1$, disable the modified integrated control.

For $K(t) = 0$, for any value of T_H, enable the modified integrated control.

The proposed modified control is validated by using the benchmark of a PV-diesel hybrid mini-grid. The next chapter provides more details about the benchmark and presents a number of simulation results.

CHAPTER 5
PV-DIESEL HYBRID MINI GRID SYSTEM MODEL AND SIMULATION RESULTS

5.1 Introduction

In this chapter, simulation results are used to validate the analysis presented in the Chapter 3 and to demonstrate that the proposed control strategy can efficiently both reduce the frequency variation and make the genset operate in the desired operation region. First, a brief description of the benchmark of PV-diesel hybrid mini-grid implemented in PSCAD is given. Details about the model of the integrated control of the EWH are then presented. Finally, the simulation results for different cases of the mini-grid are presented and discussed in this chapter.

5.2 Mini- Grid Structure and Model

A PV-diesel hybrid mini-grid model, which is implemented in a PSCAD/EMTDC environment and presented in [18, 23] is adapted in this work to study the impact of controlling EWHs based on system frequency (the integrated control). The architecture of the PV-diesel hybrid mini-grid system is shown in Figure 5-1.

The main components of this mini-grid are a diesel plant, a step-down transformer (600/240V), an overhead low voltage distribution line (240V) supplying a public area, and 20 residential houses. Each house has one EWH. Finally, six rooftop PV panels are installed in six houses. The rated capacity of each system is 4kW. Some of these component models are taken from the mini-grid model [18] or a PSCAD library, while others, such as controllable load (EWH) and its integrated control, are modeled in PSCAD by the author.

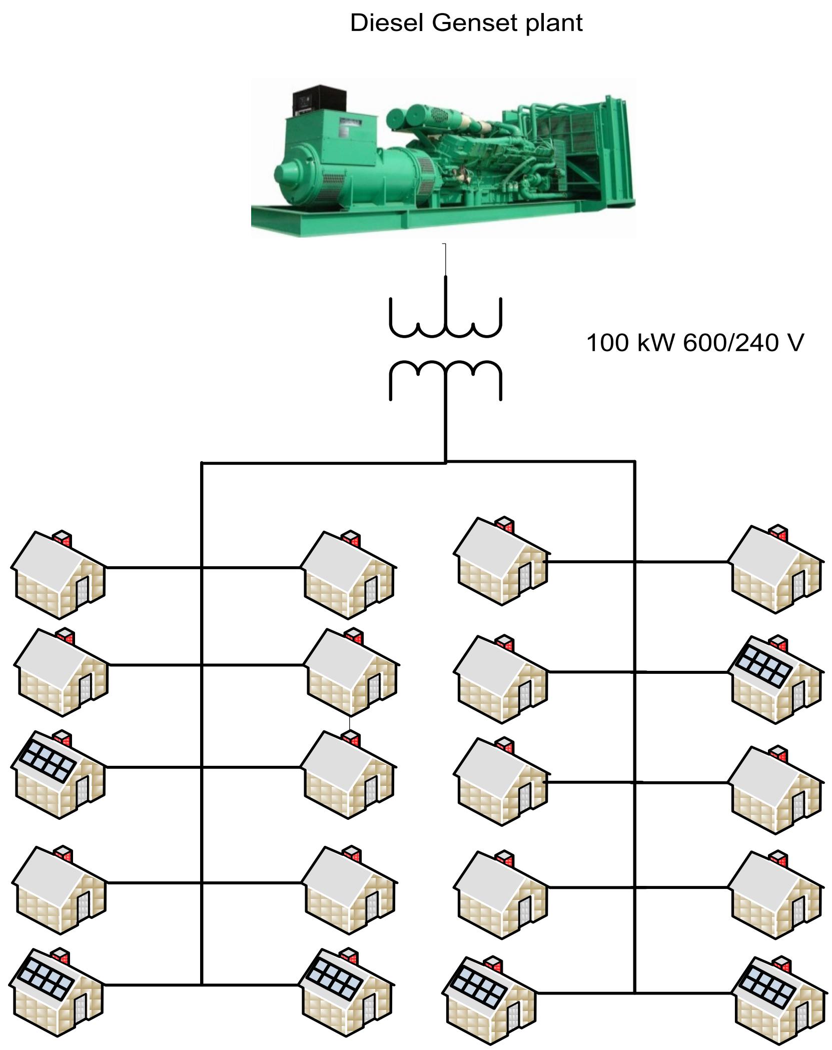

Figure 5-1: The architecture of hybrid PV-diesel mini-grid

5.2.1 Diesel Genset Plant

The diesel genset plant consists of three diesel gensets. Two are rated at 95kW, while the third one is rated at 30kW. One of the two 95k W diesel gensets is used as a back-up source. The 30kW diesel genset is used to supply electricity in the light load period during the night instead of using a 95kW genset to avoid using dump load. The other 95kW genset is used to supply the electricity during the rest of the day. Since the night load is not included in the study because of the demands from EWHs and uncontrollable loads are low and do not change much, the parameters and droop curve of the 30 kW of the diesel genset will not be considered. The parameters of 95kW genset are described in Chapter 2, section 2.1.1.1.

5.2.2 Step-Down Transformer

The transformer used in this mini-grid is a 100kVA standard distribution transformer. It is located near the diesel genset plant and is used to step down the voltage from 600V to 240 V. The parameters of the 100kVA transformer were obtained from [55] and are shown in Table 5-1.

Table 5-1: Simulation parameters of the step-down transformer

	Transformer's Simulation Parameters
Rated Power	100 kVA
Primary Voltage	600 V
Tap	0.95:1
Secondary Voltage	240 V
Copper Losses	0.045 pu
No Load Losses	0.02

5.2.3 Low Voltage Distribution Line (240V)

The output power of the transformer is distributed through a low-voltage single-phase overhead line. The power line used in this study is a typical wood pole line. It is wired using 4/0 AWG Aluminum, XLPE for both line and ground, and the drop lines are wired with 1/0 AWG Aluminum, XLPE. The line parameters are shown in Table 3-2 [55].

Table 5-2: Parameters of the Single-phase lines (per line conductor)

element	Drop Lines	Pole-Pole Lines
R	0.549 Ω / km	0.27 Ω / km
L	0.23 mH / km	0.24 mH / km
C	0.055 μF / km	0.72 / km

5.2.4 PV system

In this hybrid PV-diesel mini-grid, six rooftop PV panels are used. Each one is installed in one house. The PV inverter is connected to the drop lines of the houses. Therefore, the PV panel will supply the electricity not only to the houses with PV panels, but also to other houses in this mini-grid. The rated power of each PV system is 4kW, which means that all PV systems can supply 24kW as maximum value. The PV inverter as mentioned in Chapter 2 is modeled as a current source. The model of the PV inverter is already available in the benchmark

The PV profile used in this work was estimated for Montreal (Latitude 45°55' N and Longitude 73° W) using HOMER software and data taken from the NASA weather information center for a sunny day as shown in Figure 5-2 [56] . In order to observer the impact of the proposed control in the worst case (PV gives the maximum power possible that make diesel genset operates at low efficiency), the PV profile used in this study is based on the longest day (17h) of the year.

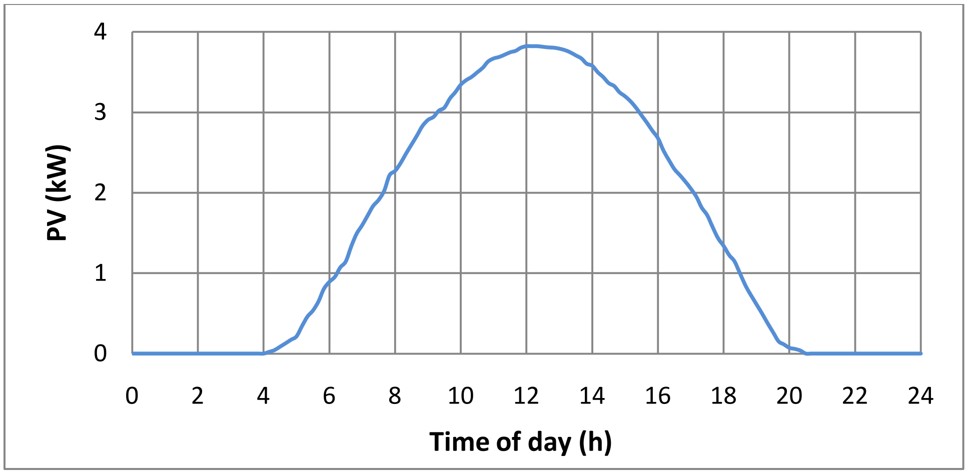

Figure 5-2: Sunny PV power profile

5.2.5 Ac loads

The AC loads considered in this study correspond to residential loads and a community center, including a small shopping mall.

5.2.5.1 Community load center

The load profile of the community center is based on reference [57] and is shown in Figure 5-4.

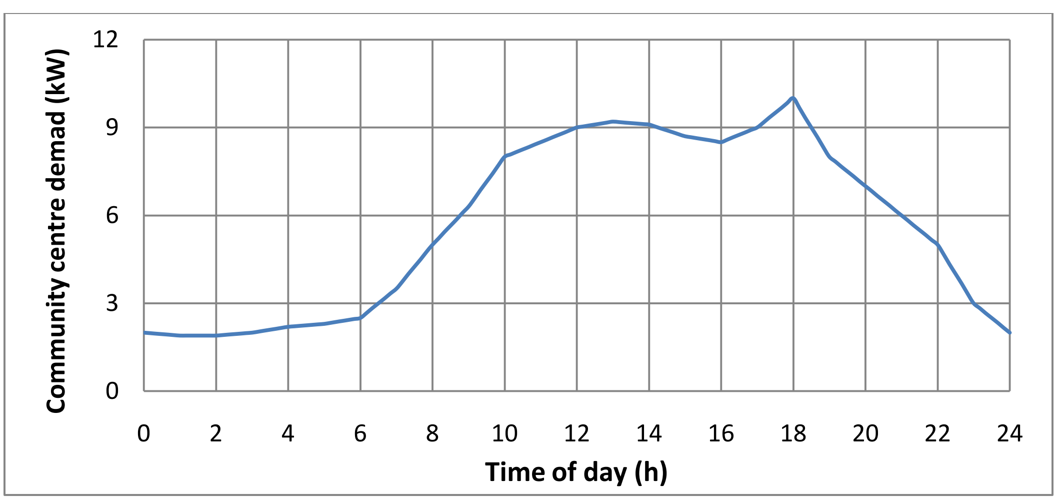

Figure 5-3: The community center load profile

5.2.5.2 Residential loads

The mini-grid supplies power to 20 houses. Each house has controllable and uncontrollable loads.

A. Uncontrollable loads:

A residential load profile for a house without EWH based on [57] was scaled to have a daily energy consumption around 32 kWh/day and was used as reference for all 20 houses to determine the 24 h load profile of the mini-grid for uncontrollable loads. This load profile does not include EWH loads. There is no distinction between weekend and weekday data. The 24-hour profile of the uncontrollable residential loads is shown in Figure 5-4.

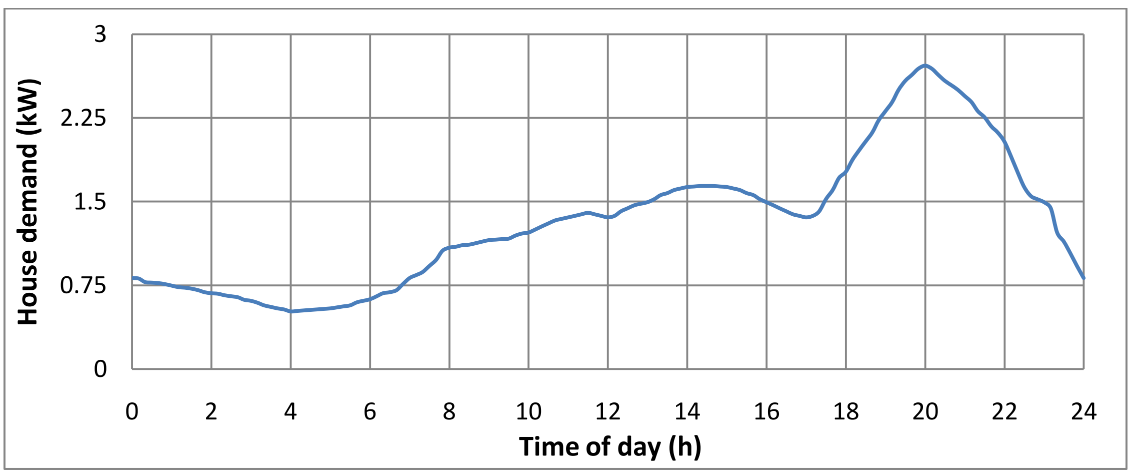

Figure 5-4: The load profile of the uncontrollable loads

B. Controllable loads (EWHs)

EWHs are used as controllable loads to assist the frequency regulation and power balancing in this work. There are 20 EWHs in this mini-grid. The average demand of a EWH at base case (T_d=120 °F (48.89°C), ASHREA Wd profile) is shown in Figure 5-5 to show the demand patterns of the EWH.

