Economic Dispatch and Demand Side Management in Diesel Hybrid Mini-Grids

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ABSTRACT

Economic Dispatch and Demand Side Management in Diesel Hybrid Mini-Grids

Moustafa Dalal-Bachi

Remote communities are frequently supplied by diesel power plants with multiple generator sets. The load profile of these communities is characterized by a large peak to average load ratio. This variation of the load makes the choice of the amount of power that each generator should provide, for optimal operation, more difficult. A generator set should not operate below 30% of its rated capacity, and a new generator set is added to the system when the diesel power plant operates at around 85% of the rated capacity. Besides, a generator set should not be constantly cycling on and off, since it increases the maintenance cost and fuel consumption. The usage of renewable energy sources such as wind and photovoltaic (PV) presents great potential for reducing the cost and fuel consumption of remote power systems. However, it further complicates the sizing and the control of the diesel power plant due to its intermittent, fluctuating and stochastic nature.

The objective of this thesis is to investigate the potential of Demand Side Management (DSM) based on Electric Water Heater (EWH) controlled by frequency to mitigate the difficulties created by the renewable energy sources and enhance the economical operation of diesel hybrid power systems.

In this research, the characteristics of the diesel generator set, PV, and the electric water heater are studied. In addition, multi gensets working in parallel with economic dispatch based on secant method are presented. The mini-grid benchmark, the fuel cost for each generator set, EWH model and economic dispatch algorithm are all simulated using Matlab/Simulink.

The performance of the proposed system under various levels of PV power 0%, 25% and 50% are also investigated. The simulation results indicate that using ~~a~~ DSM in multi-genset hybrid mini grid enhances system performance considering fuel consumption, efficiency, the number of hours generator set work per day and cycling of the generator sets.

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Acronyms:

- Genset: Generator Set.
- EWH: Electric Water Heater.
- DSM: Demand Side Management.
- PV: Photovoltaic.
- RES: Renewable Energy Source.
- ED: Economic Dispatch.
- UC: Unit Commitment.
- IPPD: Improved Pre-prepared Power Demand.
- MLC: Minimum Loading Constraint.
- MPC: Maximum Power Constraint.
- MOP: Minimum Operating Time.
- IC: Internal Combustion.
- MPPT: Maximum Power Point Tracking.
- RIPPD: Reduce Improved Pre-prepared Power Demand.
- RUC: Reduced Unit Commitment.
- ASHRAE: American Society of Heating, Refrigeration and Air-conditioning.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The integration of renewable sources into fossil fuel based electricity system (hybrid grid system) has increased over the past decades especially after the significant growth of fossil fuel cost. In particular, the integration of renewable resource and diesel genset makes it the most appropriate generating approach for isolated communities [1]. The main advantages of a hybrid mini grid system are reducing the fuel consumption and guarantee a reliable power supply.

In isolated communities with low population densities, supplying electricity by extending the transmission line from national power grid is costly and some locations are impossible because of geographical obstacles. Therefore, those communities utilize their own generation and distribution system to supply electricity, this scheme is called mini-grid system.

1.2 Hybrid mini-grid

Mini-grid usually refers to a power grid which has

- A limited amount of power [2].
- Should be isolated from national power grid.
- Has a low voltage distribution system.

Usually the main source of a mini-grid system is a diesel genset, could be one or more gensets, but the main issue is the cost of fuel and its transportation. In some rural area the transportation of fuel may cost 1 litre to transport 1 litre of diesel. For that, adding renewable energy sources (RESs) will reduce the fuel consumption, generation cost and moreover the pollution produced by gensets. On the other hand, a reliable supply with the same power quality of only diesel system is not as straight forward as suggested in the literature [3]. Figure 1-1 shows the conventional mini-grid system comparing to hybrid mini-grid system using simplified diagrams.

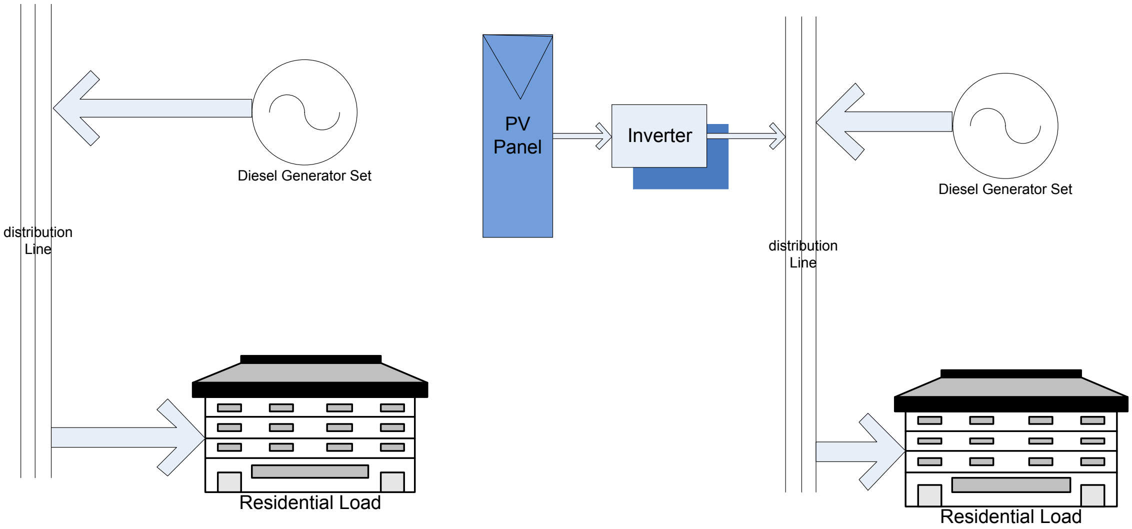

Figure 1-1: Mini-grid system with/without PV panels

The reason is that RESs are considered as fluctuating and non-dispatchable sources that may cause trouble in hybrid power system. Moreover, balancing the power generation with demand becomes even more complicated problem since the load demand in isolated communities varies extensively in a day as seen in the literature [4]. One option that will be explored in this work is the use of demand side management in a residential type hybrid mini-grid to enhance the system performance. This will be done by using an advanced supervisory controller for the diesel power plant and frequency based controllers for the Electric water heaters (EWH) which are the controllable loads of the system, as shown in Figure 1-2.

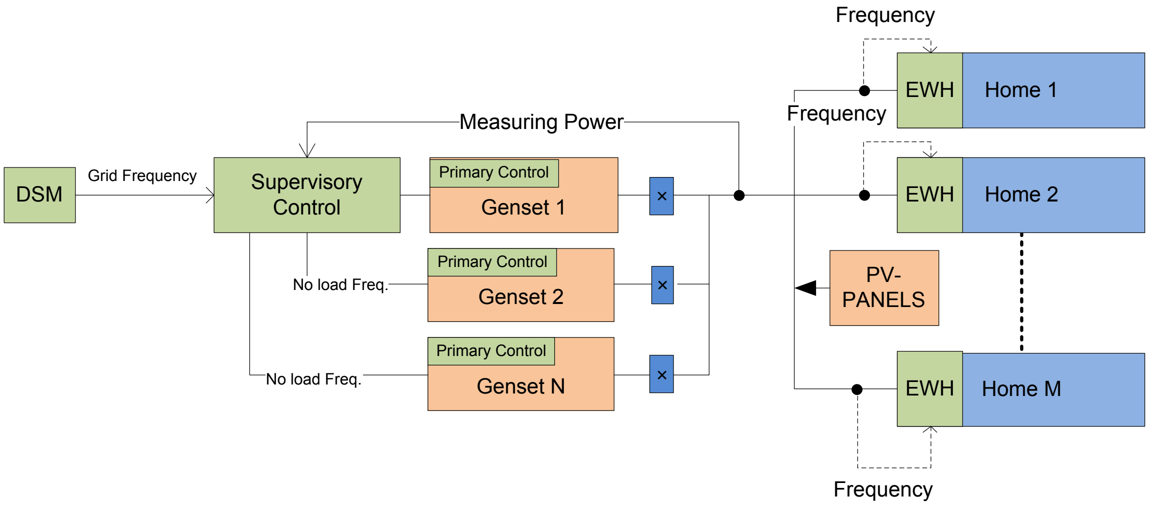

Figure 1-2: Simplified schematic diagram of the studied system where each green box contains a controller

1.3 Overview of unit commitment and economic dispatch

The economic dispatch (ED) function is usually implemented in the diesel power plant controller and it assigns the power out of each genset to reduce the total generation cost. This activity is often executed on a minute basis at each control center or Independent System Operator (ISO) [5]. Cost curves of genset can be modeled as polynomial functions. Equal incremental cost is a criterion used to solve the traditional ED problem [6].

Mathematically, using Karush–Kuhn–Tucker conditions, the problem is to minimize the fuel consumption (F_T) which is represented by equation (1-1) and subject to the inequality constraints shown in equation (1-2), equation (1-4), equation (1-5) and, equality constraint shown in equation (1-3). That is:

Minimise:

$$F_T(\mathrm{P}) = \sum_{i=1}^{M} S_i F_i(P_i) \tag{1-1}$$

Subject to:

$$P_i min < P_i < P_i max \tag{1-2}$$

$$P_{plant} - \sum_{i=1}^{M} P_i = 0 \tag{1-3}$$

$$T_{dwell_{on}} > 15min \tag{1-4}$$

$$T_{dwell_{off}} > 20min \tag{1-5}$$

Where:

$\mathrm{S_i}$ is a boolean term, 1 when genset in On and 0 when genset is Off

$\mathrm{P_i}$is the power demanded from each genset

$\mathrm{F_T}$ is the total fuel consumption

M is the number of gensets

$\mathrm{P_{plant} = P_{load} - P_{PV}}$

$\mathrm{T_{dwell\ on}}$ is the time needed until the unit goes off

$\mathrm{T_{dwell\ off}}$ is the time needed until the unit goes on

This is a mixed integer nonlinear problem which will be easier to solve by dividing it into two sub problems: Unit commitment (UC) and economic dispatch (ED).

There are many classical methods to solve the ED problem such as priority list [7], dynamic programming [8], and Lagrangian relaxation method [6]. Among those methods, the priority list method is a simple method but the quality of solution is rough. Similarly dynamic programming, which is based on the priority list method, is a flexible method that gives optimal solution but requires more computational time in finding the optimal solution. However, these methods are well suited for small size unit commitment (UC) problems. The Lagrangian relaxation method provides fast solution but it may suffer from the numerical convergence problem.

The Secant method [9], which is used in this research, solves those problems. It has more optimized solution [10] than other methods, it's easy to include more constraints, and it requires less computational time. The unit commitment problem can solved by using

Improved Pre-prepared Power Demand (IPPD) that include the unit status information such as which unit should works and what is the power limit of that unit.

1.4 Research objectives:

This research is to study the possibility of applying Demand Side Management (DSM) control through Electric Water Heaters (EWH) in an isolated community which is powered by a PV-diesel hybrid system. DSM will be used to change the load demand from the gensets to bring them to a low cost operating point.

The objectives of this research are:

- Implement multi-diesel genset plant working in parallel using economic dispatch algorithm.
- Incorporating a EWH which is typically used in house.
- Developing the simulation software to efficiently simulate the EWH. The simulation should be able to make the DSM adjust the set point temperature which affects the average power consumed by the EWH.
- Investigate the outcome of the implemented DSM in an isolated community powered by PV-Diesel hybrid system. The implemented DSM strategies will use the frequency to change the set-point of controllable load which will change the power consumption. This objective can be divided into several small parts such as to simulate the decrease of the energy demand when the DSM control was applied to the residential load, which is an EWH, as well as to study how the system

efficiency changes and the impact of maintenance cost of diesel genset with the DSM.

1.5 Outline of the thesis

Chapter 2 deals with the characteristics and behaviour of the 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 elaborates on the economic dispatch problem and the benefit of using it in a multi genset scheme. It discusses the secant algorithm to solve the economic dispatch problem and use the Improved Pre-prepared Power Demand Table (IPPDT) method to solve the unit commitment problem.

Chapter 4 introduces the DSM control methods that have been used when EWHs are employed as controllable loads. Also, it discusses the modeling of EWHs and how to choose the right parameters for a DSM controller.

Chapter 5 gives a description of the hybrid mini-grid that was implemented in MATLAB software. The implementation of a model of the controllable loads (EWHs) is discussed. Moreover, it presents the simulation parameters and discusses the simulation results for different cases.

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

CHAPTER 2

MINI GRID SOURCES

2.1 Introduction

The most suitable power scheme for remote communities is the hybrid mini-grid system. The hybrid mini-grid system is superior to the traditional diesel system in many aspects. For example, the hybrid system can reduce the fuel consumption, maintenance cost and reduce pollution. Furthermore, the hybrid system is a renewable energy system that includes one or more different types of technologies, e.g. a wind turbine or a solar photovoltaic array. In this research, a PV-diesel hybrid system is considered for further analysis.

The following sections present the description of the power source components in the PV-diesel hybrid mini-grid system.

2.2 Diesel genset


Figure 2-1: Caterpillar diesel engine

A diesel engine/generator set is commonly referred to as genset, it consists of two main parts, the first one is a four strokes Internal Combustion Engine (ICE) and the second is an alternator which is usually a synchronous generator. Those two parts are coupled on the same shaft to work as a unit to convert the chemical energy in the fuel to electrical energy. Different genset sizes have different power outputs and different number of cylinders (usually 4 or 6 cylinders relative to power rate).

The genset has limitations of load capacity, frequency and voltage response and block load. The block load which is defined as the percentage of rated power instantaneously added to the genset. In this study the genset assumed is an ideal genset which means all transient responses of genset, including the block load, is out of our scope.

2.2.1 Fuel characteristics

Usually the operation cost of a fossil fuel genset is characterized by the amount of energy per unit volume and is measured in BTU/Liter (British thermal unit) BTU is defined as: *British Thermal Unit - The amount of heat (energy) required for raising the temperature of 1 pound of water by 1 degree Fahrenheit [11].*

2.2.2 Fuel consumption rate

The consumption rate is defined as the amount of fuel that is used to produce a specific amount of energy.

Chemically 1 liter of diesel fuel can produce energy up to 10.7 kWh or 34.47 kBTU and this ratio is called energy density (kWh/L) [12]. Diesel genset manufacturer datasheets usually give values of consumption relative to 25, 50, 75 and 100 % of full load [13]. The cost equation is usually defined in BTU and it can be calculated from the values of fuel consumption found in the datasheet.

For instance a 10 kW genset from GENERAC has fuel consumption as shown in Table 2-1.

Table 2-1: Consumption rate relative to percentage power

Power Percentage	**Consumption L/Hr**
25% (2.5kW)	1.3
50% (5kW)	2.5
75% (7.5 kW)	3.5
100% (10kW)	4.3

Table 2-2 shows the consumption rate in kBTU/Hr .

Table 2-2: Consumption rate in kBTU/Hr relative to percentage power

Power Percentage	Consumption kBTU/Hr
25% (2.5kW)	44.473
50% (5kW)	85.525
75% (7.5 kW)	119.735
100% (10kW)	147.104

- Note each kWh has 3412 BTU [11].
- Microsoft Excel 2010 was used to draw and find the trend line equation using Polynomial 2nd order in the form of $Y=aX^2+bX+c$.

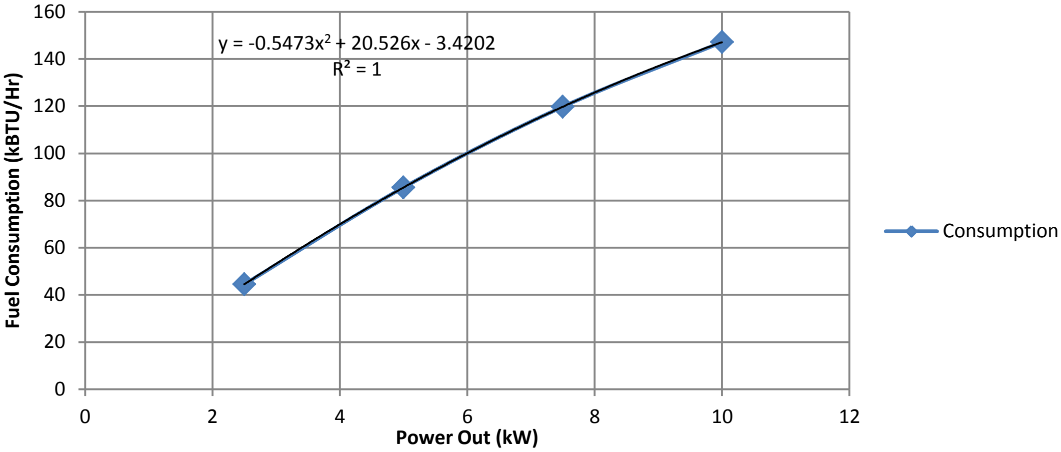

Figure 2-2: Fuel consumption for 10kW genset

Figure 2-2 shows the cost equation of genset with respect to the power output.

Please note the cost equation should be polynomial to get the incremental cost (lambda) which is important for the solution of the ED problem but in some cases a cost equation is characterized as linear equation, meaning that the value of "a" in the cost equation is equal to zero. In such a case the variable "a" is considered a very small value, around 10^{-6}.

The efficiency (kWh/L) can be found by dividing the energy output from the genset by the fuel consumption per hour as shown in Table 2-3.