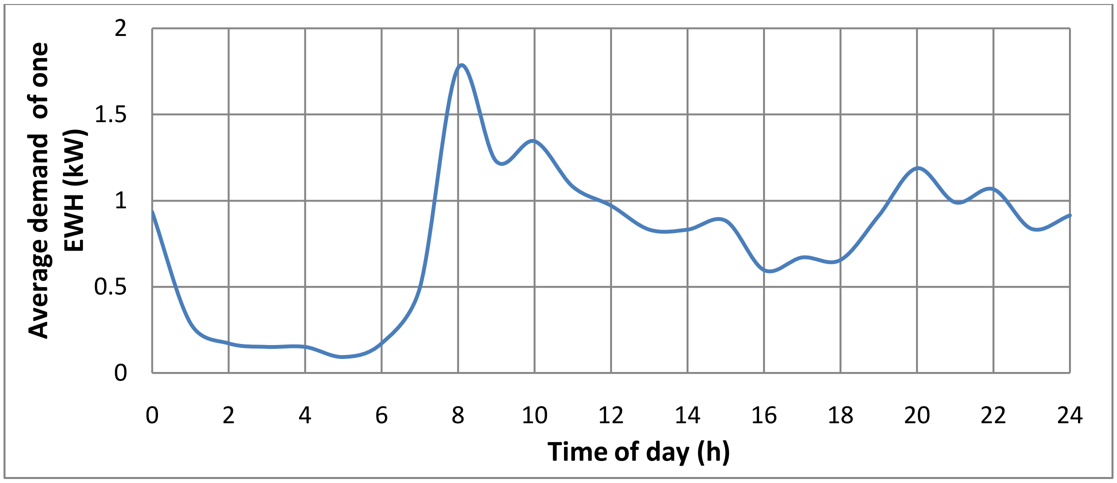

Figure 5-5: The average power consumption of a 4kW EWH at base case.

In order to study the effect of the control schemes, the electrical circuit of the EWH should be considered. Therefore, a resistance is used to represent the heating element resistance of the EWH, as shown in Figure 5-6. This resistance is connected to the mini-grid, and its switch is controlled by the thermostat by using the EWH thermal model (see Chapter 3, section 3.3.2).

In order to achieve more accurate results, the real value of the input energy (Q) to the thermal model is considered. This achieved by multiplying the RMS value of the current of heating resistance with heating resistance, as shown in Figure 5-7.

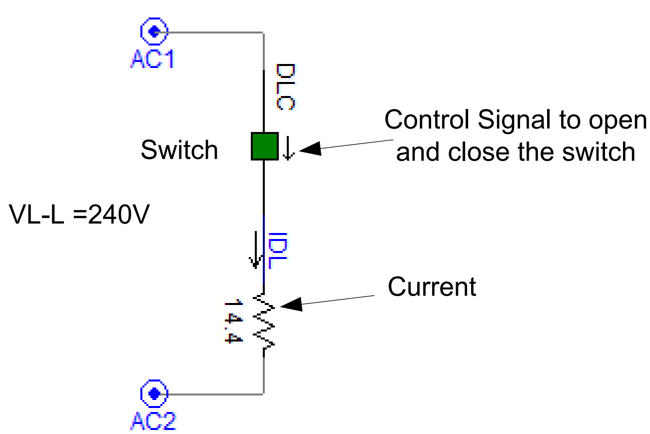

Figure 5-6: Electric circuit of the EWH

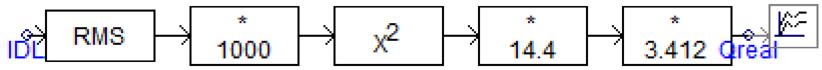

Figure 5-7: Real value of input energy (Q)

In Figure 5-6, the resistant represents the EWH element resistant and the switch represents the EWH switch. The DLC is the control signal coming from EWH thermal model and it represents the thermostat action to turn ON/OFF the EWH, depending on the hot water temperature. The value of the resistance can be easily found by using the basic power equation as shown in Eq. (5.1).

$$R = \frac{V^2}{P_{rated}} = \frac{240^2}{4 \times 10^3} = 14.4\ \Omega \tag{5.1}$$

The EWH thermal model based on the energy flow in EWH that was already modeled in Matlab/SIMULINK, is modeled in PSCAD as shown in Figure 5-8. It is used to observe the hot water temperatures and to send control signals to turn the EWH ON or OFF when the temperature reaches $T_d - \Delta$ or $T_d + \Delta$ respectively.

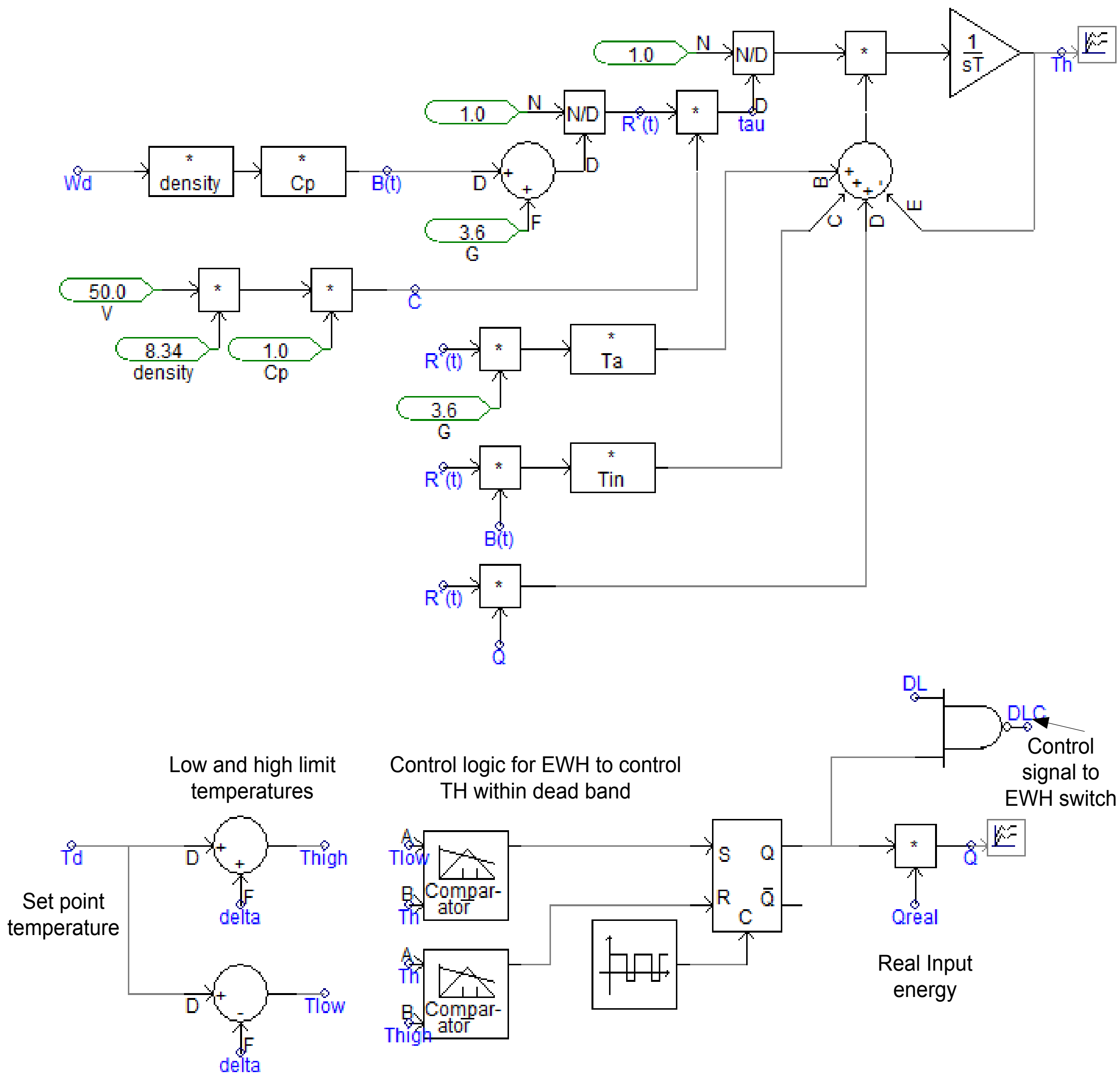

Figure 5-8: EWH thermal model in PSCAD

5.3 The Integrated Control of the EWH Model

The integrated control model is divided into two parts. The first part is the basic integrated control. This part is based on the linear relation between the set point temperatures (T_d) and the system frequency (f), shown in Eq. (4.7). The second part is the modified integrated control. This part uses the same blocks as for the basic integrated control with additional blocks for the activation conditions. For example, comparators are used for implementing the activation conditions of the modified integrated control. The previous set point $T_{d\ (old)}$ that is required for the implementation of the "activation conditions" is based on a sample and hold block. Figures 5-9 and 5-10 show the basic and modified integrated controls, respectively.

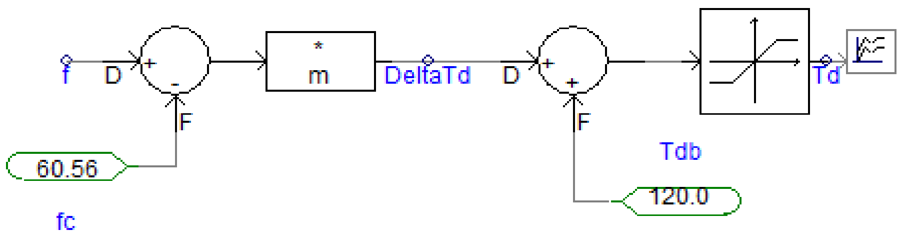

Figure 5-9: The basic integrated control

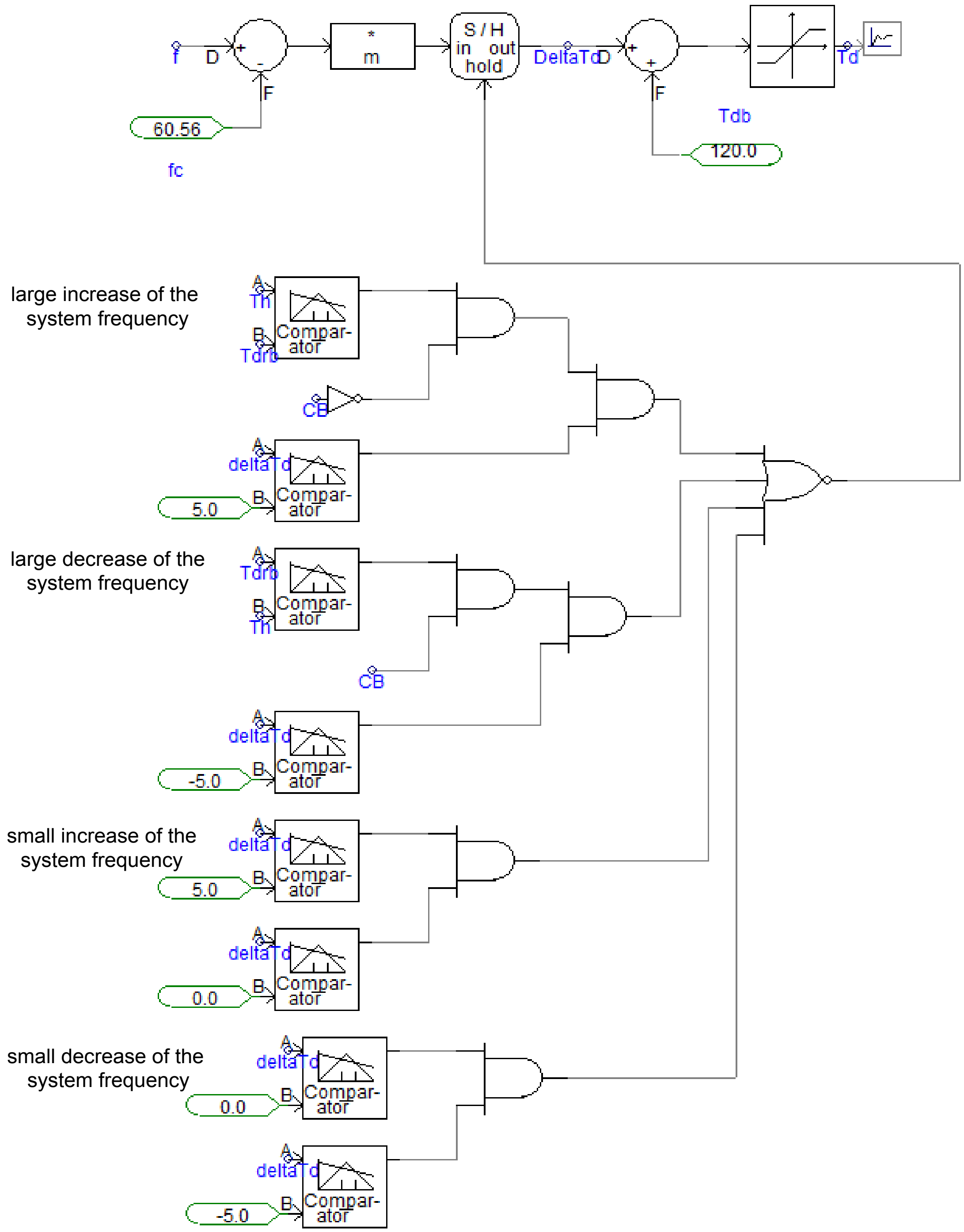

Figure 5-10: The modified integrated control

5.4 Simulation Results

5.4.1 Simulation Time and Initial Values

The time step of the simulation is 0.00001h and the total simulation is 18 hours. It starts at 6 am and ends at 12 am (midnight). The period from 12 am to 6 am is not considered because it is assumed that during this time, 30kW is used instead of 95kW. This assumption based on the fact that the consumption or the demands from EWHs and uncountable load are low and do not change much, which causes the 30 kW genset to operate in an efficient region.

Since multiple EWHs (20 EWHs) are used in this work, their initial hot water temperatures are randomized within the dead band (2*Δ). Moreover, their ON/OFF states are randomized by assuming that 50% of the EWHs are initially ON and the others are OFF.

In order to avoid EWHs ON/OFF at the same time, the *Wd* profile in this study is normally randomized with the average hot water draw (*Wd*) per hour with a standard deviation of 1.17 [58]. These initial values of hot water temperature and initial ON/OFF states of EWHs may be helpful to avoid turning EWHs ON/OFF together at the beginning of the simulation time.

5.5 Simulation Results for Different Operation Condition and Cases

In this study, different cases have been considered in order to observe the impact of DSM (EWHs control) and PV on mini-grid performance.

Case 1: The diesel genset supplies the power to the mini-grid alone. There are no PV systems in the mini-grid, and the operation of the EWHs is independent of the grid frequency (the integrated control is disabled).

The output power of the diesel genset (which is equal to the demand of the mini-grid in this case), the system frequency, the fuel consumptions of the diesel genset, the demand of 20 EWHs, and the hot water and set point temperatures are shown in the figures below.

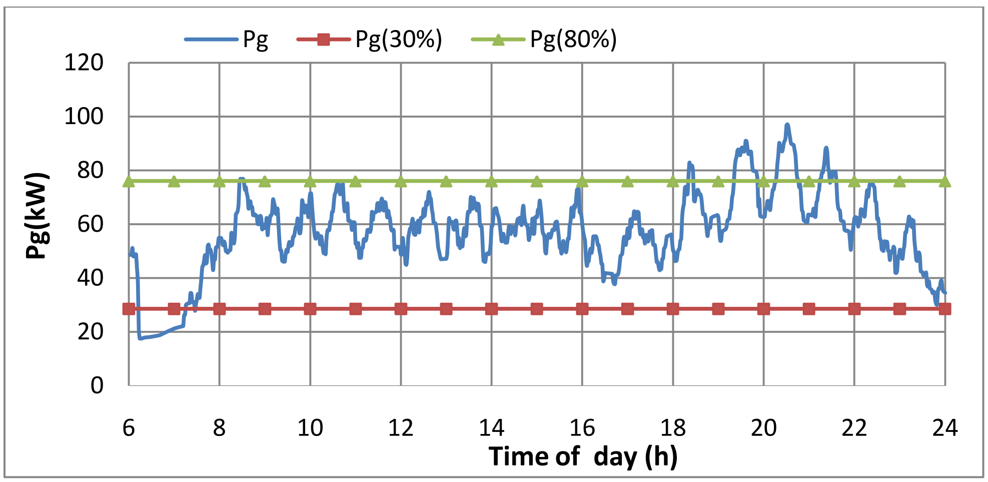

Figure 5-11: The output power of the diesel genset for Case 1

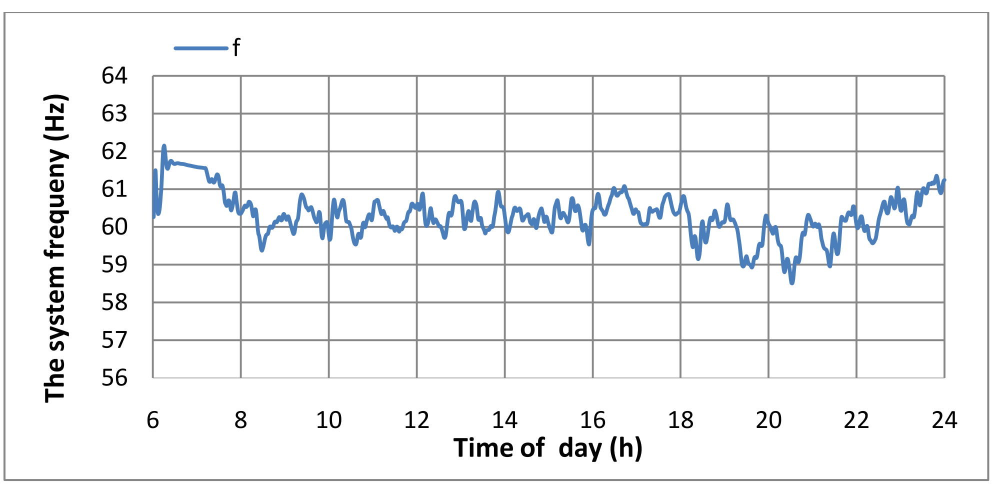

Figure 5-12: The system frequency for Case 1.

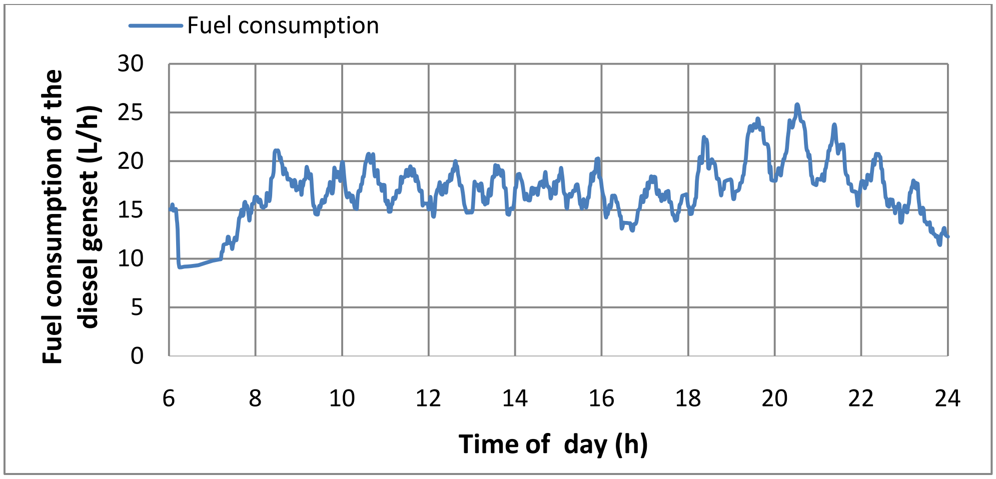

Figure 5-13: The fuel consumption of the diesel genset for Case 1

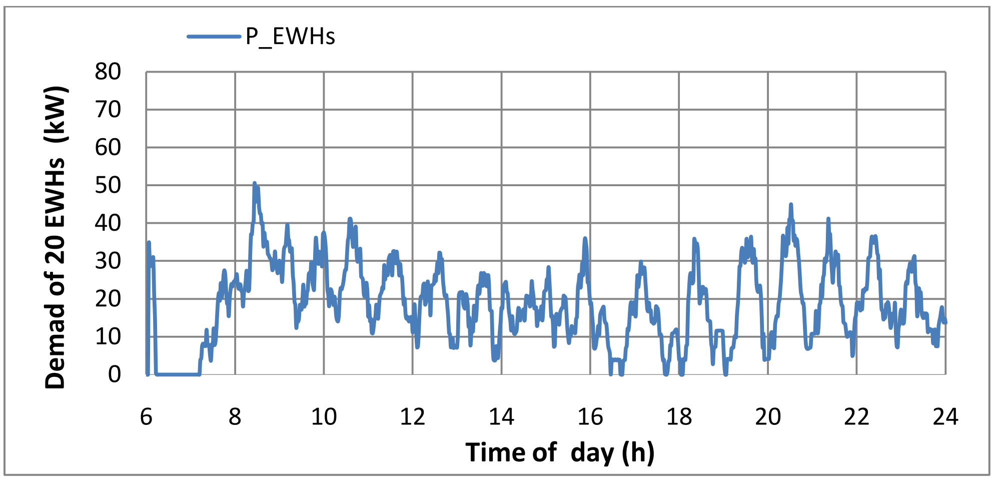

Figure 5-14: Demand of 20 EWHs for Case 1

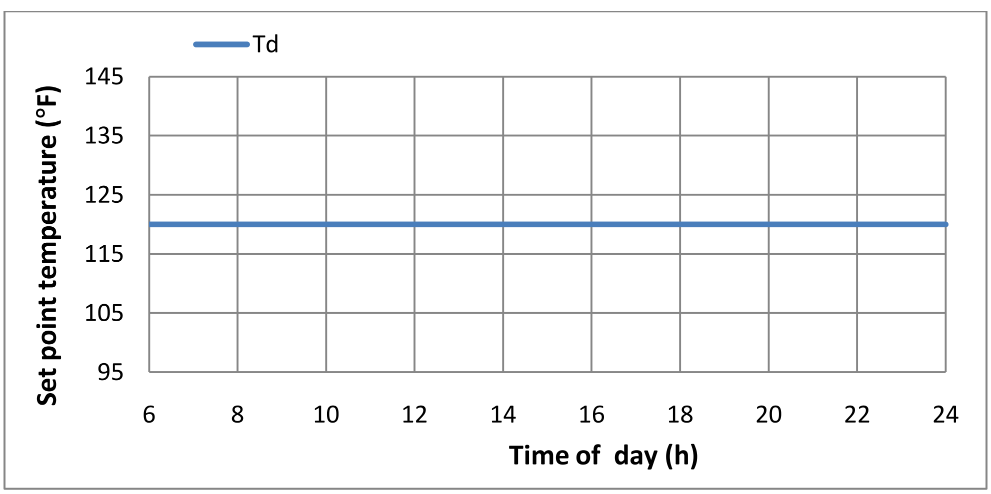

Figure 5-15: The set point temperature for Case 1

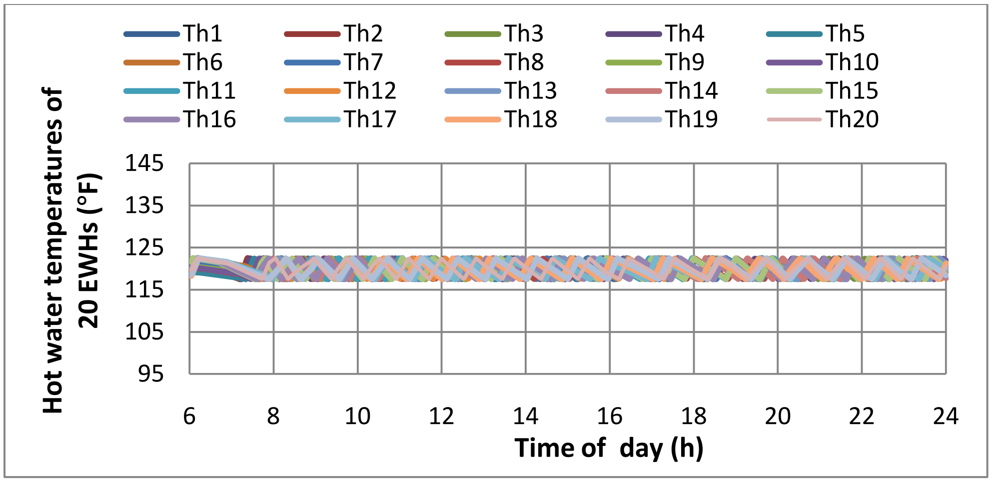

Figure 5-16: The hot water temperatures of 20 EWH for Case 1

Figure 5-11 shows that the diesel genset in the morning from 6 am to around 7:30 am works below 0.3 pu because the demand of the uncontrollable loads is low and the demand of the EWHs, also uncontrolled in this case, is low as well. After this time, the diesel genset works above 0.3 pu for the rest of the day. The peak demand of the diesel genset is quite high. It reaches approximately 97kW in the evening. Consequently, the system frequency is low at the peak period. The minimum demand from the diesel genset is approximately 17 kW and occurs in the morning around 6:30 am. The total energy supplied by the diesel genset and the total fuel consumption are approximately 1027kWh and 304L, respectively, for the time period from 6:00 am to midnight. The peak demand of 20 EWHs is around 50kW, and it occurs at the morning around 8 am. Since the integrated control is not activated, the hot water temperatures of the 20 EWHs remain between 117.5 to 122.5°F (47.5 to 50.28°C) and T_d remains constant at 120°F (48.89°C) for all EWHs.

Case 2: The PV systems supply power to the loads with the diesel genset and the integrated control of EWHs is still disabled. The output power of the diesel genset (which is equal to the demand of the mini-grid minus PV power), the system frequency, the PV of six PV panels, the fuel consumptions of the diesel genset, and the demands of 20 EWHs are shown in the figures below.