Table 2-3 : Efficiency with respect to load percentage

Power Percentage	**Efficiency (kWh/L)**
25% (2.5kW)	1.923
50% (5kW)	2.00
75% (7.5 kW)	2.14
100% (10kW)	2.32

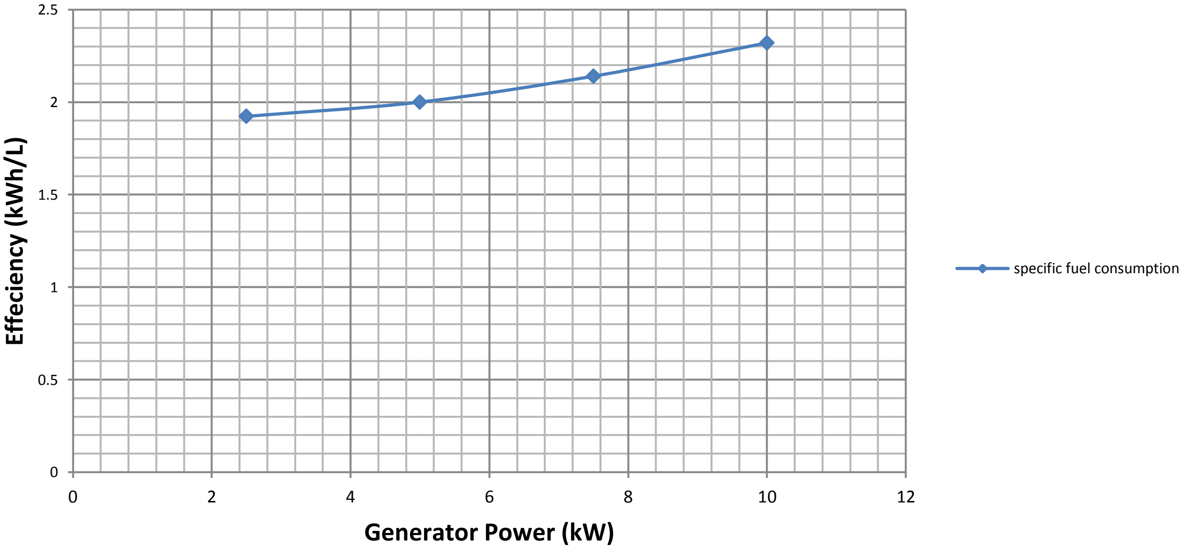

Figure 2-3: efficiency vs. power for 10 kW genset

From Figure 2-3 one sees that the 10kW genset will work more efficiently during full-load as opposed to light load.

The ideal genset should extract all the energy available in the fuel, which is 10.7kWh/L, but for this genset the energy extracted from the fuel at 25% load is 1.923 kWh/L. For that, these load ratios efficiency is 18.76% and 22.63% at full load which calculated by using equation (2-1).

$$\eta = \frac{output\ enery}{Fuel\ Enegy} * 100\ \% \tag{2-1}$$

Therefore it’s clear that this genset has very low efficiency and its use should be avoided.

Diesel engines can suffer damage [14] as a result of misapplication or misuse, namely internal glazing or carbon buildup as shown in Figure 2-4. This is a common problem in generator sets caused by not follow maintenance and operating guidelines. Ideally, diesel engines should not run below 30% of their rated load. Short periods of running the genset at light loads are allowed if the genset is brought up to full load, or close to full load, on a regular basis [14].

Figure 2-4: Carbon build-up

However, if the system used one genset as the main power source, the genset will operate at light load in some period of time which will reduce the total efficiency and life time cycle and increase the maintenance cost.

To illustrate the idea, a 175kW diesel genset from GENERAC [13] is used to compare its loading under two load profiles shown in Figure 2-5 and Figure 2-6, with peak power values of 142 kW and 122 kW respectively.

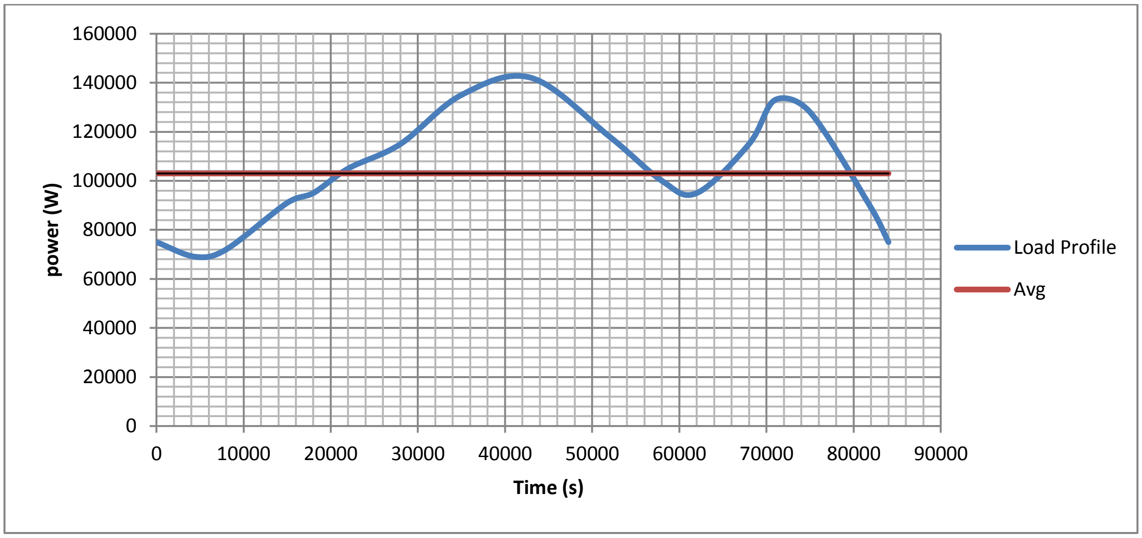

Figure 2-5: Load Profile 1 with peak 142kW

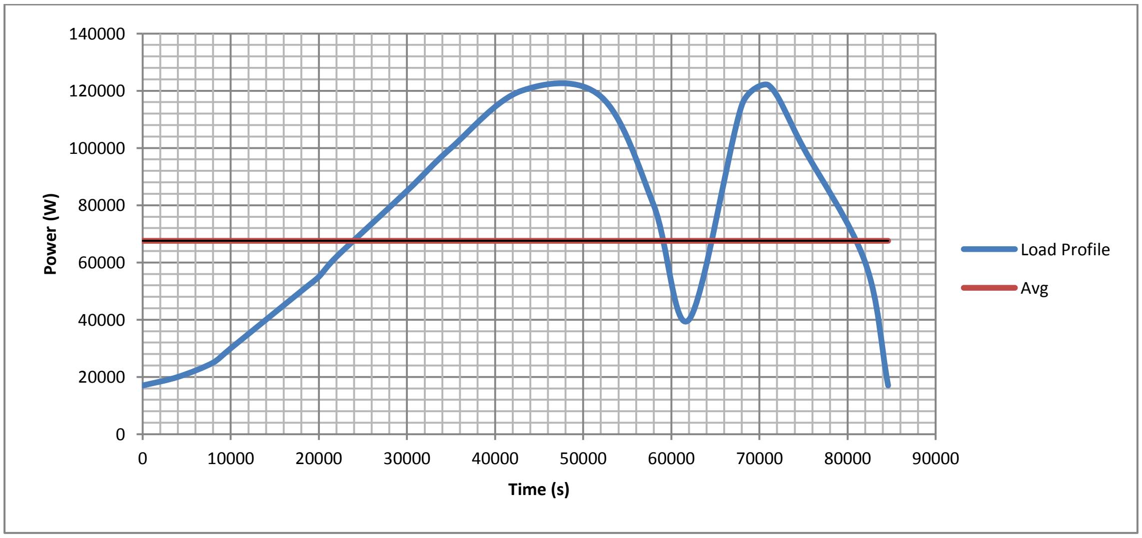

Figure 2-6 : Load Profile 2 with Peak 122kW

The fuel consumption equation for 175kW genset is $Y = 0.0051X^2 + 7.4422X + 199.01$ with $R^2 = 1$, which represents the fit factor of trend line into the curve, where: Y is the consumption in kBTU, X is the power rate. Figure 2-7 shows the efficiency curve of a 175 kW genset.

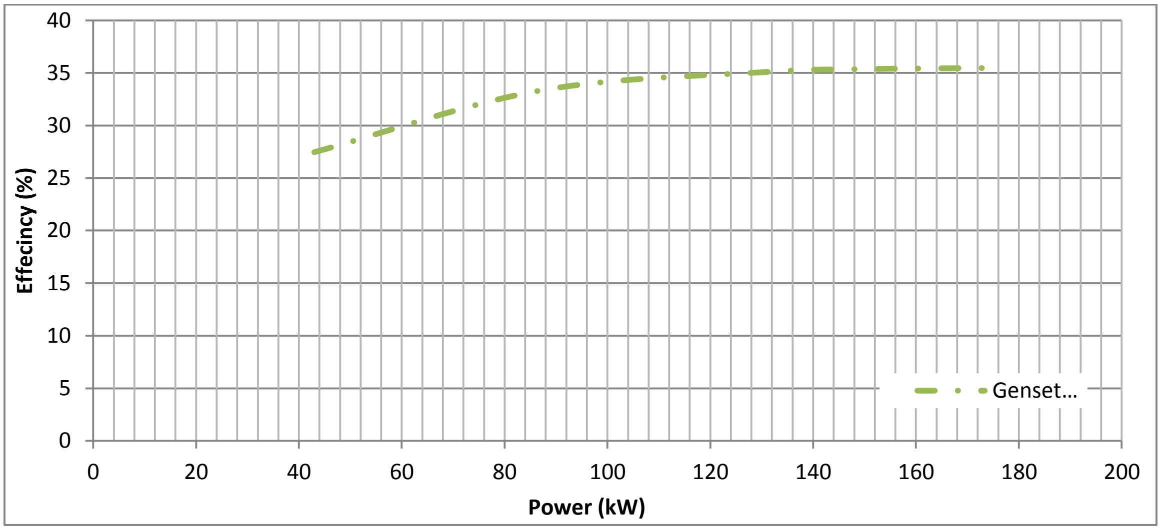

Figure 2-7: Efficiency vs. power for a 175kW genset

It is recommended by most manufacturers that a genset should not works with less than 30 % of the rated load, from Figure 2-7 at 52.5kW which represent 30% of the rated power the efficiency will be very low (29%) and overhaul cost will increased. This relation between the load and the efficiency should reduce to insure whenever the load changes, the efficiency will be high. The load profiles which shown in Figure 2-5 and Figure 2-6 are used in this study to compare between the worst case where the genset is operated in light load, which is less than 30% in some period of time, and the best case is when the genset is loaded at more than 50% most of the day.

Table 2-4: Compare consumption and efficiency for two load profiles for the same genset

	Load Profile 1	**Load Profile 2**
Consumption (L)	728	553.8
AVG. Efficiency (%)	32.71	30.73

Table 2-4 compares the consumption for the first load profile shown in Figure 2-5 with the second load profile shown in Figure 2-6. The efficiency is decreased by about 2%. The entire results and efficiency curves will be discussed in Chapter 5.

2.3 Power plant with multiple gensets

To avoid the genset to work at light load, a multi genset system with different size gensets connected in parallel can be used. In this research, the chosen gensets sizes for a 170kW power plant are 30, 60 and 80. All units should match the phase sequence and frequency; moreover the summation of active power of all the working gensets should be the same as the active power demanded by the load. The synchronizing procedure should apply for each genset before connecting to grid.

Usually identical generator sets operate well in parallel sharing load variation without any problem. But when paralleling different size units, problems can arise.

Two approaches were studied to solve the load sharing problem, the basic approach without supervisory control by using droop only, and with supervisory control that includes the economic dispatch algorithm which will be discussed in next chapter

2.3.1 Frequency primary control

Droop Speed Control refers to the prime mover governor speed control mode that allows multiple AC generators (alternators) to be operated in parallel with each other and share the load.

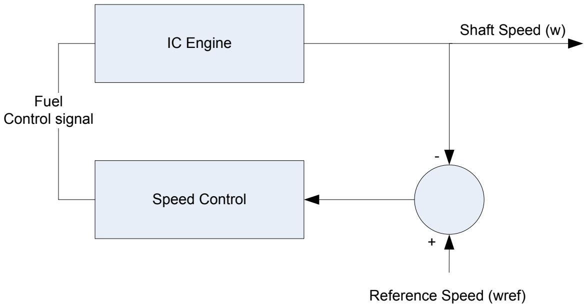

Figure 2-8: Governor Control loop

The main principle of droop is relating the frequency to the output power from the genset.

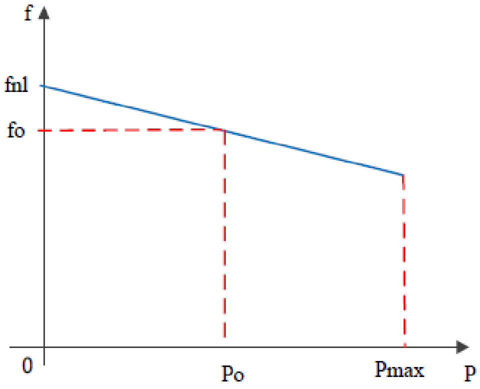

Figure 2-9: Droop Curve Frequency vs. Power

The governor is responsible to adjust the amount of fuel that is injected into the engine which affects the torque and the speed of shaft (w), which will be the frequency (f) of generated voltage, as shown in Figure 2-8. A droop characteristic can be applied by controlling the governor so that the shaft speed decreases when the load of the genset increases. This varies the load sharing of parallel connected gensets

Figure 2-9 shows the relation between the power P and the frequency f where f_{nl} refer to no-load frequency and P_{max} is the maximum power delivered by the genset.

The system frequency and the output power are defined [15] as shown in equation (2-2)

$$P_g = (1/S_p) * (f_{nl} - f) \tag{2-2}$$

Where: P_g is the output power of the genset (kW).

S_p is the droop ratio (Hz/kW).

f_{nl} is no load frequency (Hz).

f Operating frequency (Hz).

The droop ratio is usually selected by choosing the frequency range not to exceed 2- 5% of the rated frequency when the output power varies from zero to the rated power [15]. Table 2-5 shows the droop ratio and no-load frequency value that assigned to each genset. Those values will make the frequency vary ±1Hz of rated frequency which is 60Hz .

Table 2-5 : Droop parameters for 80, 60 and 30 kW gensets

Genset rated Power (kW)	**Droop Ratio (S_p)**	**No load frequency (f_{nl})**
80	0.025	61
60	0.033	61
30	0.066	61

The supervisory controller should consider the unit constraints [16] which are:

1. Minimum loading constraint (MLC) : which is 30% of rated load for each genset
2. Maximum power constraint (MPC): is set to 85% of rated genset power
3. Minimum operating time for each unit (MOP): which refers to minimum on-time requirement for diesel genset after each start-up to reduce the fluctuating of genset between on/Off and it's assigned to 20min

The total loading of the diesel plant is shared among diesel units proportional to their rated capacities. The rated capacity of the diesel plant is calculated based on operated diesel generators. The frequency of the plant is calculated using equation (2-3) as the load and output power of the plant varies

$$\mathrm{f_{plant}} = -\mathrm{P_{g_{plant}}} * \mathrm{S_{p_{plant}}} + \mathrm{f_{nl}} \tag{2-3}$$

$$where\ {}^{1}/_{S_{p_{plant}}} = A * {}^{1}/_{S_{p_{g1}}} + B * {}^{1}/_{S_{p_{g2}}} + C * {}^{1}/_{S_{p_{g3}}} \tag{2-4}$$

Where A, B and C is the logic state for each genset which equal 1 when genset is On and 0 when genset Off

f_{nl} is 61 Hz and Pg_{plant} is the summation of rated power for running genset which calculated by equation (2-5):

$$P_{g_{plant}} = A * P_{g_{g1}} + B * P_{g_{g2}} + C * P_{g_{g3}} \tag{2-5}$$

Where A, B and C is the logic state for each genset, Pg_1, Pg_2 and Pg_3 is rated power

2.3.2 Basic dispatch Strategy

Table 2-6 shows possible combination of three diesel generators and identify the logical state corresponding to the on/off status of the diesel generators as specified in the following three columns. The next two sets of columns identify upgrading and downgrading states respectively based on rated capacity of the diesel plant at each state and possible choice for an upper state with higher capacity or a lower state with smaller capacity as will be described later.

The upgrading and downgrading state are derived from logical cycling diagram of Figure 2-10 that shows the relation among the three states and explains possible changes for a state based on increase and/or decrease in capacity and switching constrains.

Table 2-6: Operating state of power plant

MAX. POWER	**Logical State**	**Genset 30kW**	**Genset 60kW**	**Genset 80kW**	**Upgrading**		**Downgrading**	
30	1	On	Off	Off	2	3	1	1
90	2	On	On	Off	3	3	1	1
170	3	On	On	On	3	3	2	1

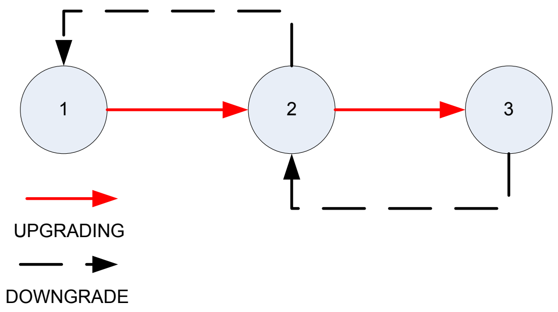

Figure 2-10: Logical cycling diagram

An upgrading transition is required when the total loading of the diesel plant exceeds the Maximum power constraint (MPC) thresholds for the current state. The acceptable state is the state with lowest capacity between the two available choices, given in Table 2-6 , for which the 5-minute average and instantaneous load values are below the MPC.

When the load becomes less than MLC a downgrading transition is performed to select an appropriate combination with higher percentage loading for the diesel plant. On other hand downgrading does not occur if the operating time of a generator for switch-off is less than Minimum operating time for each unit (MOP).

2.4 Genset rating and load factor

Normally a genset is designed with electric generator which matches the IC engine output capability. IC Engines are sized according to the actual power in kW required to meet the needs of the facility. The generator in contrast must be capable of handling the maximum apparent power which is measured in kVA.

Load factor of genset is used as one criterion for rating a genset. It is calculated by finding the product of various loads

$$Load\ Factor\ (\delta) = \%\ of\ time\ \times \%\ of\ load \tag{2-6}$$

Where:

$$\%\ of\ time = \frac{time\ at\ specific\ load}{total\ operating\ time} \tag{2-7}$$

$$\%\ of\ load = \frac{specific\ load}{rated\ load} \tag{2-8}$$

The load factor and operating time would indicate the type of genset required to supply the load

There are four types of application for genset [14] :

1. Emergency Standby Power: typically usage of 50 hours per year with maximum of 200 hours per year, load factor 70%.
2. Standby Power: Maximum 500 hours per year with load factor maximum 70%.
3. Prime Power: Unlimited hours of usage, Load factor maximum 70% with accepted 10% overload to 1 hour in 12 hours and don’t exceed 25 hours per year.
4. Continuous power: unlimited hour of usage, Load Factor 100%.

In this study, the must run unit, which is 30kW, is chosen to be Continuous power because it’s the most efficient unit as will discussed in next chapter and the rest 60 and 80 kW as prime power gensets.

2.5 Renewable sources (solar photovoltaic power)

The use of renewable energy sources such as wind and photovoltaic (PV) present great potential for reducing the cost and fuel consumption of remote power systems as well as the greenhouse gas emissions. In principle, the incorporation of renewable sources into a diesel-based system is relatively simple and they operate as passive generation units, with no participation in the control strategy of the mini-grid [17]. They usually inject the maximum amount of power that can be converted from the wind or solar irradiance using some sort of maximum power point tracking (MPPT) strategy.

The main issue in renewable resource is the highly variation of power during a day (variable solar irradiance) and highly energy variation during a season (summer/winter) which affect the power balancing and fuel consumption when combined into diesel mini-grid system.

This part will discuss the basics and the main characteristics of PV panels.

2.3.1 PV cell

The solar Cell is a semiconductor device that converts the solar irradiance into DC electricity. If a multi solar cell is connected in series or parallel then it is called PV panel. PV panel is available in wide range of power up to 100 Watts

The power of a solar cell is the product of current (I) and voltage (V), and is described by a curve such as shown in Figure 2-11

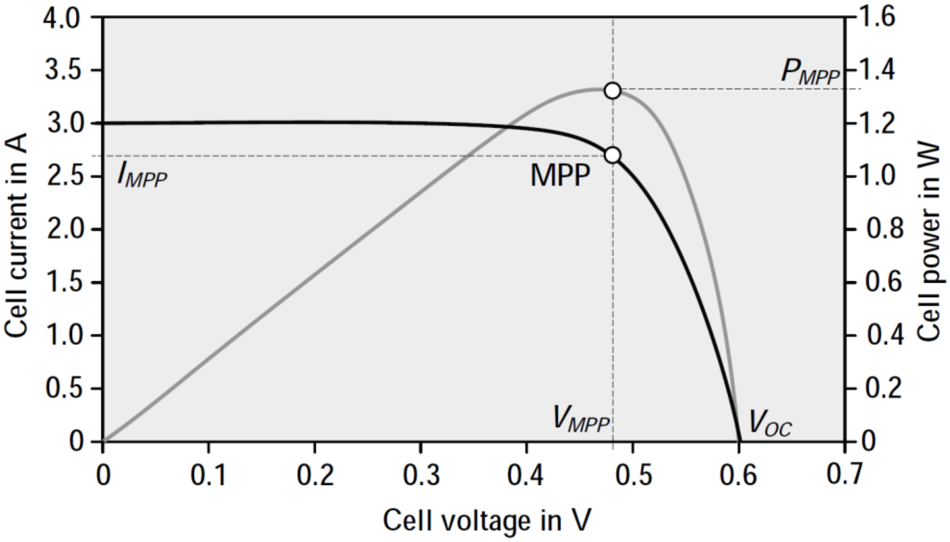

Figure 2-11: I-V and P-V characteristics of the solar cell showing the Maximum Power Point

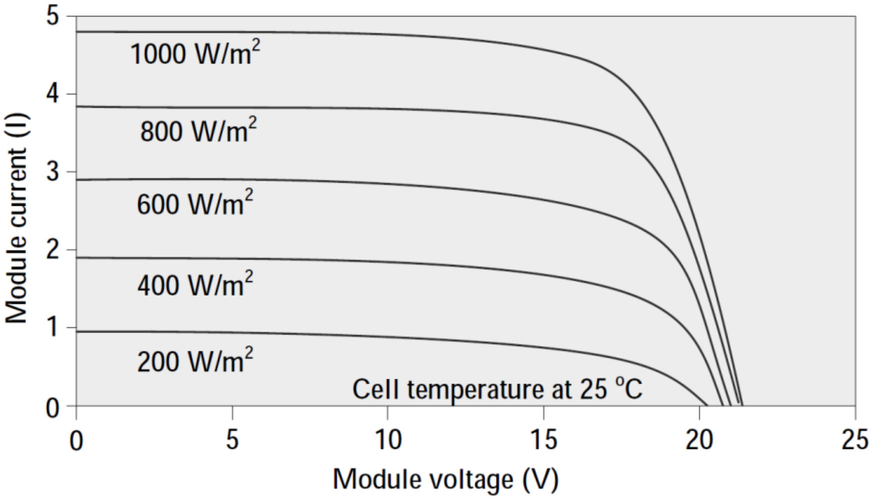

Figure 2-12: Power of the irradiance E on the I-V characteristics of a solar cell

From Figure 2-11one sees that when the current has its maximum at the short-circuit point, the voltage is zero and therefore the power is also zero. And vice versa the situation for current and voltage is reversed at the open-circuit point, so again the power here is zero. In between, there is one particular combination of current and voltage, for which the power reaches its maximum. It's called Maximum Power Point (MPP) [18] and represents the working point at which the cell can deliver maximum power for a given solar irradiance.

Moreover, the PV panel is a DC power source, for that the ac-dc converter (inverter) device should be used to connect PV panel into AC grid. The inverter should be able to track MPP always in different radiation intensity and deliver the peak power from PV panels.

A detailed discussion of PV module panels and MPP tracking is out of scope of this study; the study only considers the output power from the PV panel and assumed it as an uncontrollable power source with a profile as shown in Figure 2-13.

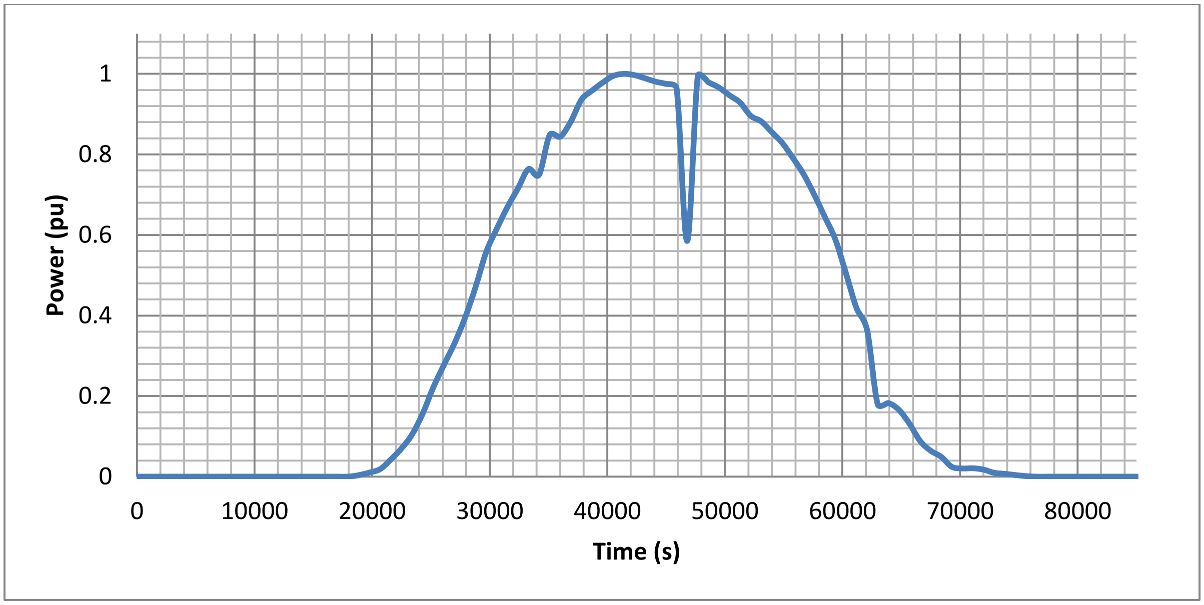

Figure 2-13: Power output from PV panel

CHAPTER 3

ECONOMIC DISPATCH

3.1 Introduction:

Electricity in stand-alone systems (mini-grids) is usually provided by diesel power plants at relatively high costs. The integration of renewable energy sources such as wind and photovoltaic (PV) can help reduces fuel consumption. However, due to the intermittent and fluctuating characteristics of these power sources, and the highly variable load profile typical of remote communities, the dispatch of the diesel gensets for operation with high efficiency and reduced unit cycling becomes more difficult.

These chapter discuses a technique that is used in this work to optimize the power shared in gensets that work in parallel to achieve the minimum fuel consumption. Figure 3-1 shows the generating plant which consist of N genset blocks, each block consist of an internal combustion engine connected to a synchronous generator. The output of those generators is connected to a single bus bar by breaker or switch gear which is responsible for the synchronizing procedure.

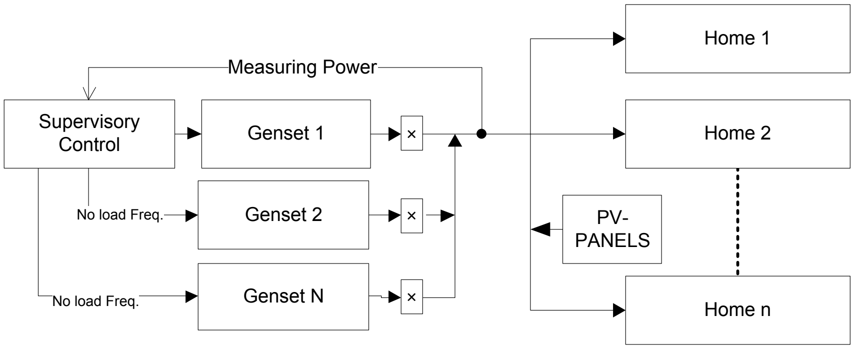

Figure 3-1: System configuration

3.2 Economic Dispatch

Economic dispatch is the process of assigning the required load demand between the available generation units such that the cost of operation is at its minimum.

In this thesis, the diesel power plant is composed of three GENERAC SD series gen-sets rated at 30 kW, 60 kW and 80 kW. It is assumed that there will be always at least one genset on, forming the grid.

The fuel consumption rate (in litres per hour) of the gensets as a function of the output power (in kW) is calculated according to equation (3-1). The parameters of each unit, shown in Table 3-1, can be obtained by curve fitting from the data provided in data sheet [13] for 25%, 50 %, 75% and 100% of rated power.

$$F_i = a_i * {P^2}_i + b_i * P_i + c_i \tag{3-1}$$

Table 3-1: Fuel Consumption Rate parameters in liter of the gensets

Unit (#)	Power (kW)	a	b	c
1	30	0.0087	-0.0535	2.8391
2	60	0.0012	0.1615	2.9007
3	80	0.0004	0.1968	4.061

Alternatively, one can consider the “efficiency” of the gensets in terms of kWh/L. Figure 3-2 presents this index for the three gen-sets used in this work. Figure 3-2 shows that while the 30 kW unit presents peak efficiency at around 50% of rated load, the efficiency of the other ones increases as the output power increases. This will certainly have an impact on the way the supervisory controller, which responsible for ED, assigns power to these gensets to meet the load demand with minimum fuel consumptions and costs.

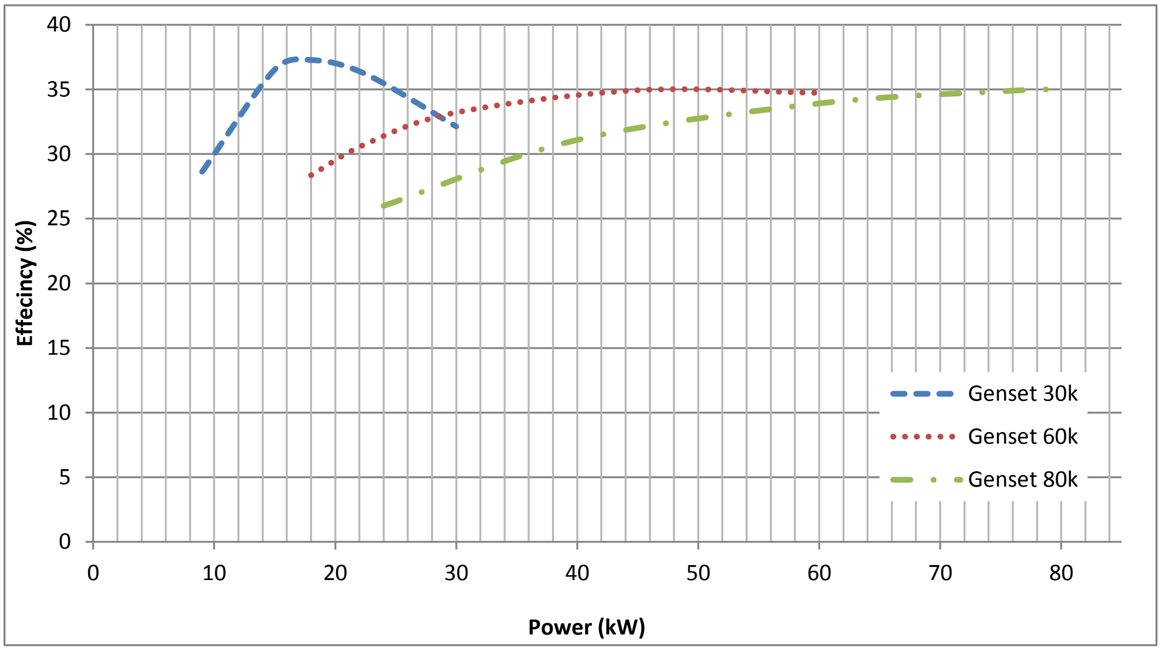

Figure 3-2 : Efficiency as a function of power for the three gen-sets used in this study

Furthermore, there are constraints that should be considered from the economical dispatch control as follows.

- Each genset should be loaded with power within the operating range, ideally between 30% and 100%.
- Load balance: the real power generated from all gensets should be equal to the load demand.
- Turn on/off time limits are defined as the minimum on/off time for each genset before the economical dispatch controller gives new orders to turn off/on the unit.
- Must Run Unit: is the genset responsible to give voltage support to the system[10] and form the grid.

3.2.1 Droop Control & Supervisory Control

The primary control, which was discussed in Chapter 2, is used by each genset in supervisory control schema to deliver the exact power between update intervals from supervisory controller.

The supervisory controller is responsible for:

- Genset commitment and economic dispatch.
- Update the no-load frequency to supply the target power at the rated frequency like 60Hz for example. This is also known as frequency regulation.
- Operating time limits.
- Load forecast.

3.2.2 Economic Dispatch Algorithm

Mathematically speaking, the problem may be stated very briefly. The objective function shown in equation (3-2) is equal to the total cost for supplying the specified load. The problem is to minimize fuel (Ft) [6] subjected to the constraint that the sum of the power generated must equal the demand load as shown in equation (2-5) and equation (3-3):

$$Ft = F1 + F2 + \cdots + Fn = \sum_{i=1}^{N} F_i(P_i) \tag{3-2}$$

Where Fn represents the fuel cost for generator *n* and P is

power demand from a genset

$$P_{Load\ demand} - \sum_{i=1}^{N} P_i = 0 \tag{3-3}$$

The following steps describe the method to find the optimum working point for all gensets:

1. Obtain the cost equation of genset as define in equation (3-1) where a, b and c represent the cost equation constant , P_i represent the output power for that unite and F_i is the fuel cost .
2. Take the first derivative of the cost equations

$$\frac{dF_i}{dP_i} = 2aP_i + b \tag{3-4}$$

3. Applying the Lagrange function

$$\frac{dF_i}{dP_i} = 2aP_i + b = \lambda \tag{3-5}$$

Where λ is the incremental cost.

4. The main constraint equation is that the sum of the power outputs from gensets should equal to the power demanded by the load as shown in equation (3-6) .

$$P_{Load} = P_{generated} = P_1 + P_2 + \cdots + P_N \tag{3-6}$$

Where N is the number of gensets

5. The power output from each unit should be in the working range for that unit.

$$P_{i,min} \leq P_i \leq P_{i,max} \tag{3-7}$$

If there is a genset working out of range then Step 6 is applied.

6. One of three conditions will applied as shown in equations (3-8), (3-9) and (3-10) [9]

$$\frac{\mathrm{dF_i}}{\mathrm{dP_i}} = \lambda \quad \text{for } \mathrm{P_{i,min}} < \mathrm{P_i} < \mathrm{P_{i,max}} \tag{3-8}$$

$$\frac{dF_i}{dP_i} \leq \lambda \quad \text{for } \mathrm{P_i} = \mathrm{P_{i,max}} \tag{3-9}$$

$$\frac{dF_i}{dP_i} \geq \lambda \quad for\ P_i = P_{i,min} \tag{3-10}$$

A SECANT method with Improved Pre-prepared Power Demand Table is used to solve ED and UC problems, the ED problem is informed by equation (3-5) and equation (3-6) and constraints of genset in equation (3-7) and minimum operating time constraint for each genset.

3.2.2.1 Improved Pre-prepared Power Demand Table

The overall problem is divided into two sub problems namely unit commitment and economic dispatch.

Unit Commitment (UC) is the process of determining which genset should work and connected to the grid to generate power.

The economic dispatch (ED) is used to optimally share the load demands between the running's units while satisfying the power balance equations and unit operating limits which will be discussed in the next section.