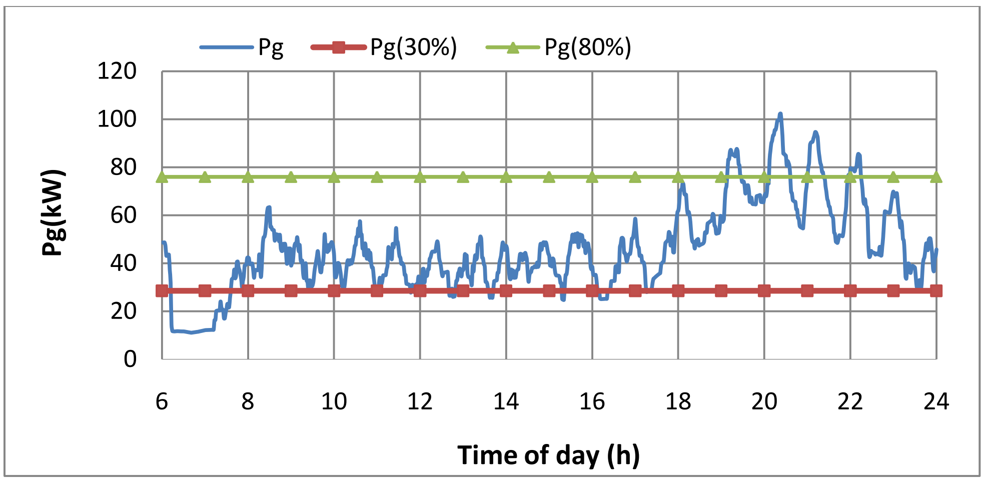

Figure 5-17: The output power of the diesel genset for Case 2.

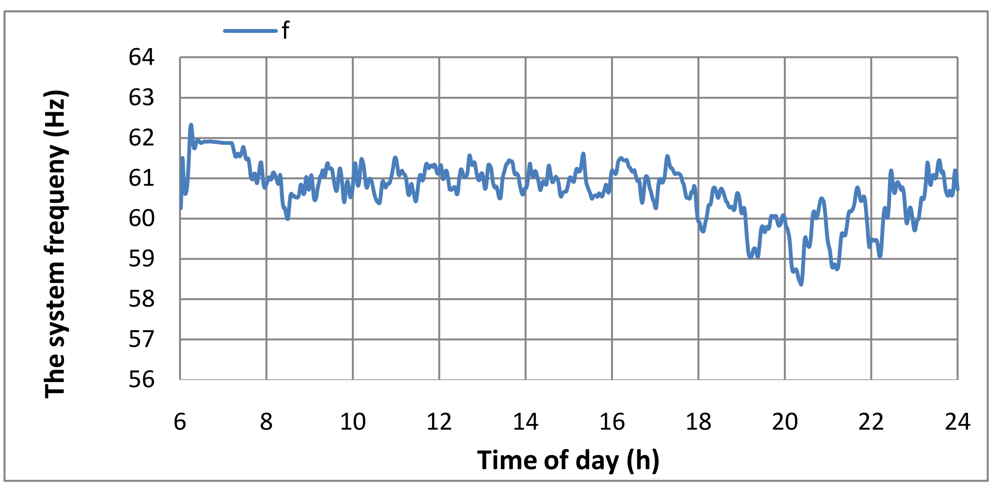

Figure 5-18: The system frequency for Case 2

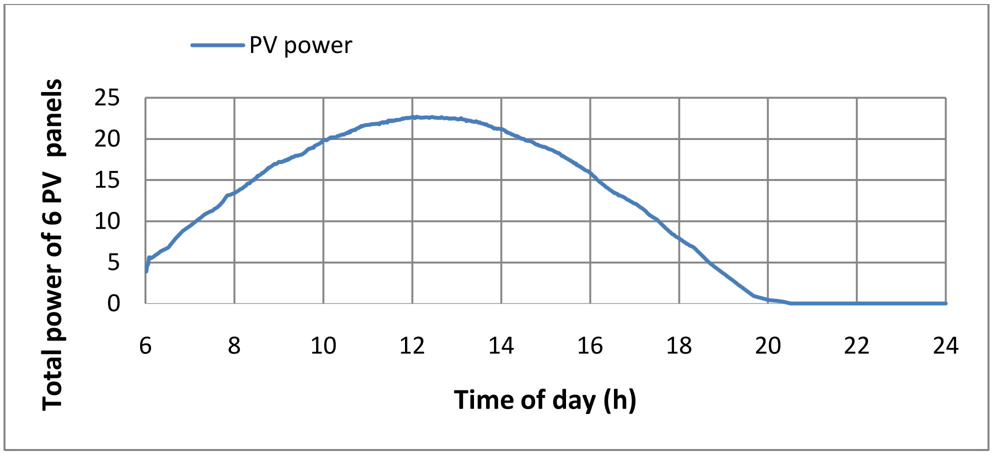

Figure 5-19: PV power of six PV panels

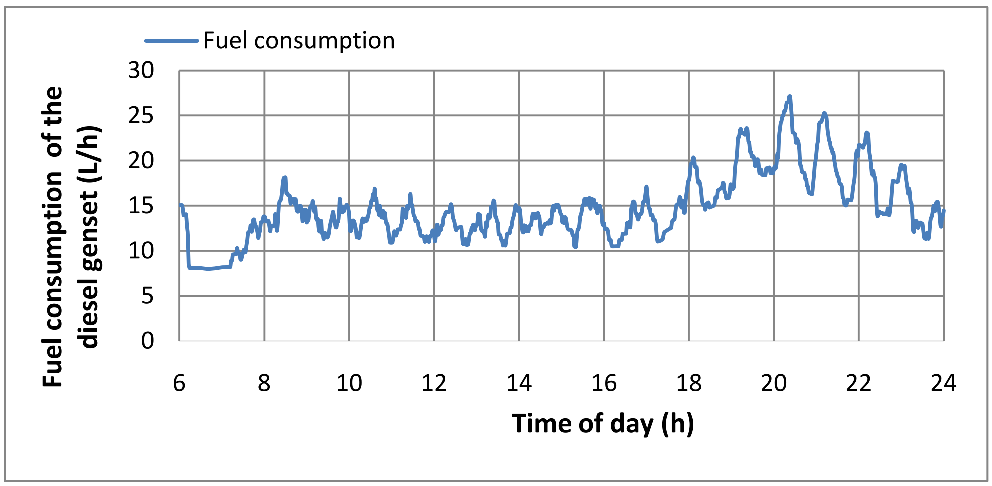

Figure 5-20: The fuel consumption of the diesel genset for Case 2

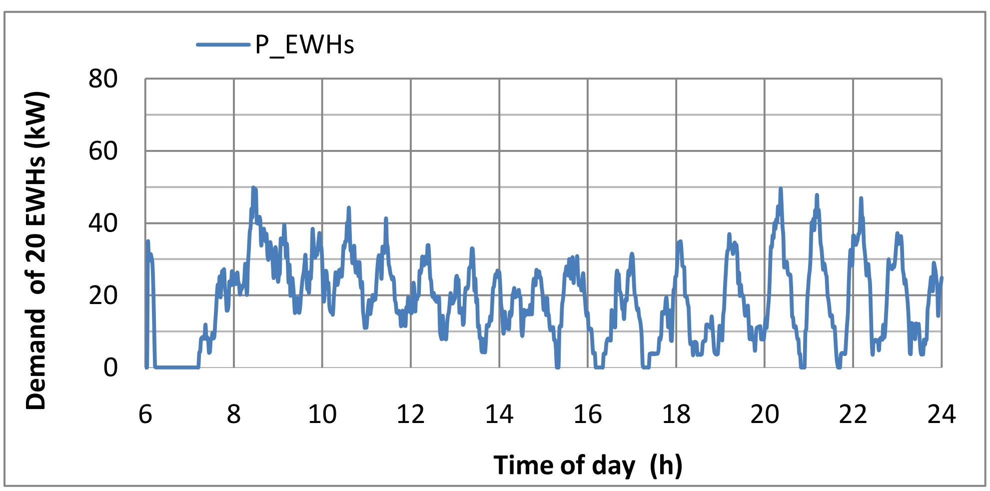

Figure 5-21: Demand of 20 EWHs for Case 1

Figure 5-17 shows that the diesel genset works below 0.3pu more than when the diesel genset supplies the power alone, which is due to the penetrations of the PV power. The results cause the diesel to work at low efficiency. Consequently, the system frequency is quite high. The peak demand from the diesel genset is slightly high compared with Case 1; it is approximately 102kW in the evening. This increase is due to the increase in the demand of 20 EWHs during the evening from 45kW in Case 1 to around 50kW in Case 2 as shown in Figure 5-21. The increase in the evening is due to the effect of PV power on the voltage variations during daytime, which affects the energy input to EWHs. Consequently, the number of EWHs with either ON or OFF operation mode will be different when compared with Case 1.

The minimum demand from the diesel genset is reduced to approximately 10 kW, which occurs in the morning around 6:30 am, and is also due to the penetration of PV power. The total energy supplied by the diesel genset and the total fuel consumption are around 828kWh and 264L, respectively, from 6:00 am to midnight. By connecting 6 PV panels and use a sunny PV profile, the PV panels supply 208kWh and decrease fuel consumption from 304L to 264L (40L), a reduction of almost 13.15%.

The penetration percentage of PV power can be calculated in this case as follows:

$$\text{Penetration percentage of PV(\%)} = \frac{\text{Energy produced by PV}}{\text{Energy produced by diesel} + \text{Energy produced by PV}}$$

$$\frac{208}{828+208} \times 100 == 20.077\% \qquad (5.2)$$

It expected that the fuel consumption reduction will be equal to the penetration percentage of PV. However, as the results show, the percentage of the reduction in fuel consumption is less than the penetration percentage of PV. The reason these percentages are not same or even approximately the same is that the fuel consumption rate (L/kWh) and efficiency of the diesel genset when the diesel genset works at low power are less than the fuel consumption rate and efficiency when the diesel genset works at high power.

The demands of 20 EWHs are almost the same as in Case 1. The peak demand of EWHs is around 50kW, and it occurs at the morning around 8 am. The hot water temperatures of the 20 EWHs remain the same as in Case 1 between 117.5°F to 122.5°F (47.5 to 50.28°C) and T_d is still constant at 120 °F (48.87°C).

Case 3: The PV systems supply the power to the loads when the diesel genset and the basic integrated control of EWHs are enabled. The basic integrated control works simply without any additional method. Initially, the basic integrated controls of 20 EWHs are not activated simultaneously at the beginning of the simulation time. There is a certain delay between them. By 7:30 am, all the integrated controls of the 20 EWHs are enabled, which is also valid for cases that use the modified integrated control. The purpose of Case 3 is to validate the previous explanation about the impact of the basic integrated control on the multiple EWHs.

The output power of the diesel genset, the system frequency, the fuel consumptions of the diesel genset, the demand of 20 EWHs, and hot water and set point temperatures are shown in the figures below.

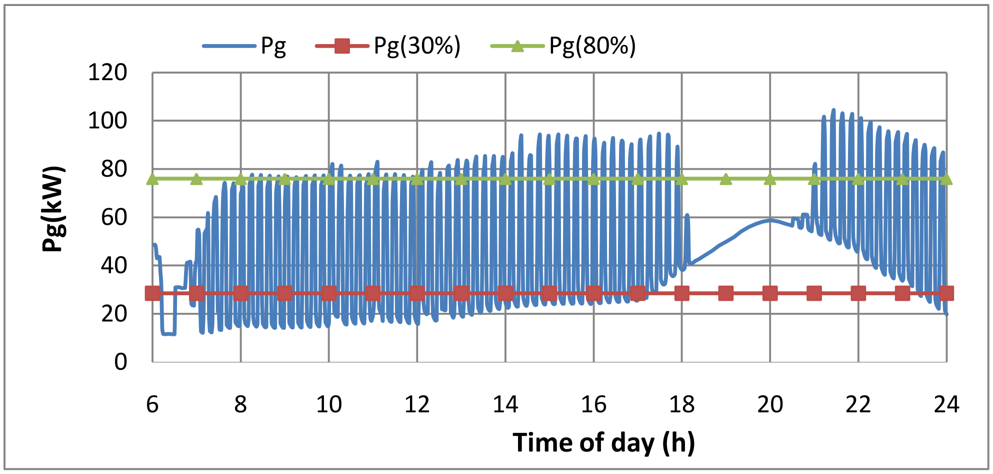

Figure 5-22: The output power of the diesel genset for Case 3

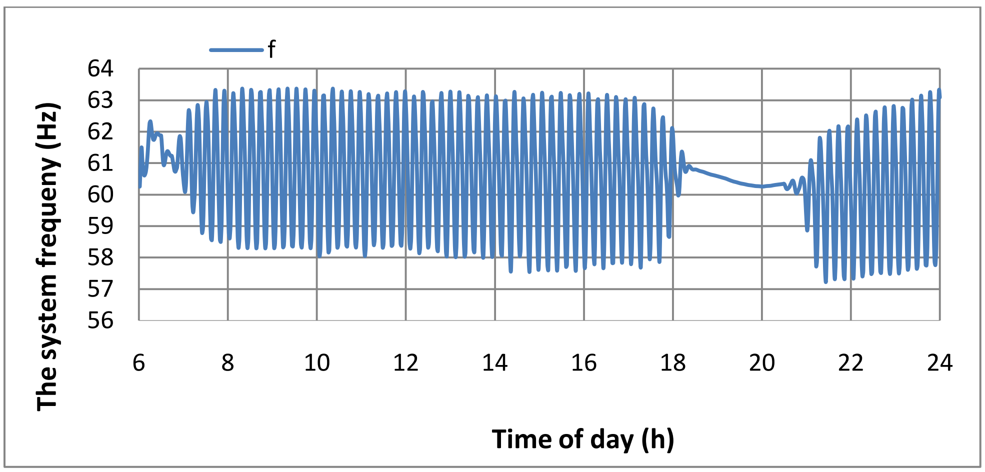

Figure 5-23: The system frequency for Case 3

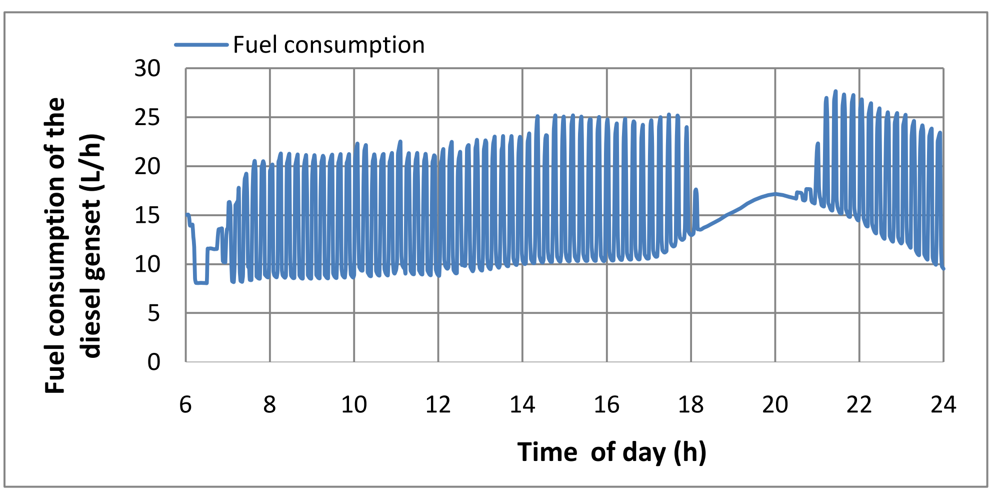

Figure 5-24: The fuel consumption of the diesel genset for Case 3

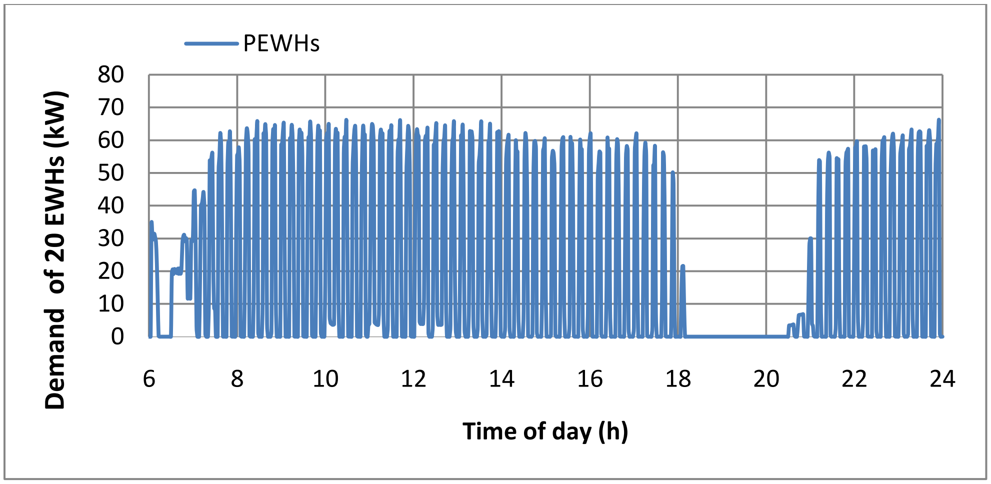

Figure 5-25: Demand of 20 EWHs for Case 3

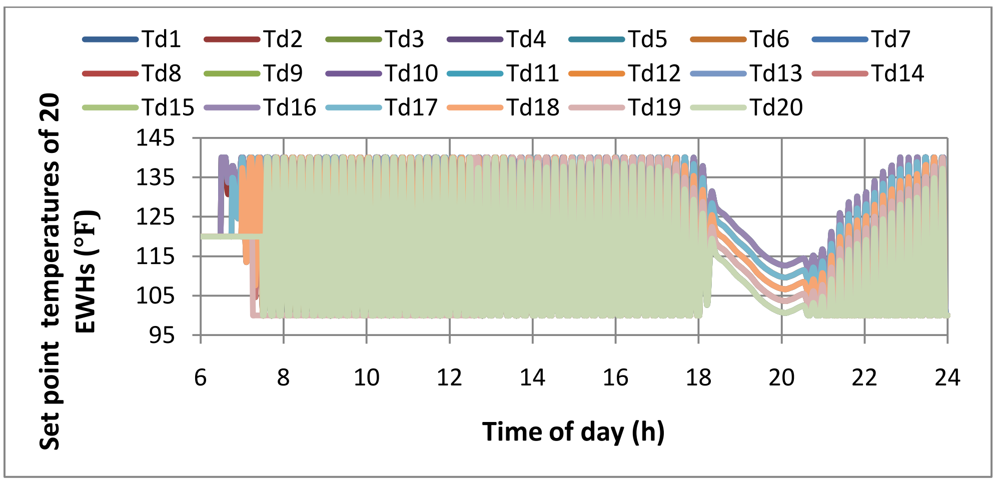

Figure 5-26: The set point temperatures of 20 EWHs for Case 3

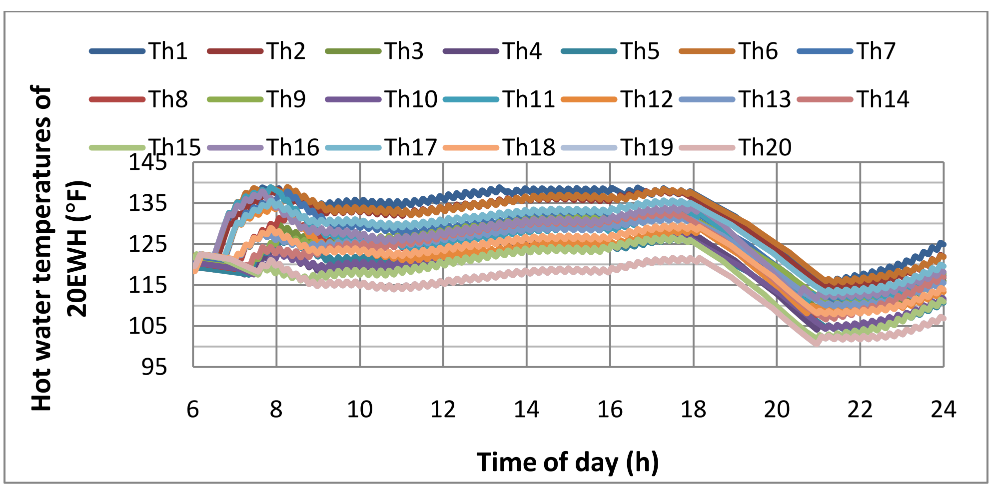

Figure 5-27: The hot water temperatures of 20 EWH for Case 3

The figures show that the basic integrated control of the EWHs makes them turn ON/OFF at the same time. Consequently, the power and frequency variations are significantly increased.

The above figures also show that during the period, 6:00 pm to 21:00 pm, all EWHs are OFF. Hot water temperatures of 20 EWHs increase and decrease frequently and this due to the increase and decrease of their T_d. However, the increase rate of T_H will be more than the decrease rate due to the effect of the input energy (Q) (see Chapter 3, section 3.4.4). When the uncontrollable load demand increases, the difference between the center frequency and the system frequency decreases, hence T_d will increase by a small rate. Thus, $T_d-\Delta$ of 20 EWHs will be always smaller than T_H of 20 EWHs. This situation continues until the uncontrollable load demand starts to decrease, and the T_H value becomes equal or smaller than $T_d-\Delta$.

Case 4: The PV systems supply the power to the loads with the diesel genset and the modified integrated control of EWHs are enabled. In this case, the control of the EWHs works with the additional activation conditions to avoid the problem of Case 3 and to improve the results of Case 1 and Case 2.

The output power of the diesel genset, the system frequency, the fuel consumptions of the diesel genset, the demand of 20 EWHs, and hot water and set point temperatures are shown in the figures below.