Hence, UC and ED problems are solved using the Secant method with predefine table called Improved Pre-prepared Power Demand (IPPD) which includes the status of committed units for all power demands.

To build the IPPD the next steps should follow:

1- Calculate the lambda value (λ) for minimum and maximum power for each genset, then arrange these λ in ascending order in a table and index them as λ_k

$$\lambda_{i,min} = 2c_i P_{i,min} + b_i \tag{3-11}$$

$$\lambda_{i,max} = 2c_i P_{i,min} + b_i \tag{3-12}$$

2- Evaluate output powers for all generators at each λ_k value. Where power can calculated by

$$P = \frac{\lambda - b}{2a} \tag{3-13}$$

Incorporate $P_{i,min}$ and $P_{i,max}$ as below:

- Set of the minimum output power limit

if $\lambda_k < \lambda_{i,min}$ then set $P_{k,i} = 0$ (3-14)

if $\lambda_k = \lambda_{i,min}$ then set $P_{k,i} = P_{i,min}$ (3-15)

But, for must run genset:

If $\lambda_k < \lambda_{i,min}$ then set $P_{k,i} = P_{i,min}$ (3-16)

- Set of the maximum output power limit

If $\lambda_k \geq \lambda_{i,max}$ then set $P_{k,i} = P_{i,max}$ (3-17)

3- Arrange all data above in a table as shown in Table 3-3

For example, Table 3-2 shows the lambda values for each genset which are calculated using equation (3-11) and equation (3-12) by applying the data of the considered genset shown in Table 3-1 .

Table 3-2: Lambda values for each genset with minimum and maximum power

	Lambda λ Values		
	Unit 1	Unit 2	Unit 3
$P_{i,min}$	0.1031	0.2318	0.2332
$P_{i,max}$	0.4685	0.2738	0.2612

The constructed IPPD table for given data is shown in Table 3-3

Table 3-3: IPPD table for 30, 60 and 80 kW genset

Index	Lambda λ	P_{g1}(kW)	P_{g2}(kW)	P_{g3}(kW)	P_{total}(kW)
1	0.1031	9	0	0	9
2	0.2318	16.396	18	0	34.3
3	0.2332	16.477	19.4	24	59.877
4	0.2612	18.0862	47.4	80	145.486
5	0.2738	18.8	60	80	158.8
6	0.4685	30	60	80	170

A unit commitment table is describes the genset status and can be built by changing the power of each genset from the IPPD table shown in Table 3-3 to logic one when the genset provide a power and to zero when the power is zero as shown in Table 3-4

Table 3-4: Unit Commitment table (UC)

Index	P_{g1}	P_{g2}	P_{g3}	P_{total}
1	1	0	0	9
2	1	1	0	34.3
3	1	1	1	59.877
4	1	1	1	145.486
5	1	1	1	158.8
6	1	1	1	170

From a specific power demand, the upper and lower rows of IPPD and UC table are selected and form the new tables called Reduce IPPD (RIPPD) and Reduced UC (RUC) tables as shown in Table 3-5 and Table 3-6.

Table 3-5: Reduced Improved Pre-prepared Power Demand table (RIPPD)

Index	Lambda λ	P_{g1}	P_{total}
1	λ_{min}	$P_i(\lambda_{min})$	$P_{total,min}$
2	λ_{max}	$P_i(\lambda_{max})$	$P_{total,max}$

Table 3-6: Reduced Unit Commitment table (RUC)

Index	P_{g1}	P_{total}
1	Logic($P_i(\lambda_{min})$)	$P_{total,min}$
2	Logic($P_i(\lambda_{max})$)	$P_{total,max}$

There are two types of neighbour fields in the RUC table:

- Binary Value in each column is the same.
- Binary Value or each column is different.

Whenever the binary values are the same, its means that the first unit in the first row will decide the commitment of the unit at given power demand.

If the binary values are different, then the algorithm will check the fuel consumption for two cases and choose the lower one as optimal solution:

Case 1:

If the load lies in working region of already operated unit then it will choose the optimal load for each one using the economic dispatch. After that it will calculate the fuel consumption.

Case 2:

Identify the genset unit should be added in the RUC table and set it to the minimum power value. Now the new power demand is equal to the power demand minus the minimum power for that unit. Then the ED is applied and calculates the fuel consumption.

After the solution is found, the control will calculate the no-load frequencies with respect to frequency set point.

3.2.2.1 Secant method for economic dispatch problem

In this section, the secant method is presented to solve the ED problem. The secant method [9] is a root finding algorithm that uses a succession of roots of secant lines to better approximate a root of a function, this method assumes that the function is approximately linear in the local region of interest and uses the zero crossing over the line connecting the limits of the interval as the new reference point, The next iteration starts from evaluating the function at the new reference point and then forms another line. The process is repeated until the root is found.

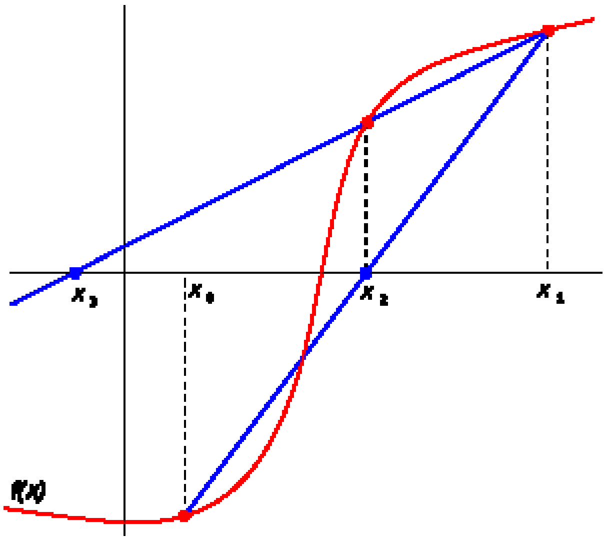

Figure 3-3: graphical representation of scant method. The red curve shows the function f and the blue lines are the secants

The main advantage of the secant method compared to other methods is the ability to find the root in 5 iterations if the guessed value is correct.

The secant method is defined by the repetition relation:

$$x_{K+1} = x_k - \frac{X_k - x_{k-1}}{f(x_k) - f(x_{k-1})} f(x_k) \tag{3-18}$$

As shown in equation (3-18), the secant method requires two initial values, x_0 and x_1, which should ideally be chosen to be close to the root and those will be chosen from RIPPD table as follow:

Power Balance Equation $f(\lambda) = \sum_{i=1}^{ng} P_i(\lambda) - PD_t$ (3-19)

$$x_{k-1} = \lambda_{min} \; \& \; f(x_{k-1}) = \sum_{i=1}^{ng} P_i(\lambda_{\mathrm{min}}) - PD_t \tag{3-20}$$

$$x_k = \lambda_{max} \; \& \; f(x_k) = \sum_{i=1}^{ng} P_i(\lambda_{\mathrm{max}}) - PD_t \tag{3-21}$$

If P_i violates the genset limits then set the genset power as follows:

- If P_i is less than the minimum limits of the genset, then P_i will be zero.
- If P_i is greater than the maximum limit of the genset, then P_i equals P_{max}.
- If the operating genset is the must run genset, then that unit is always operating in between the minimum and maximum operating range.

The flowchart in Figure 3-4 shows the secant method algorithm and how to build the IPPD table.

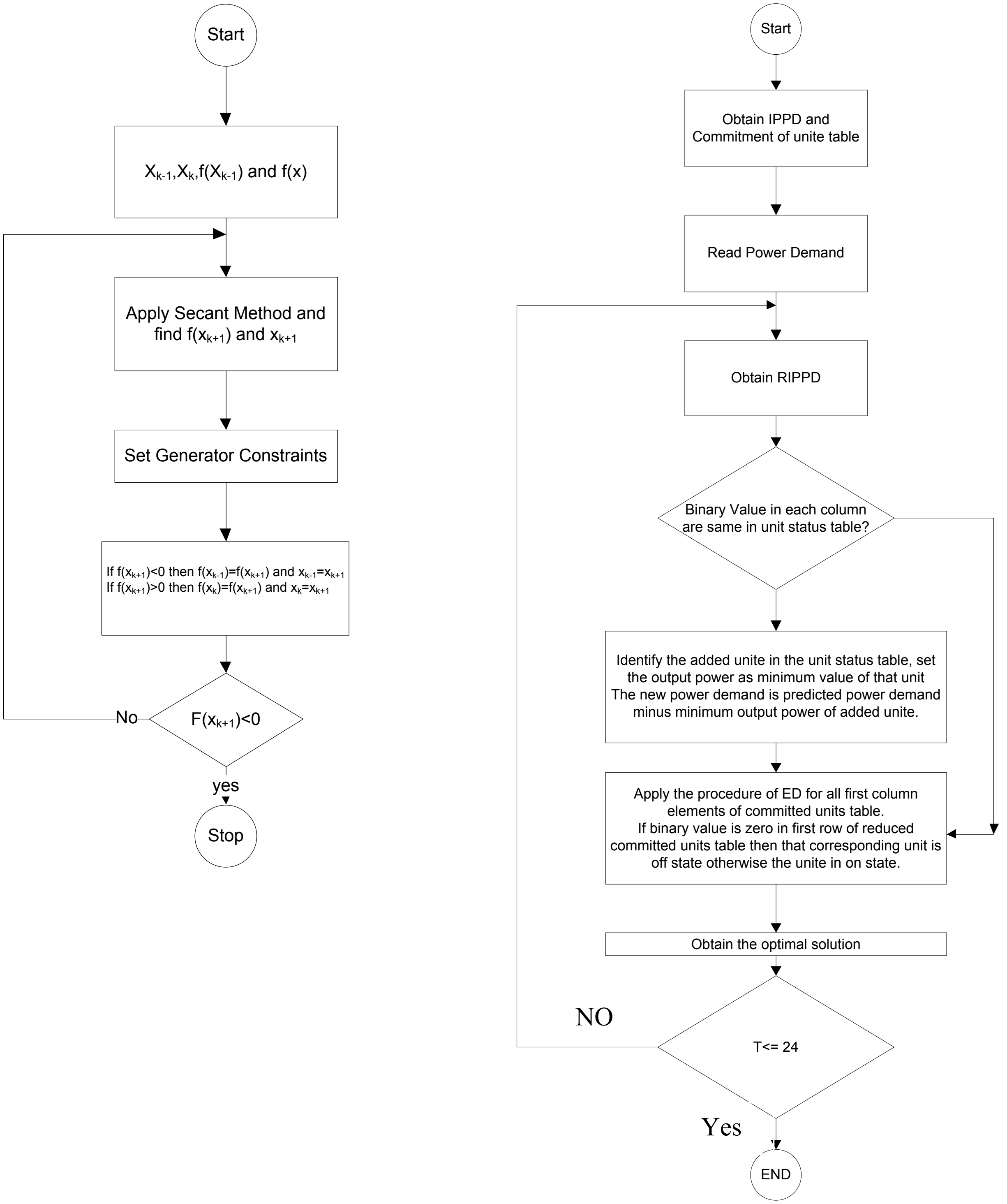

Figure 3-4: Algorithm to solve economic dispatch and unit commitment problems

CHAPTER 4

ELECTRIC WATER HEATER AND DEMAND SIDE MANAGEMENT

4.1 Introduction

Energy demand management is often referred to as demand side management (DSM). DSM usually implies actions that impact the quantity of energy consumed by users. It can also include actions targeting reduction of peak demand during periods when energy supply systems are constrained. Peak demand management does not necessarily decrease total energy consumption but could be expected to reduce the need for investments in networks and/or power plants.

A common goal of demand-side management is to smooth out the daily peaks and valleys in power demand to make the most efficient use of energy resources. This may require shifting energy use to off-peak hours, reducing energy requirements overall or even increasing demand for energy during off-peak hours.

In this work, the DSM strategy has the goal of maximizing efficiency of the diesel power plant by making the gensets operate in a region where the efficiency is optimum.

This chapter discusses the main characteristics of an Electric Water Heater (EWH), designs a module and controls it using a DSM scheme based on system frequency.

4.2 EWH characteristics

The electric water heater is usually used to supply hot water for residential use. The main parts of EWH are the tank[19] and electric resistance element as shown in Figure 4-1.

The water temperature in the tanks depends significantly on the amount of hot water drawn from the tank

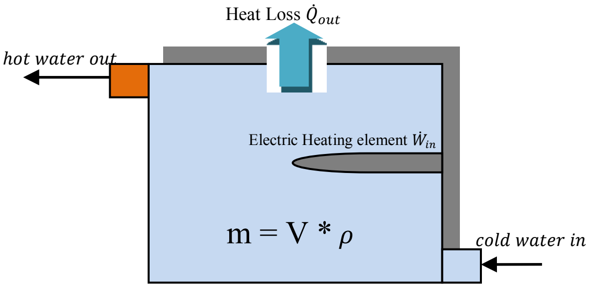

Figure 4-1: Electric Water heater in steady operation

Many models of different types of EWHs have been presented in the literature. The ideas 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 [20]. Other models were designed to obtain the EWH demand in order to control it by means of DSM [21-23]

In this study, the module of the EWH is built based on the analysis of heat transfer using energy balance for unsteady-flow systems as shown in equation (4-1) [24]

$$E_{in} - E_{out} = \Delta E \tag{4-1}$$

Where:

E_{in} represent the heat power from resistance element

E_{out} represent the heat losses and water consumption

ΔE change in internal kinetic, potential energies

In this study, the resistance element is rated at 4.5kW with a tank size of 290 Liters with insulation of foam.

Equation (4-2) describes the energy flow from the electric water heater

$$\dot{Q}_{in} + \dot{W}_{in} + \underbrace{\sum \dot{m}_i(h_i + \frac{\gamma_i^2}{2} + gz_i)}_{\text{For each inlet}} - \dot{Q}_{out} + \dot{W}_{out} + \underbrace{\sum \dot{m}_o(h_o + \frac{\gamma_o^2}{2} + gz_o)}_{\text{For each outlet}} = (m_2e_2 - m_1e_1) \qquad (4\text{-}2)$$

Where:

$\dot{W}_{out}$ is work out and equal to zero.

$\dot{Q}_{in}$represents the heating flow rate enter the tank and it′s equal to zero

$\dot{m}$ is represent the mass flow rate , it′s assumed equall in all inlet and outlet $\dot{m}_i = \dot{m}_o = \dot{m}$

$e = u + ke + pe$ but $pe = 0$ and $ke = 0 ==> e = uz$

$m_2e_2 - m_1e_1 = \Delta U$

For one inlet / one outlet and for constant mass flow for in and out:

$$\dot{Q}_{out} + \dot{W}_{in} = \dot{m} \left[h_2 - h_1 + \frac{\gamma_2^2 - \gamma_1^2}{2} + g(z_2 - z_1)\right] + \Delta U \qquad (4\text{-}3)$$

Where:

$\dot{Q}$: Heat transfer rate between heater tank and its surrounding

$\dot{W}$: is the power coming from the heater resistor

$\Delta h = h_2 - h_1$: Is the enthalpy change of liquid, it can be approximated by

$\Delta h = C_{p,av}(T_2 - T_1)$ and is measured by kj/kg

$\frac{\gamma_2^2 - \gamma_1^2}{2}$: Is the kinetic energy and because it is assumed steady state, the difference of velocity for the fluid will be zero, thus Ke=0.

$g(z_2 - z_1)$: Is the potential energy and is equal to zero because the elevation is zero.

$\dot{m}$: Is the mass flow rate and is equal to: $\dot{m} = \rho.\gamma.A$

γ: average flow velocity. A is the cross sectional area

$\dot{V} = (\gamma.A)\ is\ m^3/sec$ is the volume flow rate

ΔU : Is the energy reserved in tank in joules and is equal to $\Delta U = \rho.V.C_p \frac{dT}{dt}$

C_p : specific heat of the water (kJ/kg. °C);

ρ : Density of water (kg/L);

The equation will be:

$$\dot{Q}_{out} + \dot{W}_{in} = \rho.\dot{V}.C_p.(T_H - T_{in}) + \rho.V.C_p \frac{dT_H}{dt} \tag{4-4}$$

For the losses:

$R_{Conduction} = \frac{L}{k\ .A}$ Where: $K_{fiberglass} = 0.042\ W/m\,K$ and $A_{heater} = 3.176m^2$

$$\dot{Q}_{out} = -\frac{T_h - T_a}{R_{Conduction}} \tag{4-5}$$

At the end, the equation that represents the energy flow in EWH will be as shown in equation (4-6) [25].

$$C\frac{dT_H}{dt}=U\,SA\,(T_a - T_H(t))+Wd(t)\rho C_p\,(T_{in} - T_H(t))+K(t)Q \tag{4-6}$$

Where:

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

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

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

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

ρ = Density of water (kg/L);

C_p = specific heat of water (kJ/kg °C);

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

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

U = isolation coefficient (W/K. m^2);

Q = energy input rate (kJ/h);

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

The left side of equation (4-6) 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

It's assumed that the surrounding temperature is 20 °C, the water density is 1 kg/L, the specific heat is 4.1813 J/g/K, the surrounding area for EWH is 3.176 m^2 and the thermal conductivity for foam isolation is 0.042 W/K. m, the isolation thickness is 0.05 m and U will be 0.0021 W/K. m^2.

4.2.1 Water Draw (Wd)

The amount of hot water that is used in residential applications varies with time. For that, the hourly average water draw profile is taken from the American Society of Heating, Refrigeration and Air-Conditioning (ASHRAE) as shown in Figure 4-2 and is used is this study [26].

However, the hot water usage is usually different from one place to another and it is related to consumer behaviors and habits. The hot water consumption profile used in this work can be replaced with any profile with hourly average.

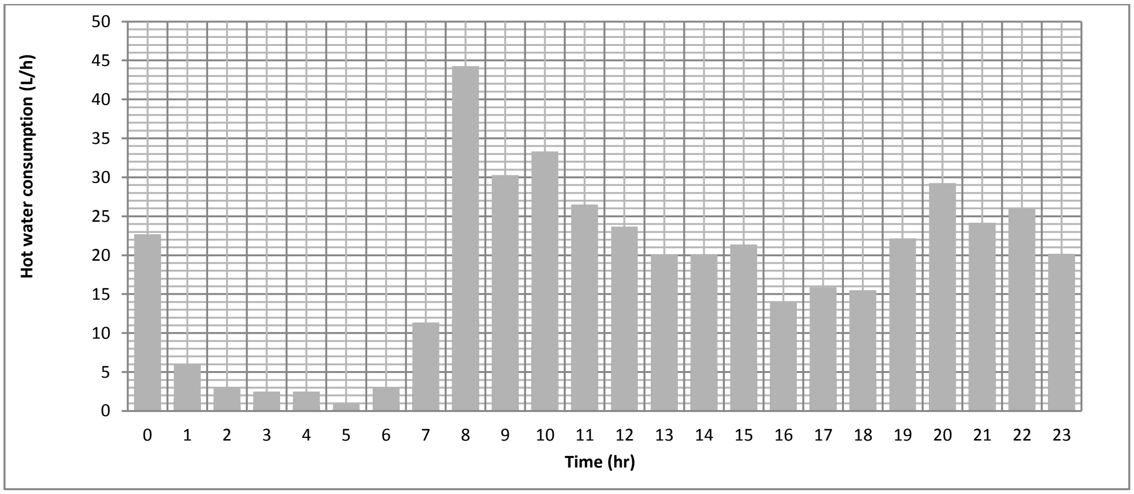

Figure 4-2: 24-hour hot water draw (Wd) profile in L/h.

Figure 4-2 shows that the demand of hot water after midnight is very low and it increases in the morning until it reaches to the peak value at 8 am.

Figure 4-3 shows the temperature in the EWH with the effect of water draw to the period of turning on/off the heater, note that the variance is ±1°C.

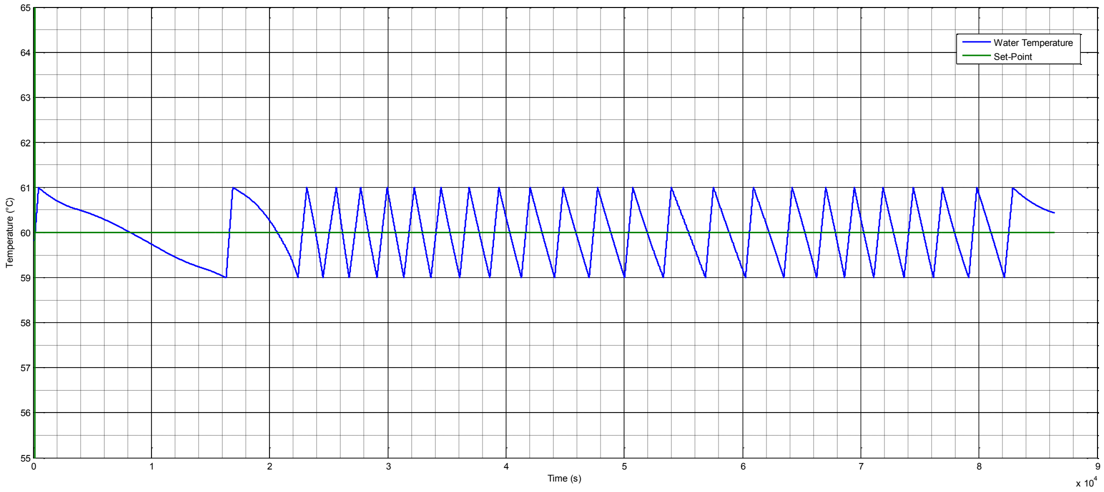

Figure 4-3: Temperature inside EWH with constant set-point

4.2.2 Control EWH

The EWH is operated using a normal thermostat with variable set point, the heating element of the EWH is turned on/off to keep the hot water temperature (T_H) within a tolerance band (± ΔT) which is 1°C of the set point temperature (Td), typically 60°C. When the heating element of the EWH is on, T_H rises until it reaches (Td+ΔT). Then the heating element is turned off and T_H decreases until it reaches (Td-ΔT).

The set point is controlled based on grid frequency using a droop curve which is defined in equation (4-7).

$$T_d = T_{db} + m(f - f_o) \tag{4-7}$$

Where:

f_0 is the nominal frequency

T_d is the set point temperature for the thermostat

Figure 4-4 presents the droop equation which is calculated when no-load frequency equal to 61 and used to calculate the temperature set-point of EWH, it's clear that when frequency increased the set point increased too. The range of set point is between 50 ℃ and 70℃ maximum [27].

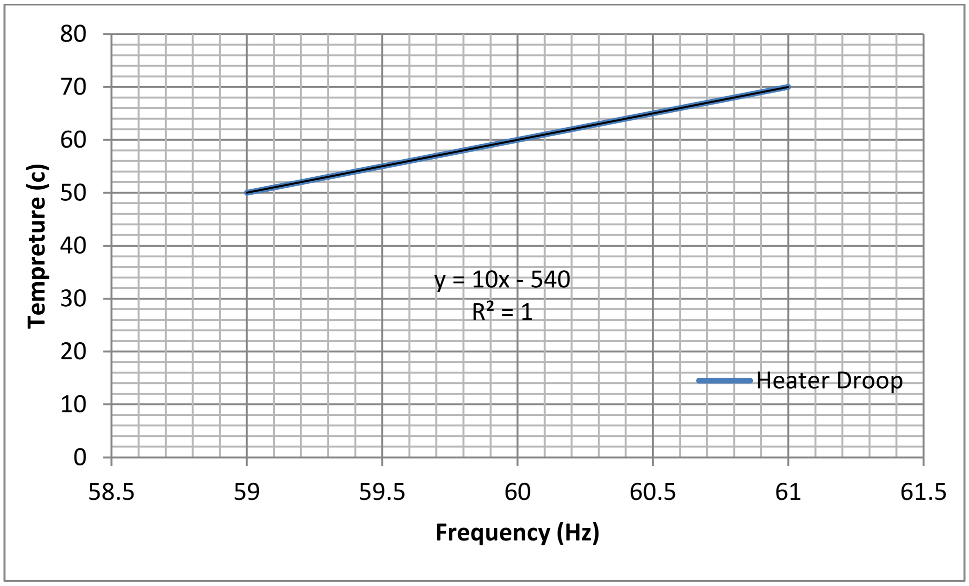

Figure 4-4: EWH Droop curve

4.3 Demand side management

The main idea of using controllable load is to increase the efficiency of the gensets, which can be achieved by controlling the value of the set-point in the load side to make the total power demanded from gensets to be decreased or increased. However, the set-point range of controllable load should respect the client satisfaction (for our example the temperature set point in EWH), for that the operator should predefine the minimum and the maximum set-point.

Accordingly, to consider the load as controllable load, the load should able to store the energy when the system need that load demand and retrieve that energy when demand by consumer when the system asking to turning off that load, for example electric water heater (EWH), refrigerator, etc.

In contrast, there are some values that should be calculated before implementing demand side management (DSM) and those values can help the operator to make a decision, those values are:

- In which load the system will be more efficient (the peaks of efficiency).
- The controllable load characteristic: to know approximately the amount of energy on it.
- The amount of controllable load is in the system.

In this study, our system consists of three gensets of 30, 60 and 80 kW with minimum power 9, 18 and 24 kW respectively and 10 residences, each with a 4.5kW controllable EWH .

Therefore, the efficiency / load curve of gensets can be obtained by increasing the load linearly with time until it reaches 170 kW, the maximum rated power of the diesel power plant, as show in Figure 4-5 Please note that this load is only given to check the simulated ED algorithm efficiency and it is not important to load the real genset with that load.

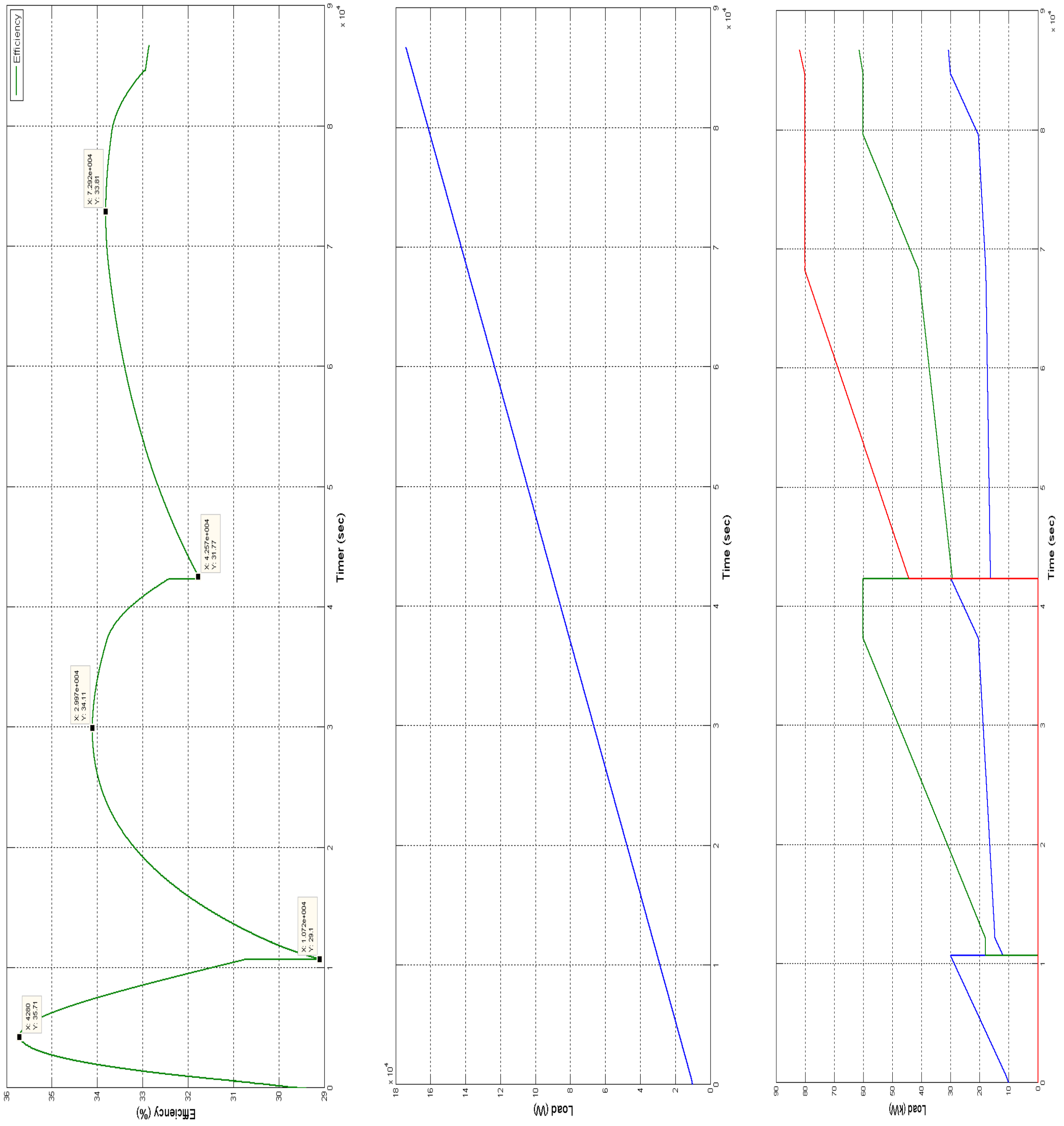

Figure 4-5: Load increased linearly, Efficiency and individual genset load

Figure 4-5 shows the points of maximum and minimum efficiency that should be considered by the operator.

As conclusion, the values that should be considered by the operator are:

- The minimum temperature range that makes the client satisfied and public safety is $58°C \pm 10°C$ [28].
- The peak efficiency for a load range in between 9 and 30 kW is 35.69 % when the gensets are loaded with 17.5kW.
- The peak efficiency for load range in between 30 and 90 kW is 34.1 % when the gensets are loaded with 65.9kW.
- The peak efficiency for load range in between 90 and 170 kW is 33.82% when the gensets are loaded with 147kW.

The forecast and DSM block are added to the control system to calculate the target frequency of the grid, and that will affect the load side set-point of EWH. The load forecast is responsible to predict the load and PV profile without EWH load. In the studied case, the load profiles are predefined as same profiles but with a shift of 10 min.

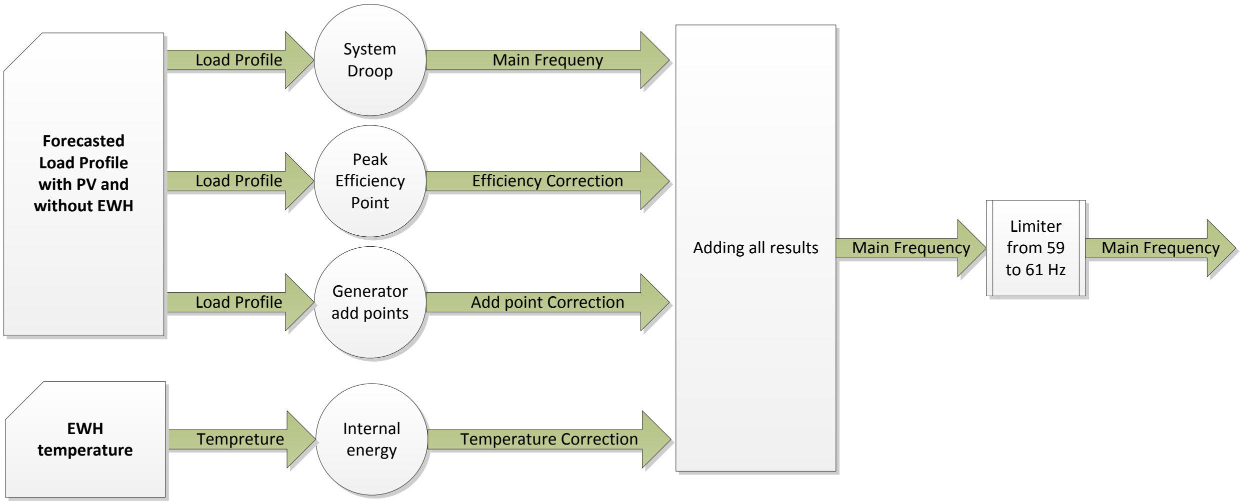

Figure 4-6: DSM and Forecast Block Diagram

Figure 4-6 shows the DSM block diagram, for the first row the system droop defines the exact frequency respective to power of the working gensets as shown in Figure 4-7. After that, there are three rows that make corrections to the assigned frequency which are:

- The Peak Efficiency point block. It is responsible to track the peak efficiency and correct the frequency to achieve that peak as shown in Figure 4-8.
- The generator adds point block. It corrects the frequency to avoid adding a new genset to increase the efficiency. This block is included in the same peak efficiency block by decreasing the frequency to the minimum when the uncontrollable load passes the peak efficiency as shown in Figure 4-8.
- The internal energy block. It corrects the frequency depending on the amount of energy inside the EWHs as show in Figure 4-9. This can be achieved by calculated the temperature of EWH module. In fact, this module will be only a mathematical representation of the EWH. In addition, this block has an advantage

of limiting the amount of energy that may be consumed by the EWHs to make the system more efficient.

All those correction blocks are varying for 1 Hz. At the end, there is a limiter to avoid the system to violate the predefined frequency range which is between 59 to 61 Hz.