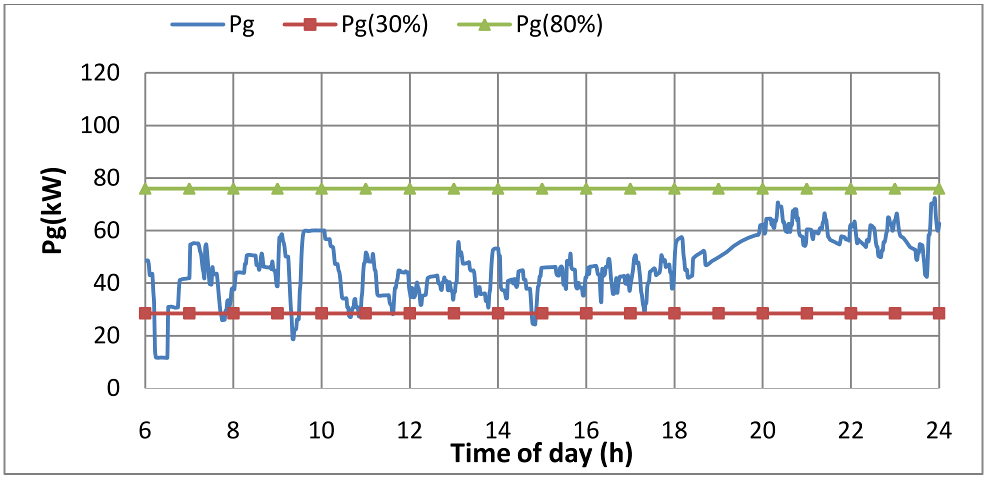

Figure 5-28: The output power of the diesel genset at Case 4

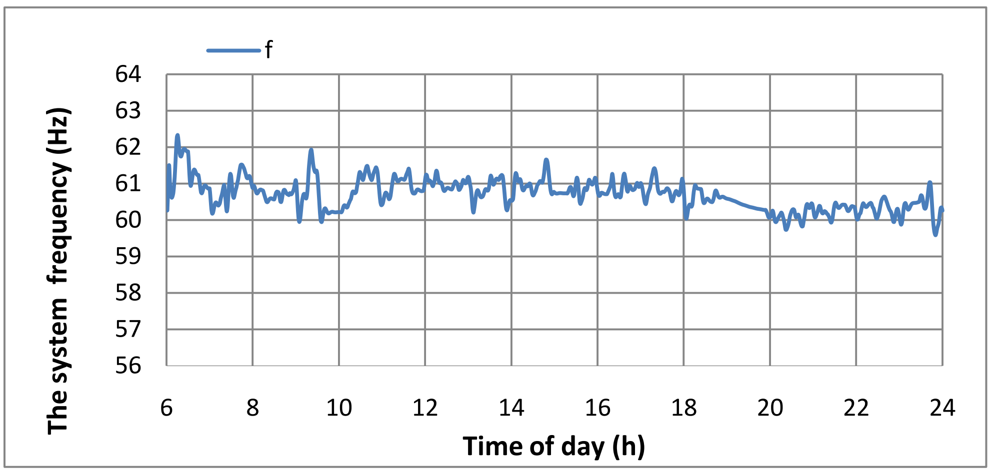

Figure 5-29: The system frequency for Case 4

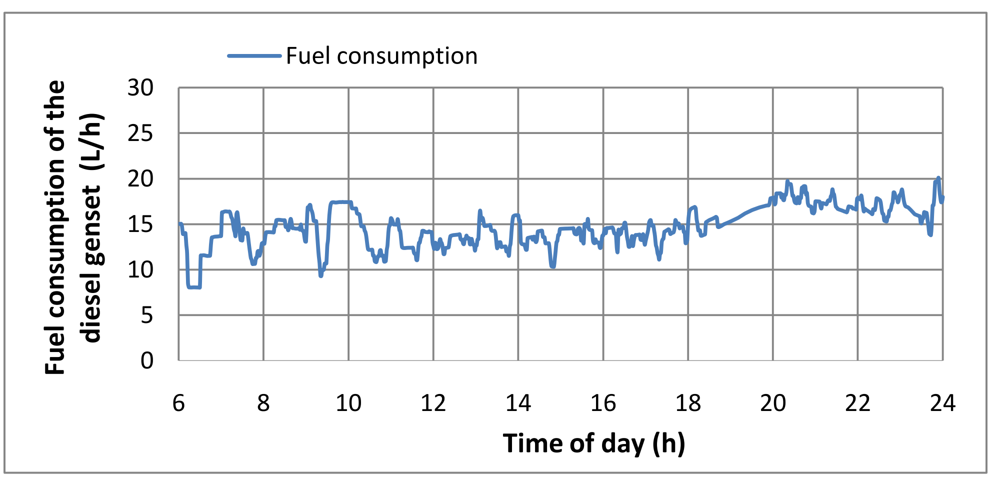

Figure 5-30: The fuel consumption of the diesel genset for Case 4

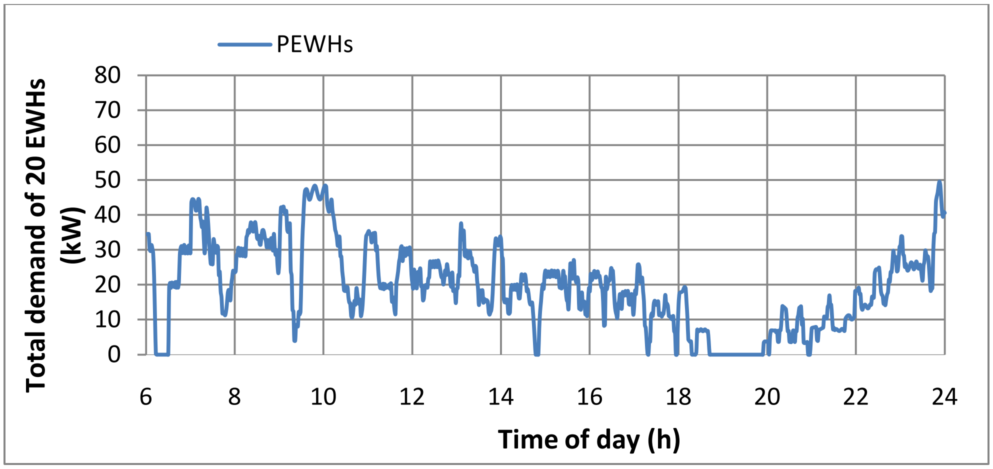

Figure 5-31: The demand of EWHs for Case 4

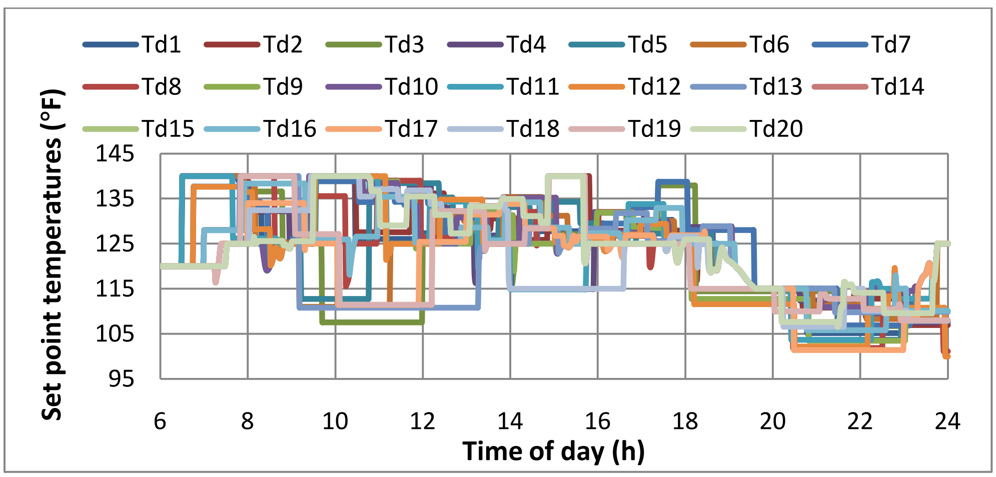

Figure 5-32: Set point temperature of 20 EWHs for Case 4

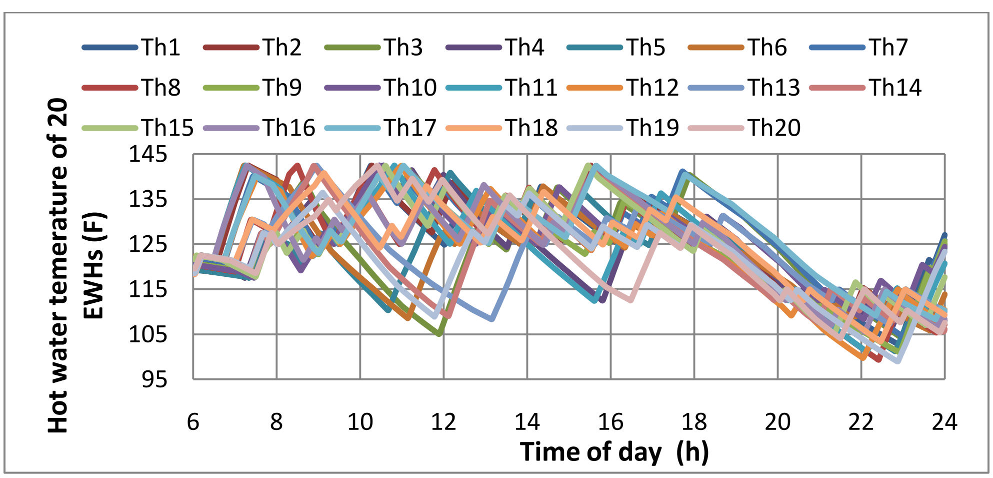

Figure 5-33: Hot water temperature of 20 EWHs for Case 4

The above figures show that using the modified integrated control improves the results. Figure 5-28 shows that the diesel genset works above 30% of its rated power. The diesel genset works below this value only twice in the morning and once in the afternoon. The peak demand from the diesel genset decreases to around 70kW. The minimum demand from the diesel genset is around 11 kW and occurs in the morning around 6:30 am. The reason that the minimum demand almost the same as in Case 2 and Case 3 is because of the limitation of the EWHs control when *Wd* is low. It is also due to the delay time that is used between the integrated controls of EWHs at the beginning of the simulation time that mention in Case 3.

In this case, the total energy supplied by the diesel genset and total fuel consumption is approximately, 845kWh and 265L, respectively, from 6:00am to midnight. The basic integrated control increases fuel consumption by 1L compared with the Case 2, when PV is used. Figure 5-29 shows that the system frequency varies less than in the previous cases.

Figure 5-31 shows that the peak demand of EWHs is around 48kW. The integrated control makes many of the EWHs OFF during the peak period. Since the modified integrated control is used, the hot water temperatures of the 20 EWHs vary between 97.5°F to 142.5°F. T_d varies between 100 to 140 °F (37.78 to 60°C).

Case 5: The diesel genset supplies power to the mini-grid alone and the modified integrated control of EWHs is enabled. There are no PV systems and EWHs are controlled based on the system frequency (modified integrated).

The output power of the diesel genset (which is equal to the demand of the mini-grid), the system frequency, the fuel consumptions of the diesel genset, the demand of 20 EWHs, and the hot water and set point temperatures are shown in the figures below.