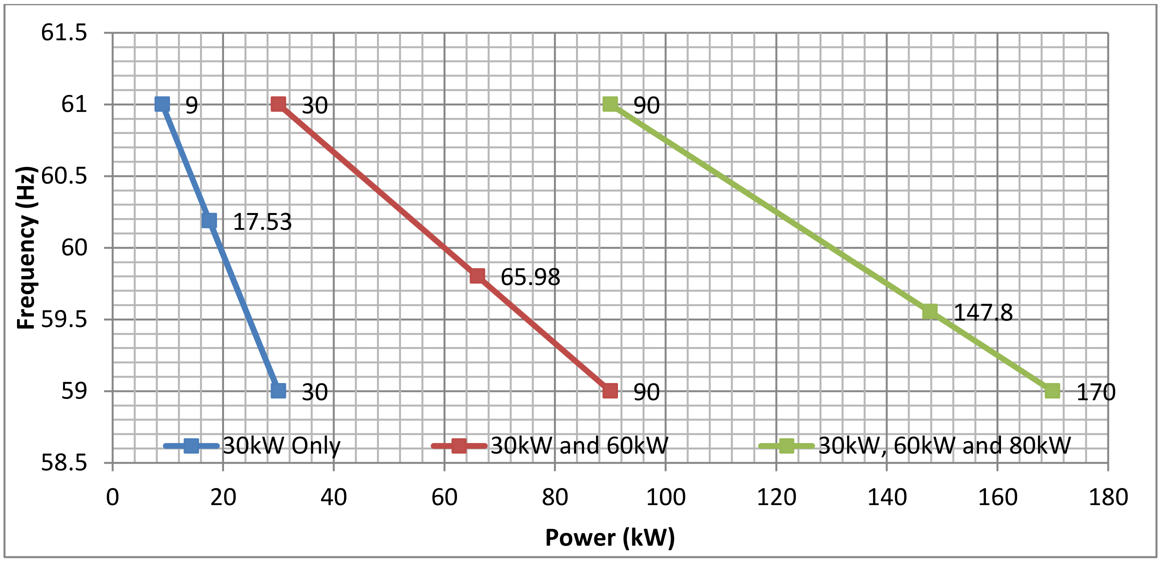

Figure 4-7: System Droop for multi combinations of genset

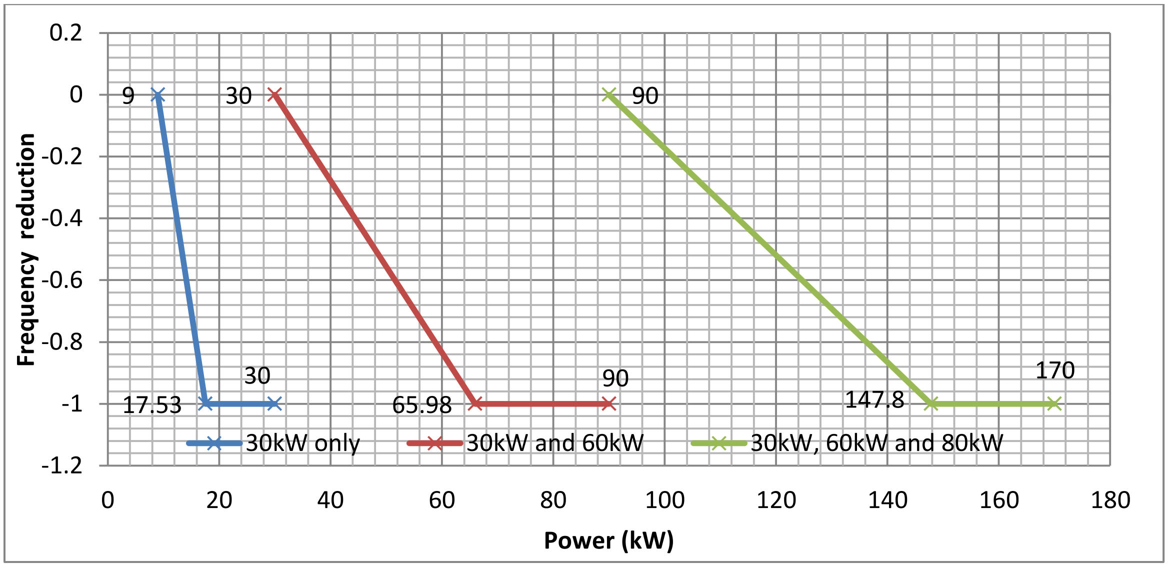

Figure 4-8: Efficiency Correction Block

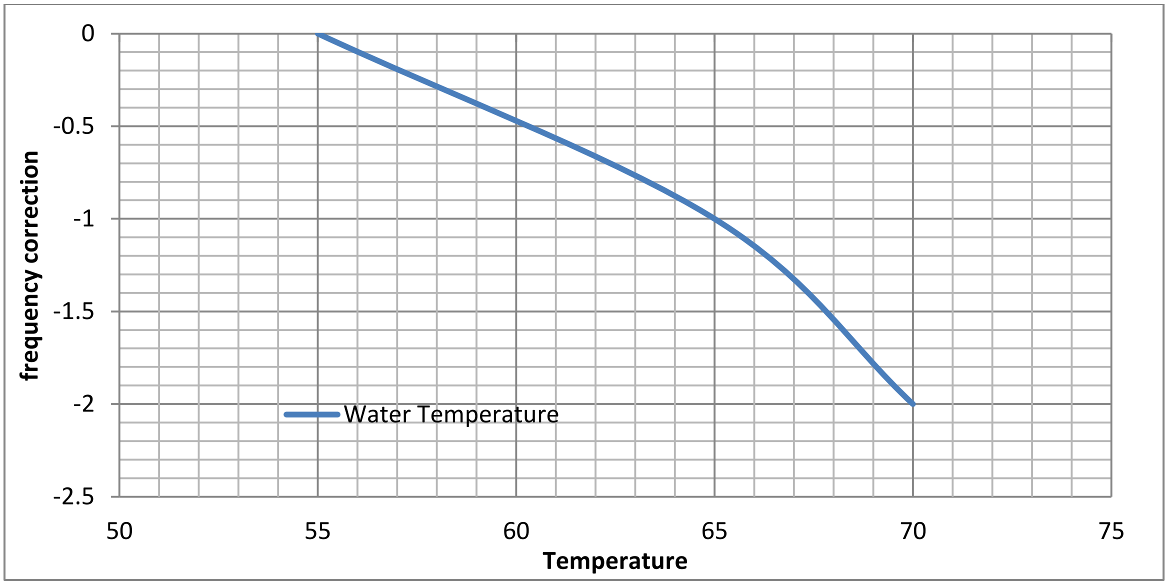

Figure 4-9: Temperature correction block

From Figure 4-8 and Figure 4-7, one sees that the frequency will decrease until the load reaches 17.53kW which is a peak efficiency point, the droop frequency will be 60.18Hz at the end. After correction the frequency will be 59.18 Hz, at that frequency the EWH will stop working because the set-point is near the minimum and the system now working on the peak efficiency, if uncontrollable load increased more than 17.53kW then the frequency will be 59 Hz and EWH stay off to avoid adding new genset.

From Figure 4-9 the temperature correction is responsible to reduce the frequency whenever the temperature inside the EWH is increased; this will grant reduction of energy consumed by EWH especially when EWH temperature is above 65 °C the frequency correction will be increased to reach 2 Hz to grant that this region will never be reached by EWH.

The proposed DSM control is validated by using the studied benchmark. The performance improvement, with respect to fuel consumption and genset cycling, is demonstrated in the next chapter.

CHAPTER 5

PV-DIESEL HYBRID MINI GRID SYSTEM MODEL AND SIMULATION RESULTS

5.1 Introduction:

This chapter discusses the implementation and simulation results of a hybrid mini-grid system with DSM which controls the Electric water Heater (EWH) by frequency. It focuses on a multi genset diesel power plant and on the benefits of using an Economic Dispatch (ED) algorithm.

First, a brief description of the benchmark based on a hybrid mini-grid PV-diesel and its implementation using Matlab/Simulink are presented.

Finally the simulation result will be presented and discussed.

5.2 Mini grid module

A PV-diesel hybrid mini-grid model is implemented in a Matlab/Simulink environment to study the impact of controlling EWHs based on grid frequency. The architecture of the PV-diesel hybrid mini-grid system is shown in Figure 5-1.

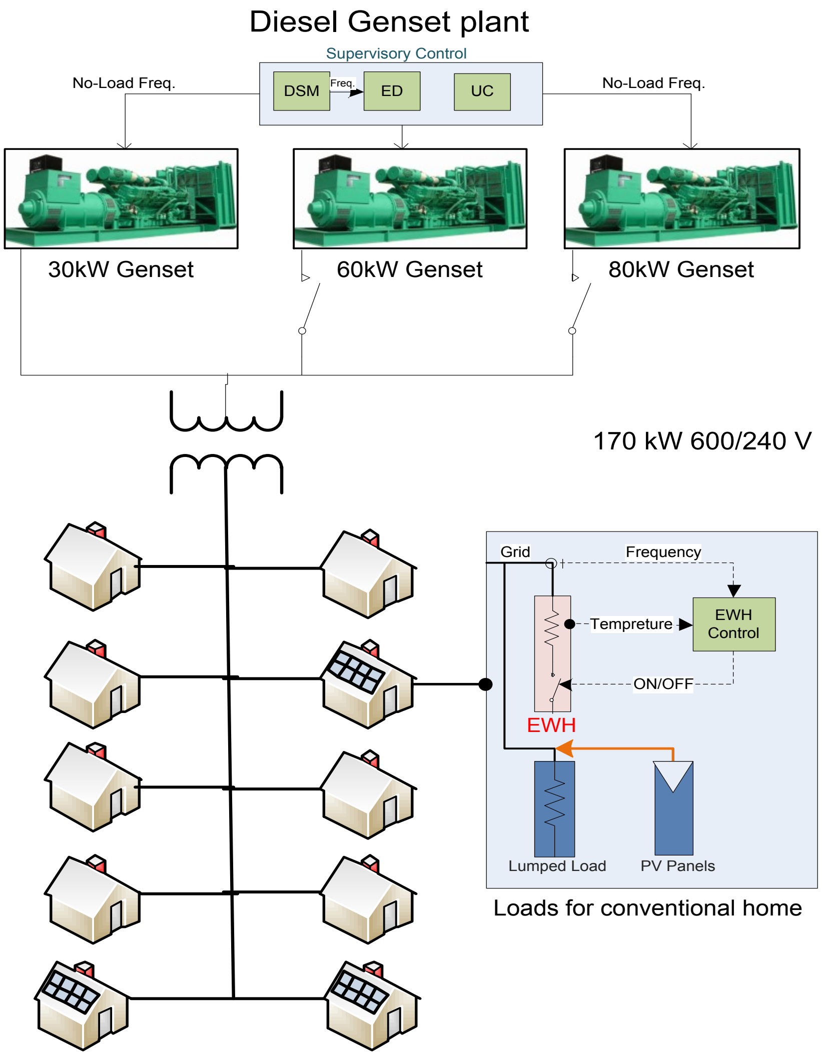

Figure 5-1: The architecture of hybrid PV-diesel mini-grid

The main components of this mini-grid are a diesel plant, and 10 residential houses. Each house has one controllable EWH over frequency.

A Renewable Energy Source (RES) which is a PV panel is modeled by a power profile as shown in Figure 2-13. Different cases are studied for different levels of PV peak power, namely 0, 44 kW and 88 kW.

5.2.1 Residential loads

The power demanded by the 10 houses is represented by an uncontrollable lumped load profile and also by a controllable load which is EWH based.

Two cases with different load profiles are compared. The First one with 103 kW average powers as shown in Figure 5-2 which represents a high demand load, the second one is 75kW average power as shown in Figure 5-3 which represents a light load case. The EWHs which are used in every residence are identical: 4.5 kW single-heating element units with a hot water tank of 290 liters, the only different between EWH is the hot water draw profile and inlet water temperature.

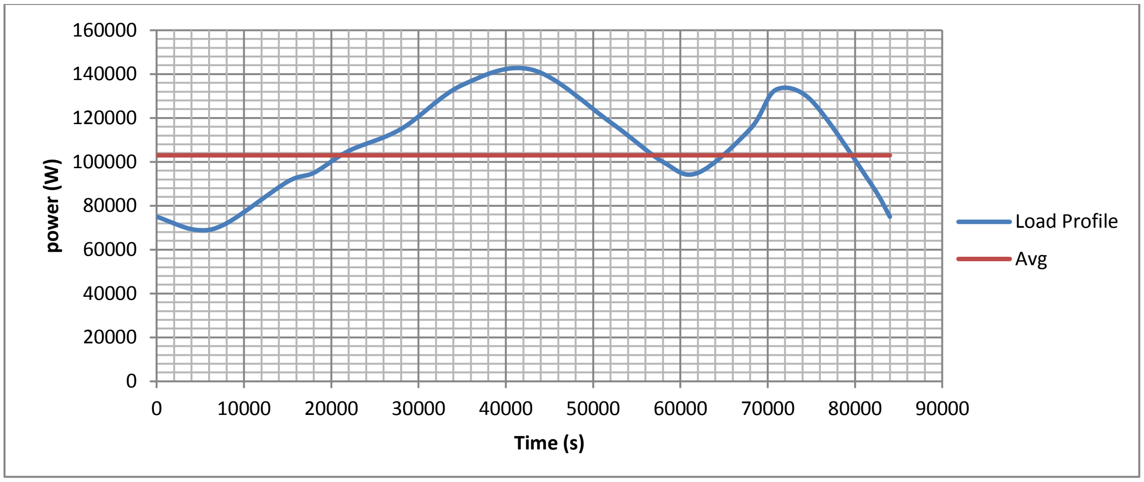

Figure 5-2: 1^{st} Load Profile 103kW average without EWH

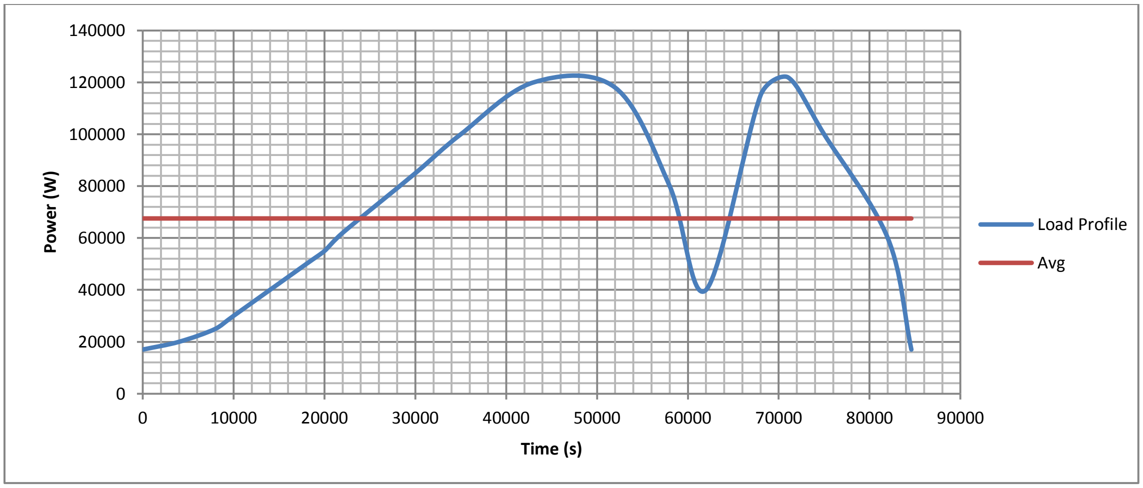

Figure 5-3: 2nd Load Profile 75kW average without EWH

5.2.2 Electric water heater

Ten EWHs are used as controllable loads which will be used to increase the efficiency of diesel plant and reduce cycling of the gensets.

The EWH load profile is calculated using ASHREA hourly average hot water consumption, as discussed in Chapter 4, and shown in Figure 5-4

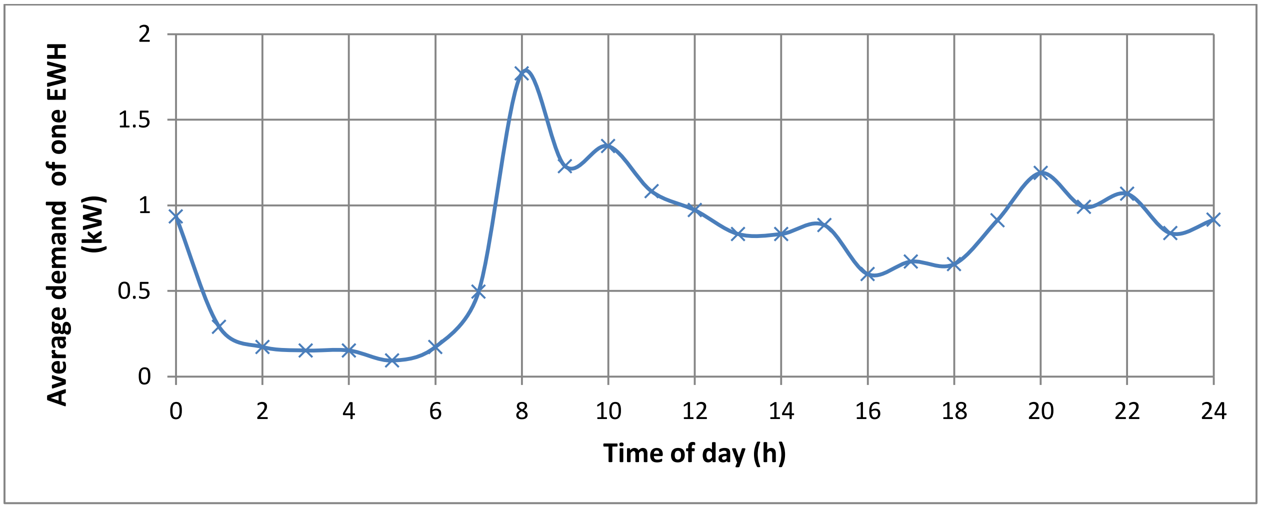

Figure 5-4: The average power consumption of a 4.5kW EWH

However, the research only concerns the active power used by the EWH. For that the EWH is modeled using Matlab/Simulink/Simscaps as shown in Figure 5-5 and load demand from EWH is summed with lumped load and subtract from PV power profile as shown in Figure 5-6 to form, at the end, the load demanded from the diesel power plant.

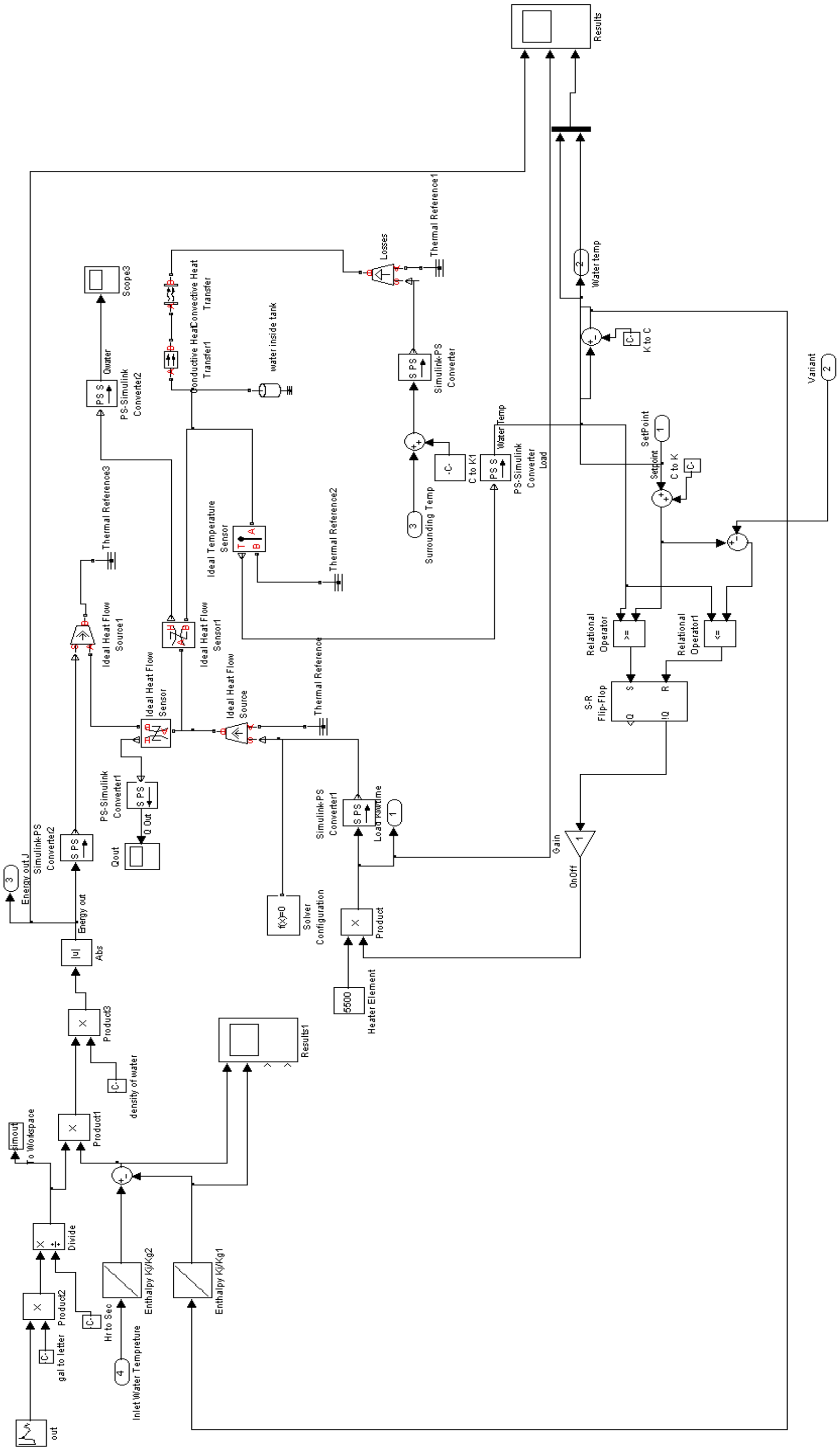

Figure 5-5: Water heater simulation including heater on/off control with temperature range

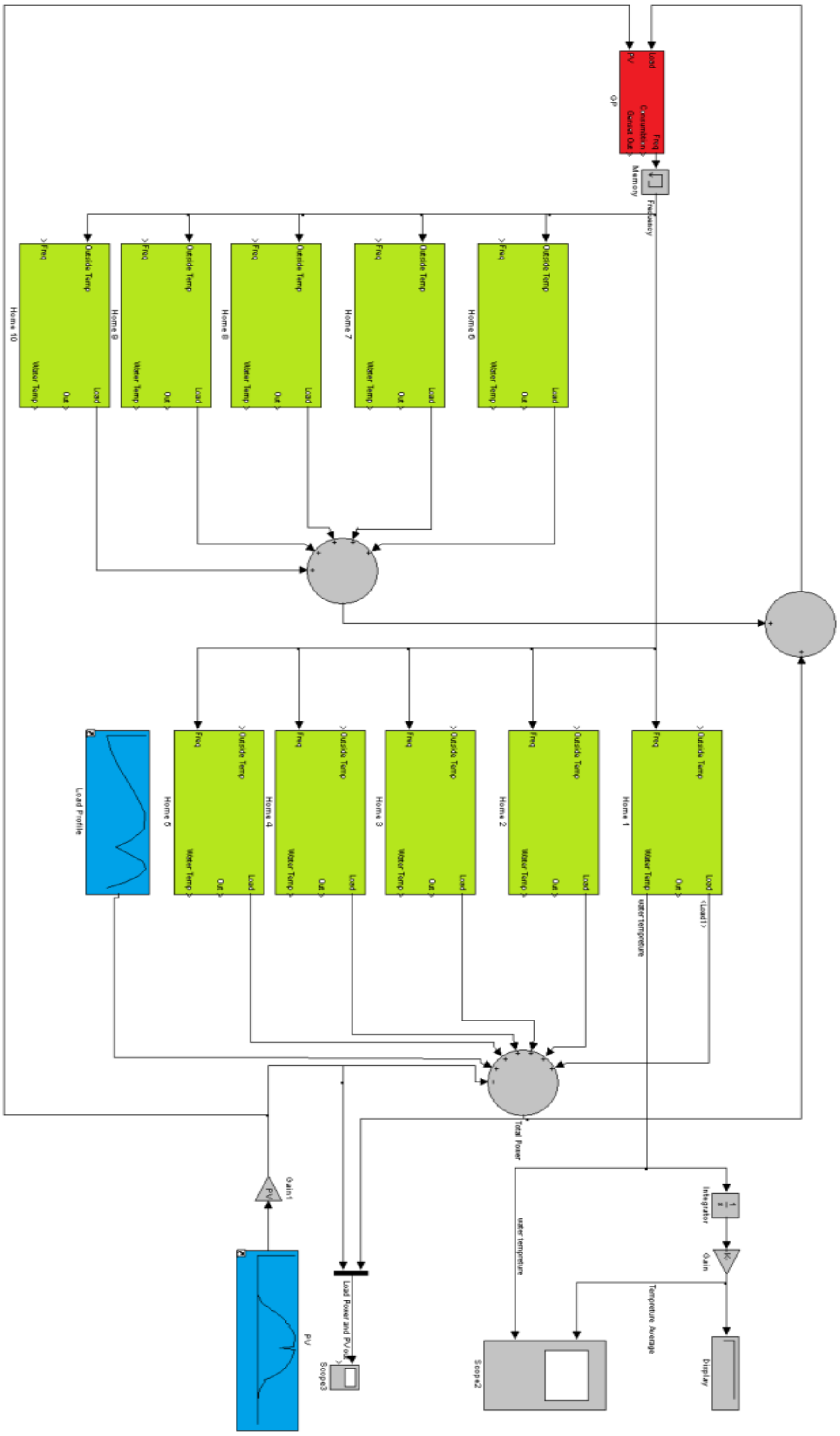

Figure 5-6: Simulink Mini-Grid System green represent houses

Moreover, the EWHs have Droop control responsible to change the set-point regarding to frequency as shown in Figure 5-7

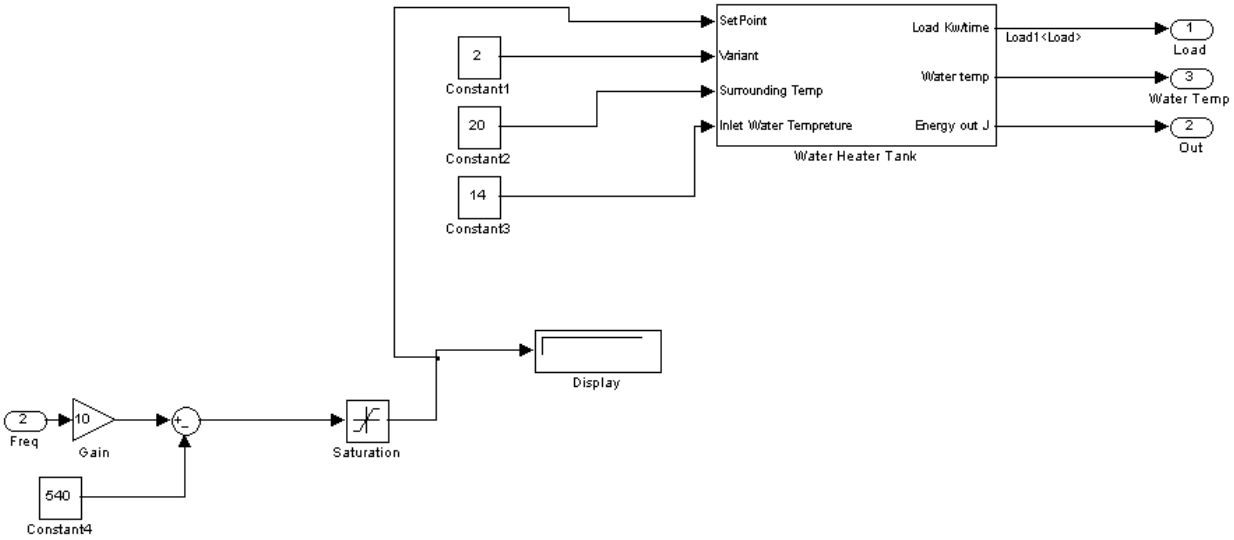

Figure 5-7: EWH include the droop control

5.2.3 Diesel power plant

The diesel power plant consists of three genset rated at 30, 60 and 80 kW. They are committed and despatched according to the logic used in the supervisory controller.

The research only considers the steady state of diesel genset and ignores the transient response. For that, the gensets module only considers the fuel consumption from genset with respect to load and frequency output at steady state.

Moreover, the supervisory module has three main blocks as shown Figure 5-8, the first one is the ED problem solver which is responsible for calculating the reference power for each genset. The second one is the primary controller which is responsible to calculate the no-load frequency with respect to the reference frequency that comes from the DSM and load distribution for each genset. The last one is the DSM which is responsible for assigning a frequency for the droop control which, at the end, controls the power consumed by the EWHs.

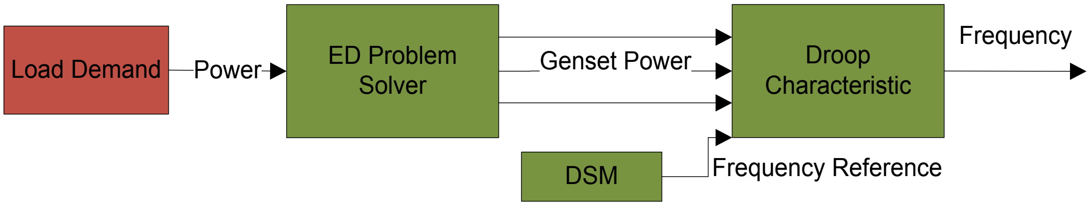

Figure 5-8: Block diagram of diesel power plant

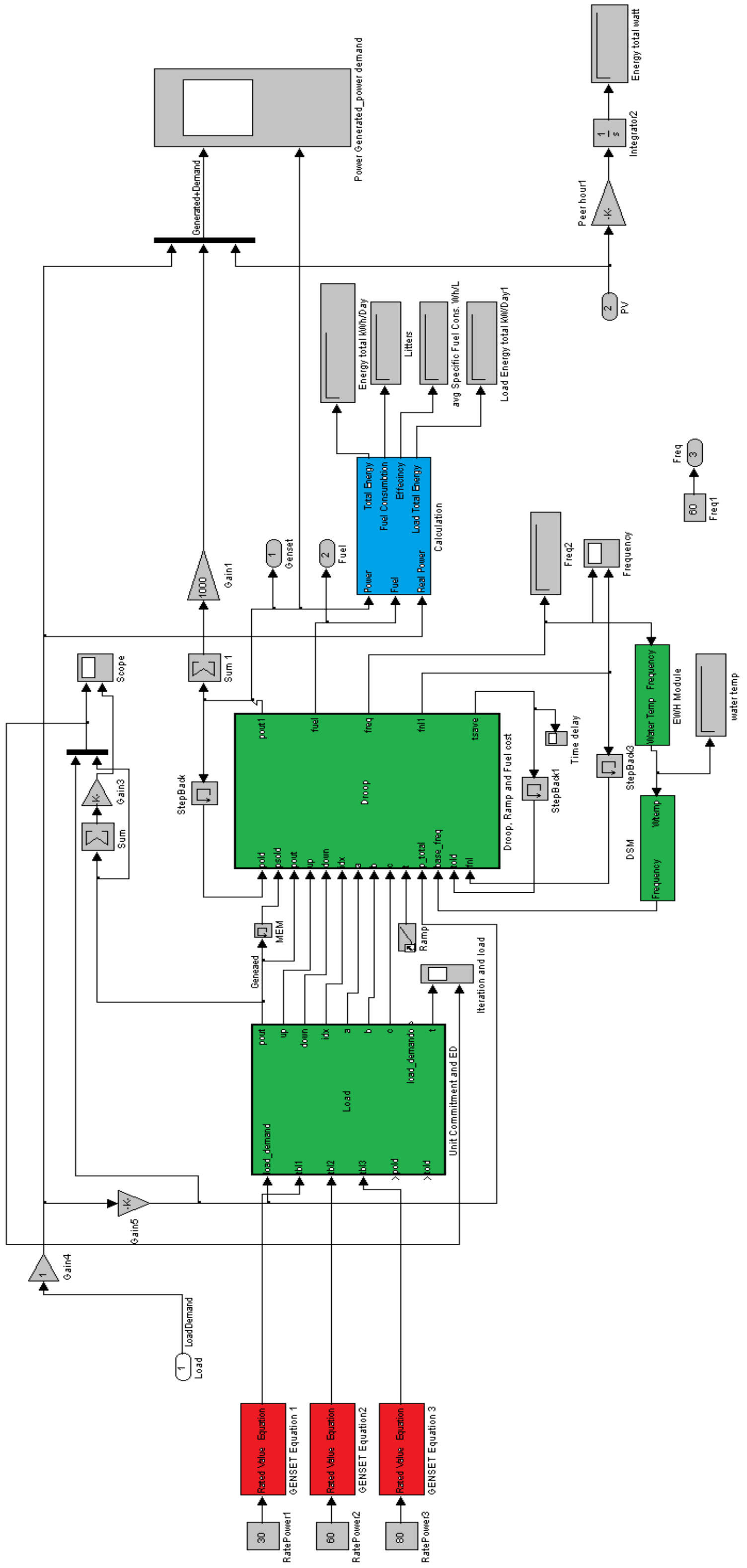

Figure 5-9: Diesel Power Plant using Simulink green represent main blocks

5.3 Simulation results

5.3.1 Simulation configuration

The time step of simulation is 1 sec and total time is 86400 sec which represents 24 hr.

The initial temperature of all electric water heaters is assumed to be 60 °C for all houses. Inlet water temperature is 20 °C and the predefined hot water draw vary from one house to another by ±10% which will help avoiding all EWH to turn on /off together.

5.3.2 Simulation result for different cases:

In this thesis, different cases and sub cases are considered in order to illustrate the impact of using DSM, PV and Multi-genset working with ED in a hybrid mini-grid.

Each case will focus on the amount of fuel consumed, the efficiency, the percentage of genset working per day and cycling of gensets when using no PV, PV of 44 kW and PV of 88 kW.

Two lumped load profiles are included to illustrate the impact of varying the power demand on the system.

Case1: Diesel genset working without ED:

(i) Single diesel genset:

A single genset with peak power of 175kW is chosen to generate power in the diesel plant. This case compares two lumped load profile without DSM. The EWH has fixed set-point at 60 °C. This case will illustrate the difference of efficiency when the load reduced while using one genset.