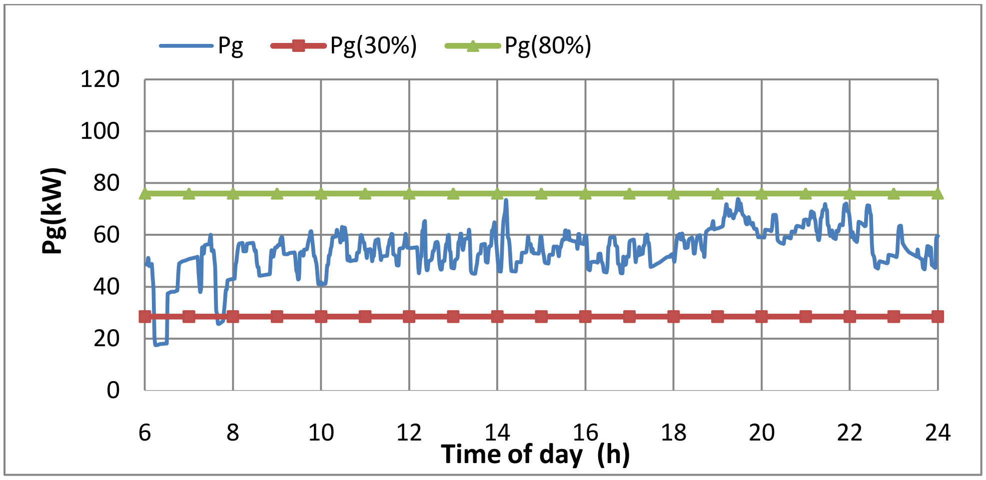

Figure 5-34: The output power of the diesel genset at Case 5

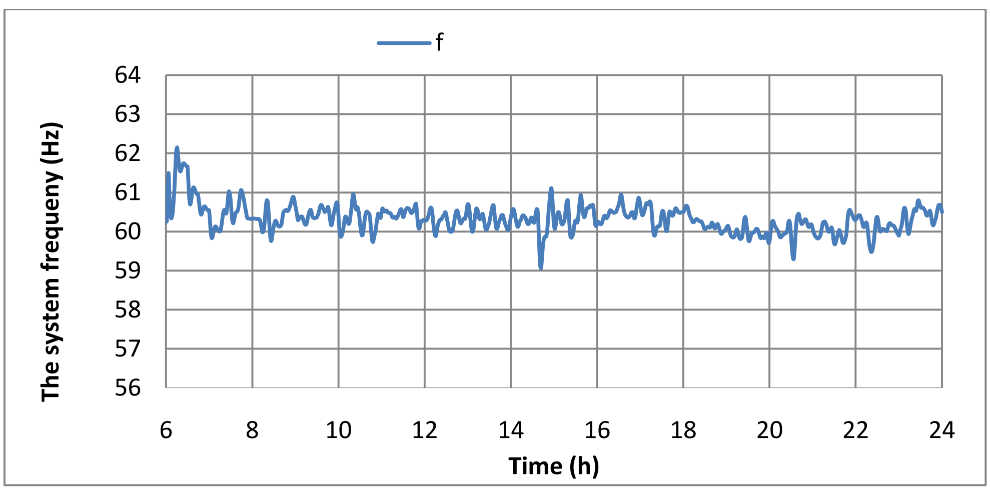

Figure 5-35: The system frequency for Case 5

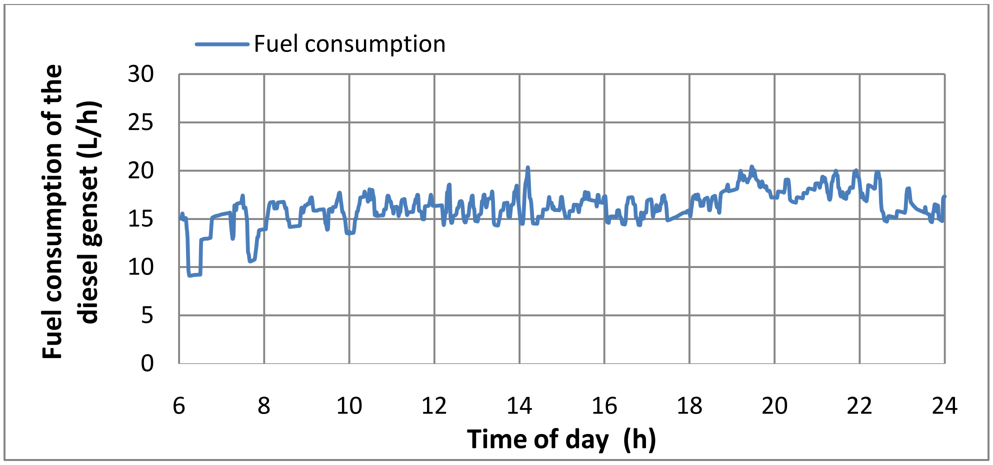

Figure 5-36: The fuel consumption of the diesel genset for Case 5

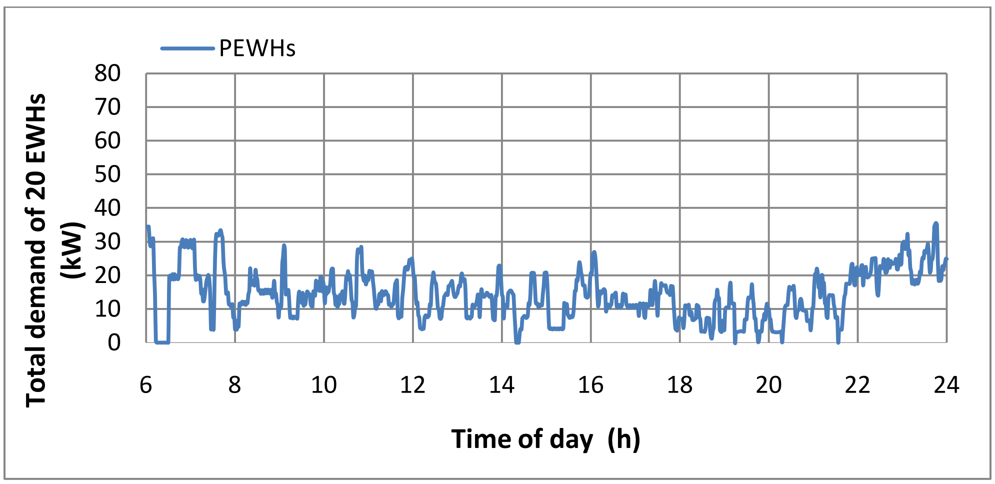

Figure 5-37 The total demand of EWHs for Case 5

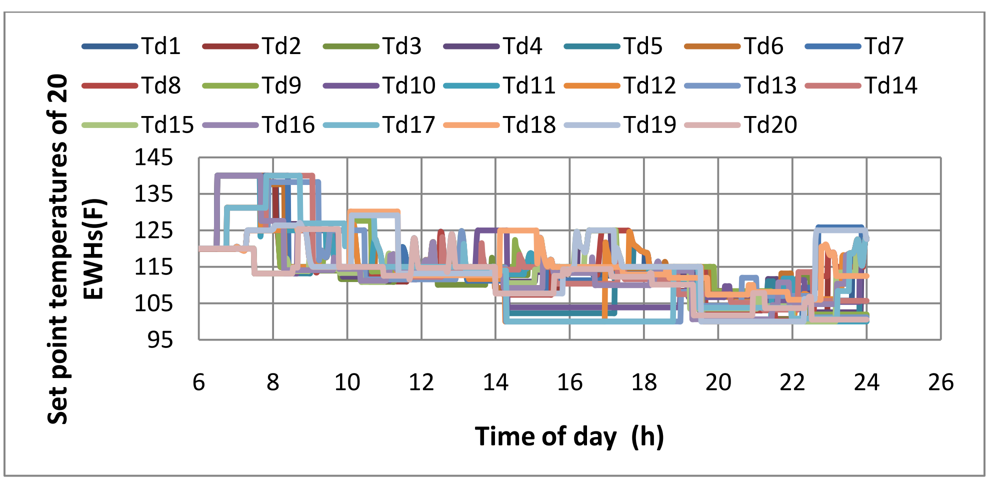

Figure 5-38: Set point temperatures for signal EWHs for Case 5

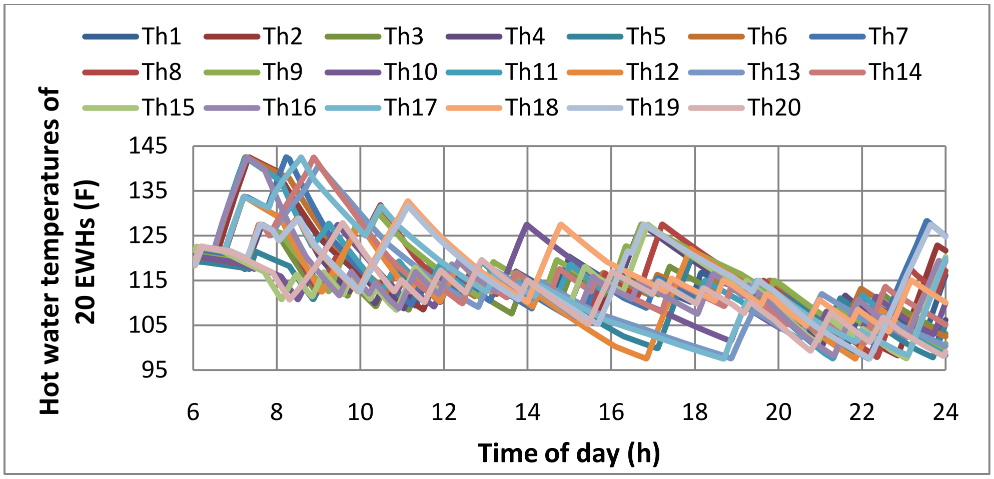

Figure 5-39: Hot water temperature of 20 EWHs for Case 4

The above figures show that the modified integrated control improves the results in terms of peak load period. The genset works below 30 % of its rated capacity only twice in the morning as shown in Figure 5-34. As a result, the system frequency is kept within a small range. In terms of total energy consumption, the genset in Case 5 supplies less energy compared with Case1, without control and no PV systems. Consequently, the total fuel consumption decreases as well.

In this case, the total energy supplied by the diesel genset and total fuel consumption is approximately, 976kWh and 292L, respectively, from 6:00 am to midnight. The modified integrated control decreases the fuel consumption by 12L compared with Case 1 without control and no PV systems). In this case, the fuel consumption decreases because of the effect of the modified control in the peak load shaving. The peak demand from the diesel genset decreases to around 73kW.

Figure 5-37 shows that the peak demand of EWHs is approximately 39kW. The modified integrated control reduces the numbers of EWHs that are ON during the peak period. Since the modified integrated control is used, the hot water temperatures of the 20 EWHs vary between 97.5°F to 142.5°F. T_d varies between 100 to 140°F (37.78 to 60°C).

5.6 Summary of the Results

The purpose of this section is to give a summary of the simulation results to determine the gains from using the modified integrated control and PV power in terms of frequency, power variations, and fuel consumption. The results are summarized in Table 5-3.

Table 5-3: Summary of the main results obtained from the simulated cases

	Case 1	Case 2	Case 3	Case 4	Case 5
Average frequency (Hz)	60.30836	60.70827	60.59087	60.6956	60.42723
Max. Frequency (Hz)	62.15038	62.3315	63.37288	62.3315	62.15038
Mini. Frequency (Hz)	58.50196	58.35954	57.24161	59.57844	59.54829
Standard deviation	0.58469	0.698857	1.610082	0.419226	0.356685
Energy from diesel (kWh)	1027.91	828.629	864.619	843.155	976.193
Fuel Consumption (L)	304.29	264.054	273.653	265.438	292.405
PV Energy (kWh)	0	208.414	208.414	208.414	0
Energy consumption of 20 EWHs	337.299	340.063	350.521	352.622	285.079

Table 5-3 shows that the standard deviation of the system frequency is increased by 19% when there are PV systems and there is no EWHs control (Case 2). When the basic integrated control of EWHs is used, the standard deviation is increased by a large amount because of the oscillations that occur as a result of turning ON/OFF the EWHs simultaneously. In Case 4, which uses both the modified integrated control and PV systems, the standard deviation is decreased by around 40% compared with Case 2 with PV systems and no control. Finally, with modified control and no PV systems (Case 5), the standard deviation is decreased by around 39% compared with the Case 1 with no PV and no control.

Table 5-3 shows that the average system frequency is not affected much by using the control of EWHs, but it is affected by PV power. When there are PV systems and no EWHs controls (Case 2), the average system frequency is increased by 0.78% compared with the base Case 1 without PV systems. In Case 4, which uses the modified integrated control and PV systems, the average system frequency is decreased by 0.02% compared with Case 2 with PV systems and no EWHs control. In Case 5, which uses the modified control and no PV systems, the average system frequency is increased by 0.19% compared with the base Case 1 with no PV systems and no EWHs control.

In addition, Table 5-3 shows the energy produced by the diesel genset, the energy produced by PV systems, the energy consumption by 20 EWHs, and finally the fuel consumption of the diesel genset for the period from 6:00 am to midnight (18h). The energy consumption from the diesel genset and the fuel consumption, when there are PV systems and no EWHs control (Case 2), are decreased by 19.38% and 13 %, respectively, compared with the base Case 1. In Case 4, which uses the modified integrated control and PV systems, the energy consumption of the diesel genset and the fuel consumption are increased by 1.75% % and 0.524 %, respectively, compared with Case 2 with PV systems and no EWHs control. In Case 5, which uses the modified control and no PV systems, the energy consumption of the diesel genset and the fuel consumption are decreased by 5%

and 3.9%, respectively, compared with the base Case 1 with no PV systems and no EWHs control.

Another important result shows by how much time the diesel genset works below 30% and above 80% of its power rating. Figure 5-40 shows the total time that the diesel genset is below 30% and above 80% in each simulation case.

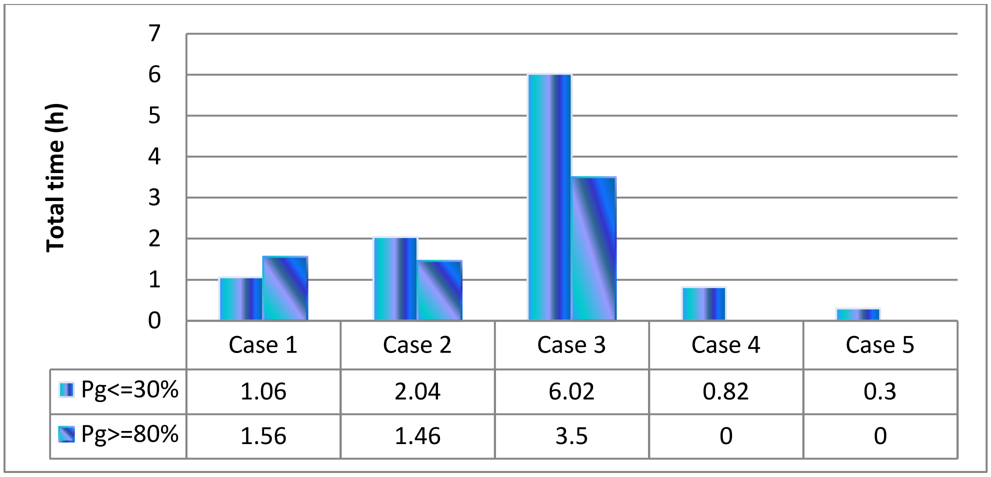

Figure 5-40: Total time that diesel genset being below 30% and above 80% in each simulation case

Figure 5-40 shows that the diesel genset works more often below 30 % when there are PV systems compared with cases without PV systems and without EWHs control. The diesel genset works for two hours below 30%. In the operation above 80%, the situation does not change much for Case 2 compared with Case 1. In Case 4, which uses the modified integrated control and PV systems, the diesel genset works for less time below 30%. It works for almost 0.82 h (49.2 minutes) in a different time period. Moreover, the diesel genset does not work above 80% in Case 4. Finally, in Case 5, which uses the modified integrated control without PV systems, the diesel genset works only 0.3 h (18 minutes) below 30% and does not work above 80%.

CHAPTER 6
CONCLUSIONS AND FUTURE WORK

6.1 Summary

Remote communities are usually not connected to the main electricity grid or to natural gas networks. They often rely on diesel generators for producing electricity at high prices. Several renewable energy sources (RESs) such as photovoltaic (PV) and wind could be cost effective to meet part of the energy needs. However, RESs are considered fluctuating and intermittent power sources. In addition, the demand on the mini-grid varies significantly with the time of day. Traditionally, energy storage devices have been used to provide power smoothing and frequency regulations, but this solution is quite costly.

This thesis focused on an alternative solution, the DSM approach, to assist frequency regulation and to make the genset operate at the desired region. Electric water heaters (EWHs) were found to be good candidates for this approach because of their power ratings and intrinsic thermal energy storage capabilities.

In order to design proper controls for EWHs, the generation's side and demand side characteristics were investigated. The droop control and the recommended operation region of a diesel genset were defined. Based on the fuel consumption rate and diesel fuel efficiency, this recommended operation region was from 30 to 80%. In addition to the diesel genset, the characteristics and behaviour of PV power were studied.

EWH parameters and behaviour were discussed in depth. A EWH was modeled in Matlab/SIMULINK, and a typical 24-hour water draw profile was used to observe the power consumption of the EWH. Analytical equations were derived and used for estimating how much power a EWH can take or drop during each hour of the day by varying the set point temperature (T_d). The key parameters of EWH that affect the operation were identified. It was found that the power consumed by EWH is strongly related to the set point temperature (T_d) and to the hot water draw (W_d). The first parameter was a good choice for control purposes while the second was considered a disturbance parameter.

The methods to control EWH in terms of DSM were reviewed. Two types of controls have been used in the literature: external control and integrated control (control set point temperature by using the system frequency). This thesis focused on the latter. The design consideration of the integrated control and its parameters were studied. It was demonstrated that the design considerations in the basic integrated control of EWH are different in case of a small power system (mini-grid) compared with the more common case of a large interconnected system.

The impact of using the basic integrated control on the system frequency when multiples EWHs are used was investigated. It was found that using the basic integrated control in case of large variations in the load demand from the diesel genset produced large variations in the system frequency, causing the EWHs to turn ON/OFF simultaneously. Hence, a modified integrated control was proposed as solution for issues associated with the basic integrated control, which was based on adding activation conditions that consider T_H and the operation mode of the EWH to control the state of the integrated control (either enable or disable).

The performances of the basic and modified integrated controls were investigated by using a hybrid PV-diesel mini-grid benchmark. A brief explanation of the hybrid mini-grid benchmark that implemented in PSCAD software and its components was presented.

Five different cases were considered: Case 1, only diesel genset; Case 2, PV systems and the diesel genset without using EWHs control; Case 3, PV systems, the diesel genset and the basic integrated control of EWH: Case 4, PV systems, the diesel genset and the modified integrated control of EWH; and Case 5, the diesel genset and the modified integrated control of EWH without PV systems. The simulation results of those five cases were presented and discussed.

It was found that using PV systems decreases the fuel consumption of the diesel genset by 13%; however, it increases the frequency and power variation in terms of standard deviation by approximately 20%. The results also demonstrated that the basic integrated control, without additional activation conditions, increases the frequency and power variation, which is because the T_d of 20 EWHs increases and decreases by large values.

In addition, the simulation results indicated that the modified integrated control helped to reduce the frequency and power variation in both cases—with PV systems or without PV systems. Although the proposed modified integrated control did not reduce the fuel consumption with the PV systems, it kept the fuel consumption almost the same compared with the cases without the control. It was also found that the modified integrated control reduced the fuel consumption in the cases without PV systems. Finally, the modified integrated control reduced the peak loads and significantly reduced the amount of time that the genset operated below 30% or above 80%.

6.1 Future Work

Future work suggestions related to this study are as follow.

6.2.1 The Impact of Using High Variable PV Power Profile on the Performance of the modified Integrated Control

As shown in the PV power profile used in this study, the PV power varies smoothly with time. This is due to the assumption that the profile is for a typically sunny day. In reality, the weather can be cloudy for part of the day or the whole day. If this is the case, the power produced by the PV system will vary significantly. Consequently, the system frequency will vary by large values. Therefore, it is very important to find a method to compensate for these variations. The modified integrated control in this situation can be a good solution.

6.2.2 Implement the Modified Integrated Control of EWHs in Wind-Diesel Hybrid

Wind power (WP) is a clean source of electricity in many places around the world. However, WP, like PV power, is considered a fluctuating and non-dispatchable source that can cause disturbances in hybrid power systems. The issue of power variation due to meteorological effects is even bigger for wind systems, since PW varies with the cube of the wind speed. Therefore, further research is recommended to implement the modified integrated control of EWHs to compensate for the power variation in wind power and to assist with frequency regulation.

6.2.3 Develop control strategy to vary the input power of the EWH with the modified integrated control of EWH

The rated power of the heating element P_{rated}, has an enormous effect in periods that EWH is ON, t_{on}. When P_{rated} is high, the EWH element will heat the water in a short time, particularly when Wd is low. Increasing T_d by means of the modified integrated control is limited to increasing t_{on} by large value when Wd is low. If the input power of the EWH is controlled by using either voltage control strategies or multi-resistance elements of the EWH, and T_d is controlled by using the modified integrated control, the EWH could be ON for a sufficient length of time. This method may assist the frequency regulation and give better results.

REFERENCES

[1] D. S. Prull, "Design and integration of an isolated microgrid with a high penetration of renewable generation," Ph.D. dissertation, University of California, Berkeley, 2008.

[2] A. B. Kanase-Patil, R. P. Saini, and M. P. Sharma, "Integrated renewable energy systems for off grid rural electrification of remote area," *Renewable Energy,* vol. 35, no. 6, pp. 1342-1349, 2010.

[3] S. Henderson, "Renewable Energy and Off-Grid Housing in the Yukon Baseline Report," CANMET Energy Technology Centre Varennes, March 2005.

[4] C. V. Nayar, "High Renewable Energy Penetration Micro-Grid Power System using a Variable Speed Constant Frequency Generator," in *Paths to Sustainable Energy*, A. W. N. Jatin Nathwani, Ed., ed Rijeka, Croatia: InTech, 2010, pp. 511-536.

[5] H. S. Jacobus, "Solar-Diesel Hybrid Power System Optimization and Experimental Validation," M.S. thesis, University of Maryland, Maryland, 2010.

[6] M. Tokudome, K. Tanaka, T. Senjyu, A. Yona, T. Funabashi, and K. Chul-Hwan, "Frequency and voltage control of small power systems by decentralized controllable loads," in *International Conference on Power Electronics and Drive Systems (PEDS)* 2009, pp. 666-671.

[7] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "Microgrids," *IEEE Power and Energy Magazine,* vol. 5, no. 4, pp. 78-94, 2007.

[8] J. P. Barton and D. G. Infield, "Energy storage and its use with intermittent renewable energy," *IEEE Transactions on Energy Conversion and Management,* vol. 19, no. 2, pp. 441-448, 2004.

[9] J. Kondoh, I. Ishii, H. Yamaguchi, A. Murata, K. Otani, K. Sakuta, N. Higuchi, S. Sekine, and M. Kamimoto, "Electrical energy storage systems for energy networks," *Energy Conversion and Management,* vol. 41, no. 17, pp. 1863-1874, 2000.

[10] F. Katiraei and C. Abbey, "Diesel Plant Sizing and Performance Analysis of a Remote Wind-Diesel Microgrid," in *IEEE Power Engineering Society General Meeting*, 2007, pp. 1-8.

[11] A. A. Sallam and O. P. Malik, *Electric distribution systems*. Hoboken, N.J.: Wiley-IEEE Press, 2010.

[12] M. E. Jun Hong B.Eng., "The Development, Implementation, and Application of Demand Side Management and control (DSM+c) Algorithm for Integrating Microgeneration System within Built Environment " Ph.D. dissertation, University of Strathclyde, Glasgow, 2009.

[13] R. G. Pratt, C. C. Conner, E. E. Richman, K. G. Ritland, W. F. Sandusky, and M. E. Taylor. "Description of Electric Energy Use in Single Family Residences in the Pacific Northwest", DOE/BP -13795-21, Bonneville Power Administration, Portland, Oregon, 1989.

[14] J. W. Black and M. Ilic, "Demand-based frequency control for distributed generation," in *IEEE Power Engineering Society Summer Meeting*, 2002, pp. 427-432

[15] L. Paull, D. MacKay, H. Li, and C. Liuchen, "Awater heater model for increased power system efficiency," in *Electrical and Computer Engineering Canadian Conference* 2009, pp. 731-734.

[16] A. Sepulveda, L. Paull, W. G. Morsi, H. Li, C. P. Diduch, and C. Liuchen, "A novel demand side management program using water heaters and particle swarm optimization," in *IEEE Electric Power and Energy Conference (EPEC)* 2010, pp. 1-5.

[17] M. R. Dehbozorgi, "Improving electrical power systems reliability through locally controlled distributed curtailable load," Ph.D. thesis, The University of New Brunswick, Canada, 2000.

[18] F. Katiraei, D. Turcotte, A. Swingler, and J. Ayoub, " Modeling and Dynamic Analysis of a Medium Penetration PV-Diesel Mini-Grid System " in *Proceedings of 4th European Conference on PV-Hybrid and Mini-Grid*, Greece May 29-30, 2008.

[19] V. Friedel, "Modeling and Simulation of a Remote Wind/Diesel Micro-Grid," M.S. thesis, Royal Institute of Technology, Stockholm, 2009.

[20] S. Krishnamurthy, T. M. Jahns, and R. H. Lasseter, "The operation of diesel gensets in a CERTS microgrid," in *IEEE Power and Energy Society General Meeting -Conversion and Delivery of Electrical Energy in the 21st Century*, 2008, pp. 1-8.

[21] A. M. Bollman, "An experimental study of frequency droop control in a low-inertia microgrid " M.S. thesis, Electrical and Computer Engineering University of Illinois, Urbana Champaign, 2009.

[22] ISO 8528-5:2005, Reciprocating internal combustion engine driven alternating current generating sets - Part 5: Generating sets

[23] R. Tonkoski, L. A. C. Lopes, and D. Turcotte, "Active power curtailment of PV inverters in diesel hybrid mini-grids," in *IEE Electrical Power & Energy Conference (EPEC)*, Montreal, 2009, pp. 1-6.

[24] W. Koczara, G. Iwanski, B. Kaminski, M. Cirstea, and N. Brown, "Power distribution in RES-Diesel autonomous power system with doubly fed induction generator for reduction of fuel consumption," in *11th International Conference on Optimization of Electrical and Electronic Equipmen*, 2008, pp. 339-344.

[25] R. J. J. B. Malosh, and S. Bubendorf, "Part-Load Economy of Diesel- Electric Generators," State of Alaska - Department of Transportation and Public Facilities, Fairbanks, 1985.

[26] *Diesel consumption chart* Available: http://www.generatorjoe.net/html/fueluse.html

[27] Tom Lambert , Hommar software user manual, 2004.

[28] R. Messenger and J. Ventre, *Photovoltaic Systems Engineering*, 3rd ed. Boca Raton, FL: CRC Press/Taylor & Francis, 2010.

[29] T. Yun Tiam, D. S. Kirschen, and N. Jenkins, "A model of PV generation suitable for stability analysis," *IEEE Transactions on Energy Conversion and Management,* vol. 19, no. 4, pp. 748-755, 2004.

[30] A. Durgadevi, S. Arulselvi, and S. P. Natarajan, "Study and implementation of Maximum Power Point Tracking (MPPT) algorithm for Photovoltaic systems," in *1st International Conference on Electrical Energy Systems (ICEES)* 2011, pp. 240-245.

[31] J. Yuncong, J. A. A. Qahouq, and I. Batarseh, "Improved solar PV cell Matlab simulation model and comparison," in *Proceedings of IEEE International Symposium on Circuits and Systems (ISCAS)* 2010, pp. 2770-2773.

[32] N. R. Canada. (2009-April-20th). *Water Heaters: Energy Considerations.* . Available: http://oee.nrcan.gc.ca/residential/personal/water-heater-oil-electric.cfm?attr=4#electric

[33] J. Lutz, C. D. Whitehead, A. Lekov, G. Rosenquist, and D. Winiarski, "WHAM: A Simplified Energy Consumption Equation for Water Heaters," in *1998 ACEEE Summer Study on Energy Efficiency in Buildings*, Asilomar, CA, 1998, pp. 171-183.

[34] G. van Harmelen and G. J. Delport, "Multi-level expert-modelling for the evaluation of hot water load management opportunities in South Africa," *IEEE Transactions on Power Systems* vol. 14, no. 4, pp. 1306-1311, 1999.

[35] M. W. Gustafson, J. S. Baylor, and G. Epstein, "Direct water heater load control-estimating program effectiveness using an engineering model," *IEEE Transactions on Power Systems* vol. 8, no. 1, pp. 137-143, 1993.

[36] J. C. van Tonder and I. E. Lane, "A load model to support demand management decisions on domestic storage water heater control strategy," *IEEE Transactions on Power Systems* vol. 11, no. 4, pp. 1844-1849, 1996.

[37] M.E. Taylor, K.G. Ritland, R.G. Pratt, Hot water energy use in single-family residences in the Pacific Northwest: regional end-use metering project REMP., Office of Energy Resources, Bonneville Power Administration, Portland, OR, DOErBP-13795-27, 1991.

[38] J. Delport, "Achieving Energy Efficiency for Hot Water Cylinders (Geysers) with the New Dual Element System," in *the 14th Domestic Use of Energy Conference*, Cape Tow, 2006, pp. 57 - 62.

[39] A. Kerim Kar and Ü. Kar, "Optimum design and selection of residential storage-type electric water heaters for energy conservation," *Energy Conversion and Management,* vol. 37, no. 9, pp. 1445-1452, 1996.

[40] K. Elamari, L. A. C. Lopes, and R. Tonkoski, "Using Electric Water Heaters(EWHs) for Power Balancing and Frequency Control in PV-Diesel Hybrid Mini- Grids," in World Renewable Energy Congress 2011 Linköping, 2011.

[41] U.S. Department of Energy (1998), Office of Energy Efficiency and Renewable Energy, 10 CFR Part 430, Energy Conservation Program for Consumer Products: Test Procedure for Water Heaters; Final Rule (1998). Federal Register 63(90): 25995-26016 (May 11, 1998).

[42] C. H. K. Goh and J. Apt, "Consumer Strategies for Controlling Electric Water Heaters under Dynamic Pricing," *Carnegie Mellon Electricity Industry Center Working Paper,* no. CEIC-04-02, 2004.

[43] P. Fairey and D. Parker, "A Review of Hot Water Profiles used in Performance Analysis of Residential Domestic Hot Water Systems," Florida Solar Energy Center, 2004.

[44] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) Handbook–Heating, Ventilating, and Air-Conditioning (HVAC) Applications (2007). Typical Residential Family's Hourly Hot Water Use. Fig. 12. Page 49.12.

[45] J. Runmin, M. H. Nehrir, and D. A. Pierre, "Voltage Control of Aggregate Electric Water Heater Load for Distribution System Peak Load Shaving Using Field Data," in *39th North American Power Symposium (NAPS)*, 2007, pp. 492-497.

[46] D. B. Jr., A. V. J. Petri, and J. T. M. Parrallegal, "DOMESTIC HOT WATER SCALD BURN LAWSUITS," presented at the Annual ASPE Meeting the Indianapolis Convention Center, Indiana, 1998.

[47] H. Klee, *Simulation of dynamic systems with MATLAB and Simulink*. Boca Raton: CRC Press, 2007.

[48] L. Ning and S. Katipamula, "Control strategies of thermostatically controlled appliances in a competitive electricity market," in *Power Engineering Society General Meeting, 2005. IEEE*, 2005, pp. 202-207 Vol. 1.

[49] Z. Xu, J. Østergaard, and M. Togeby, Demand as Frequency Controlled Reserve - Final Report of the PSO Project, Technical University of Denmark and Ea Energy Analyses, 2008.

[50] Z. Xu, J. Ostergaard, M. Togeby, and C. Marcus-Moller, "Design and Modelling of Thermostatically Controlled Loads as Frequency Controlled Reserve," in *IEEE Power Engineering Society General Meeting* 2007, pp. 1-6.

[51] Z. Xu, J. Ostergaard, and M. Togeby, "Demand as Frequency Controlled Reserve," *IEEE Transactions on Power Systems* vol. 26, no. 3, pp. 1062-1071, 2011.

[52] J. Short, Dynamic Demand on-line at http://www.dynamicdemand.co.uk/.

[53] G. Chown and M. Coker, "Interim report on frequency relaxation project," Eskom, 2000.

[54] Woodward, “Speed Droop and Power Generation”,application note 01302.

[55] R. Tonkoski and L. A. C. Lopes, "Enhanced Part Load Operation of Diesel Hybrid Mini-Grids with High Penetration of Photovoltaics," in *III Congresso Brasileiro de Energia Solar Belém*, 2010, pp. 1-8.

[56] (P. W. Stackhouse Jr. (2010, Dec. 14th). Surface Meteorology and Solar Energy. Available: http://eosweb.larc.nasa.gov/sse/)

[57] S. Papathanassiou, N. Hatziargyriou, and K. Strunz, "A Benchmark Low Voltage Microgrid Network," in *Proceedings of the CIGRE Symposium: Power Systems with Dispersed Generation*, Athens, Greece, 2005.

[58] M. H. Nehrir, J. Runmin, D. A. Pierre, and D. J. Hammerstrom, "Power Management of Aggregate Electric Water Heater Loads by Voltage Control," in *Power Engineering Society General Meeting, 2007. IEEE*, 2007, pp. 1-6.