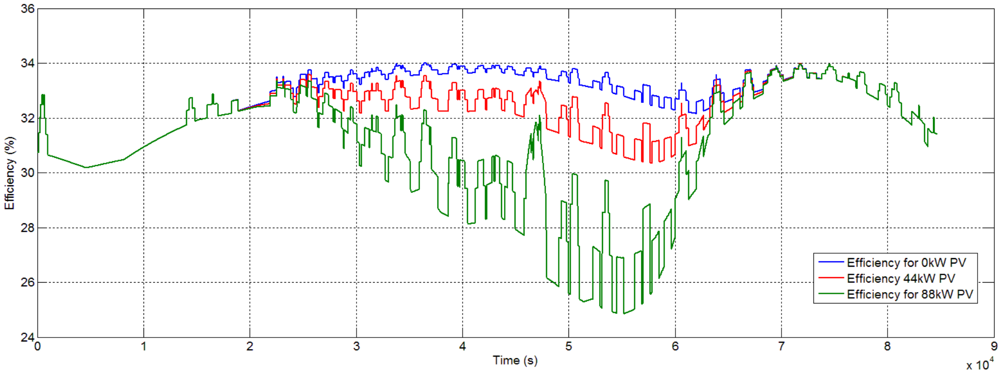

Figure 5-10: Efficiency for 1st load profile with multi-level of PV power

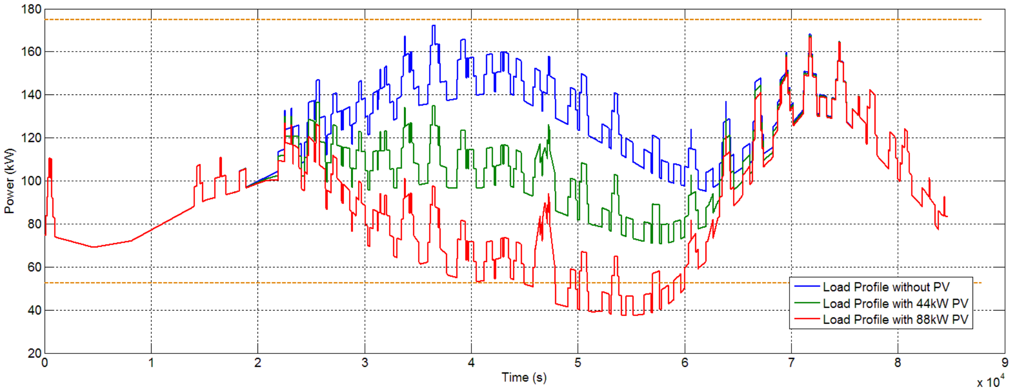

Figure 5-11: 1st Load profile with multi-level of PV power

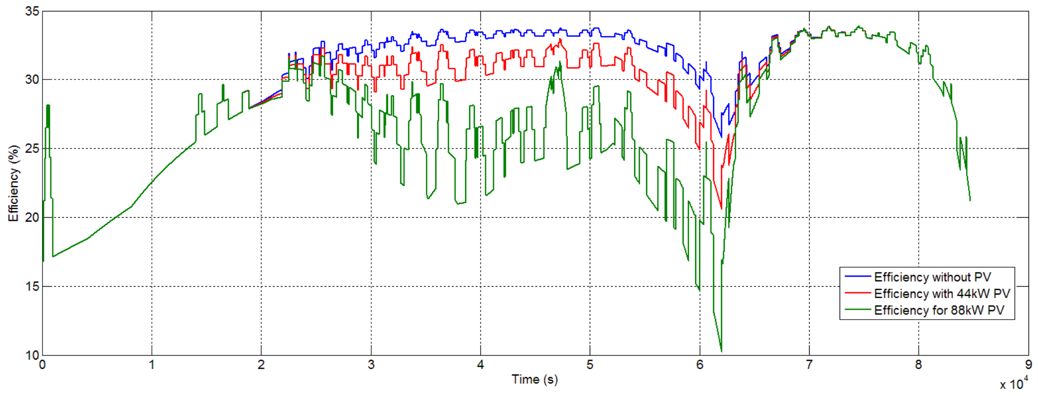

Figure 5-12: Efficiency for 2nd load profile with multi-level of PV power

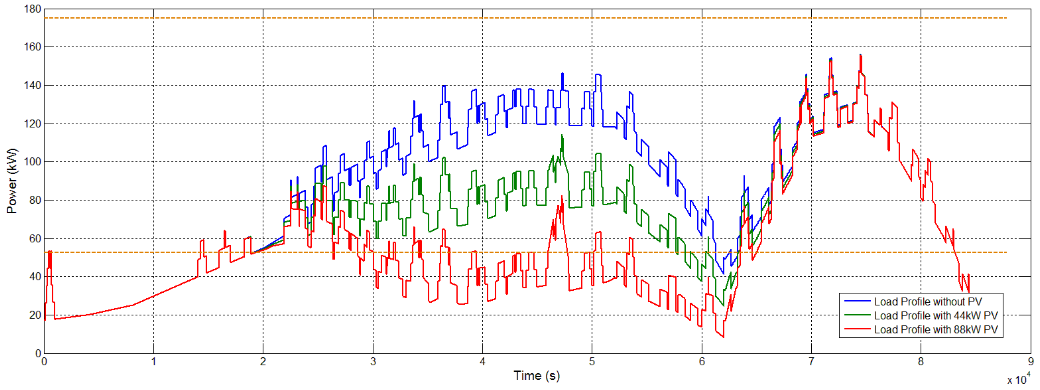

Figure 5-13: 1st Load profile with multi-level of PV power

Table 5-1 shows that a single genset with average load 103kW as shown in Figure 5-11 works very efficiently especially when PV power is zero. On the other hand, when the average load is 75kW as shown in load profile 2, the genset now works with very low efficiency when PV start to inject power into the system. Moreover it works near or even less than 30% of rated capacity with 88kW PV power as shown in Figure 5-13 where the dashed orange lines represent the limit of genset. As a result, this will reduce the genset life cycle and increase the overhaul cost. This relation between the efficiency and power should reduce to increase the average efficiency.

Table 5-1: Result of using one genset for different load profiles and PV peak power

	Load Profile 1			**Load Profile 2**		
PV Peak Power	0 kW	44kW	88kW	0 kW	44kW	88kW
Fuel Consumption (L)	779.9	689.6	602.9	603.8	515.9	431.7
Efficiency (%)	33	32.4	31.5	31.2	30.17	28.26
Cyclic	1	1	1	1	1	1
Working percentage per Day (%)	100	100	100	100	100	100
Energy Total (MWh)	2.752	2.392	2.032	2.026	1.66	1.305

(ii) Multi-Diesel genset:

There are two ways to operate diesel gensets in parallel first one is the basic case where there is no economic dispatch algorithm which depend only on primary controller and using external controller only turning on/off the units, the second way is to operate multi genset using economic dispatch algorithm which is implemented in supervisory controller. The ED algorithm was discussed in Chapter 3

a. Without supervisory controller "Primary controller Only"

This case is to illustrate the cycling problem and efficiency comparing to the case that uses supervisory control with ED algorithm.

As shown in chapter 3, a three genset system scheme is used to share the load demand. Using only the primary controller where the power always relates to frequency by droop Table 5-2 shows the result for multi genset using primary controller and commitment table shown in Table 2-6 with multi penetration level of PV power source.

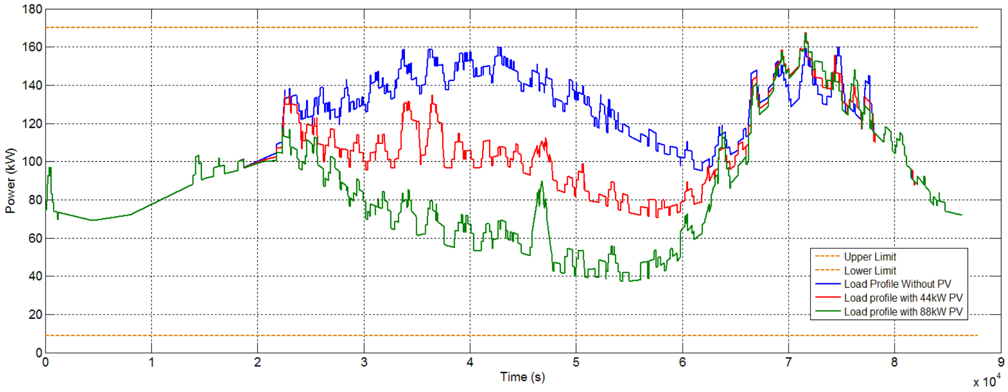

Figure 5-14 : Load Demand for 1st load profile for multi penetration level of PV power using primary control only

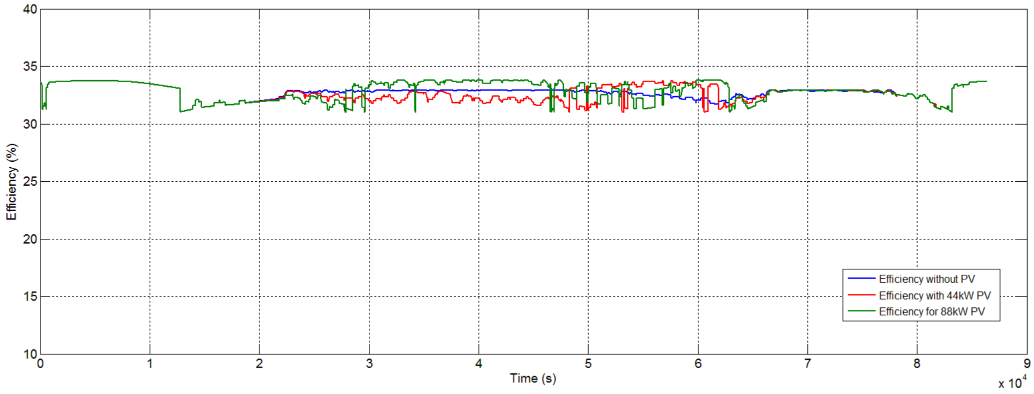

Figure 5-15 : System efficiency for 1st load profile multi penetration level of PV power using primary control only

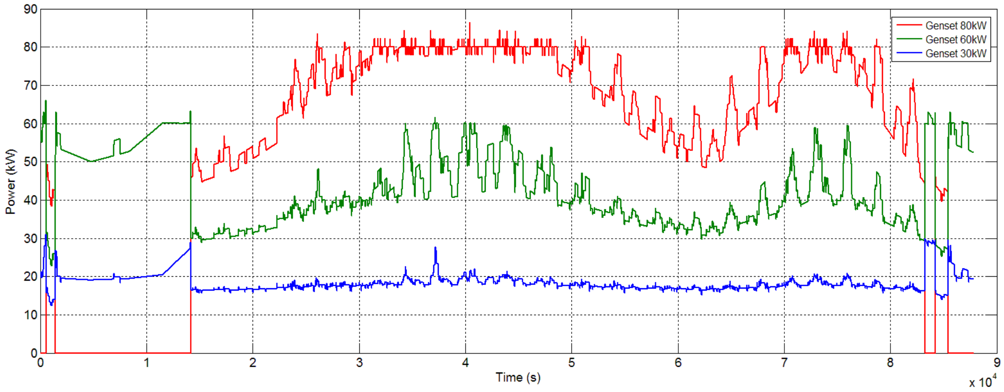

Figure 5-16: 1st load profile for each genset without PV using primary control only

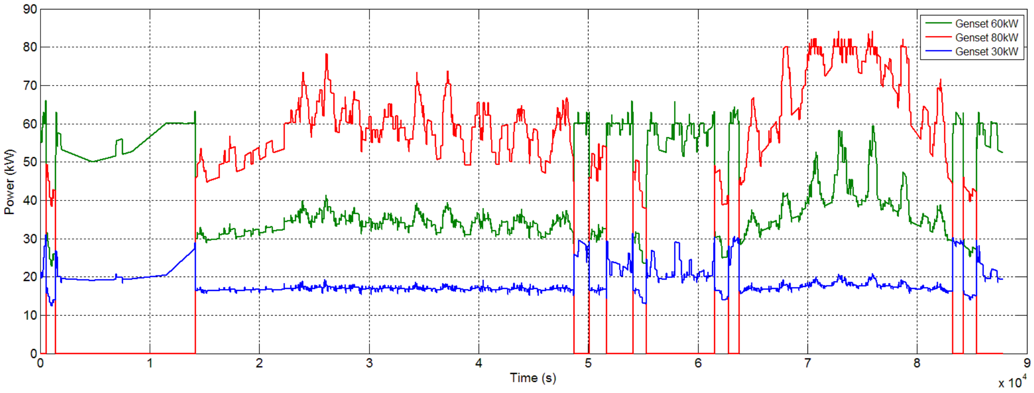

Figure 5-17: 1st load profile for each genset for 44kW PV using primary control only

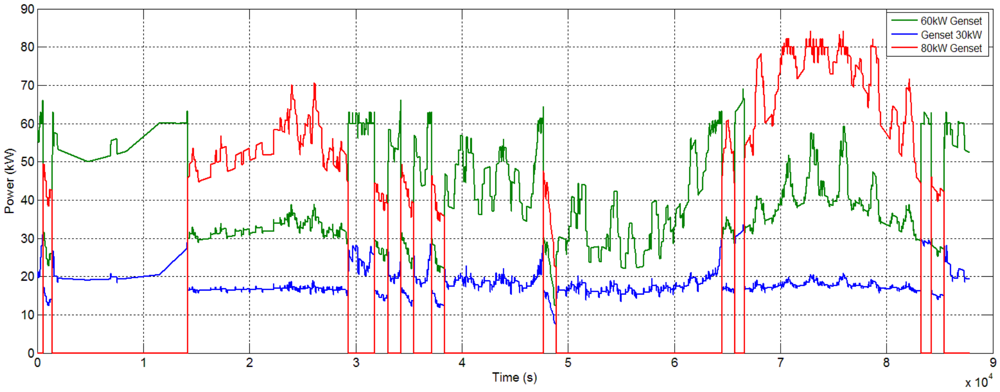

Figure 5-18: 1st load profile for each genset for 88kW PV using primary control only

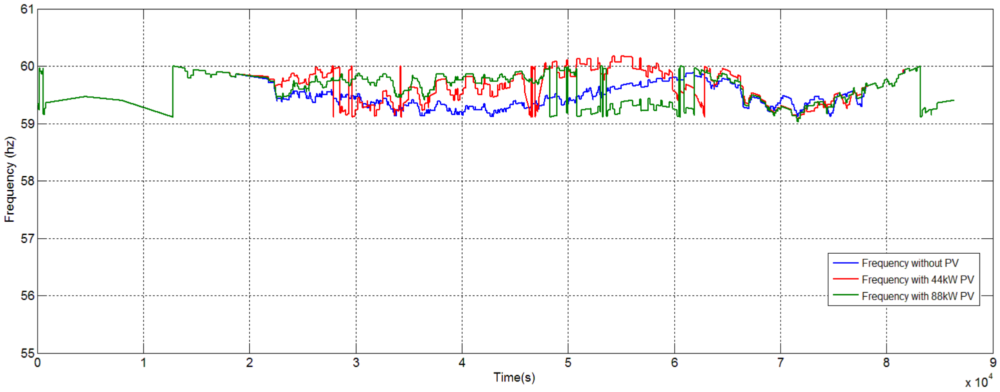

Figure 5-19: Frequency for 1st load profile multi PV power using primary control only

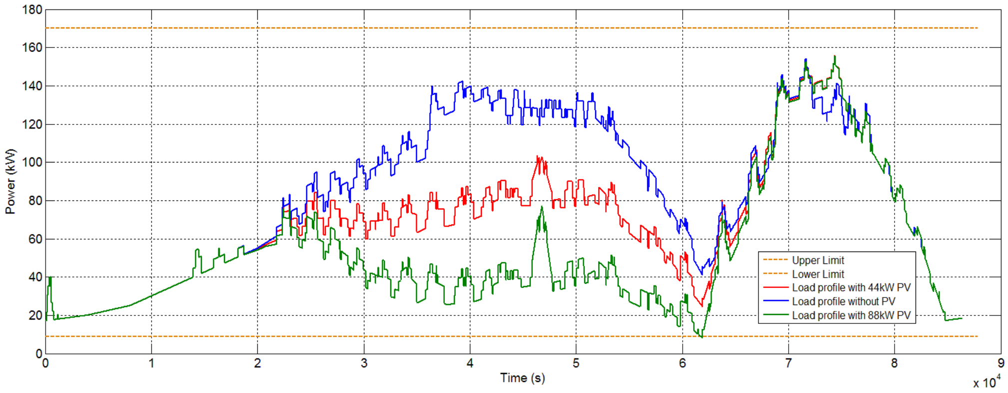

Figure 5-20: 2nd load profile for multi penetration level of PV power using primary control only

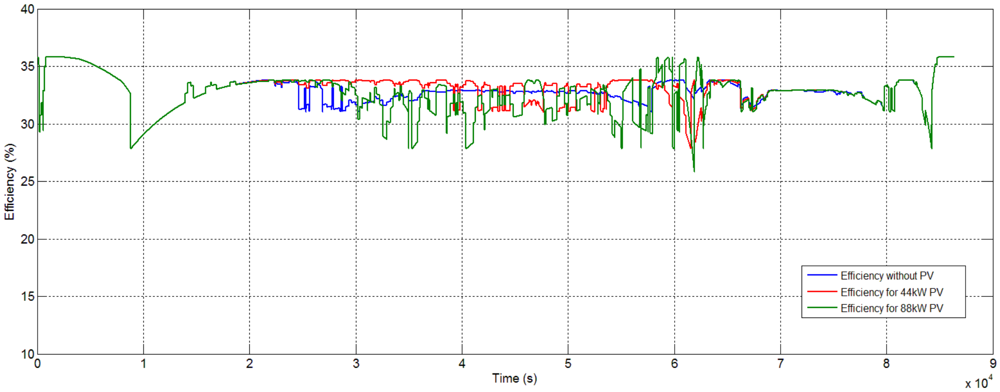

Figure 5-21: System efficiency for 2nd load profile multi penetration level of PV power using primary control only

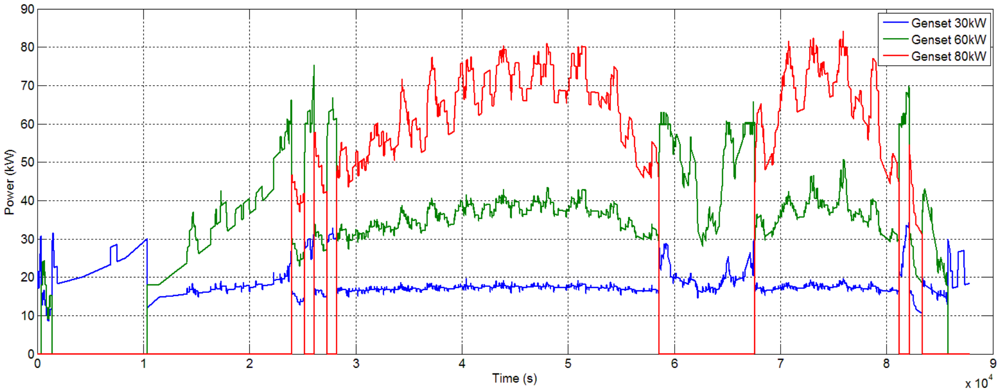

Figure 5-22: 2nd load profile for each genset without PV using primary control only

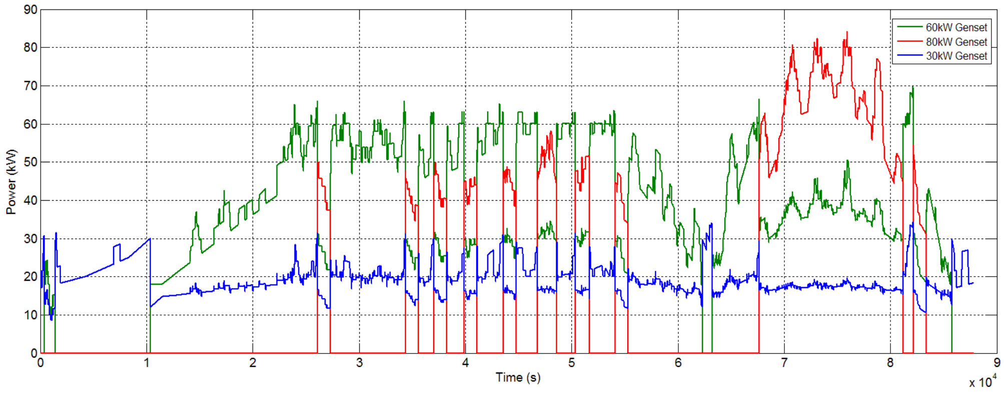

Figure 5-23: 2nd load profile for each genset for 44kW PV using primary control only

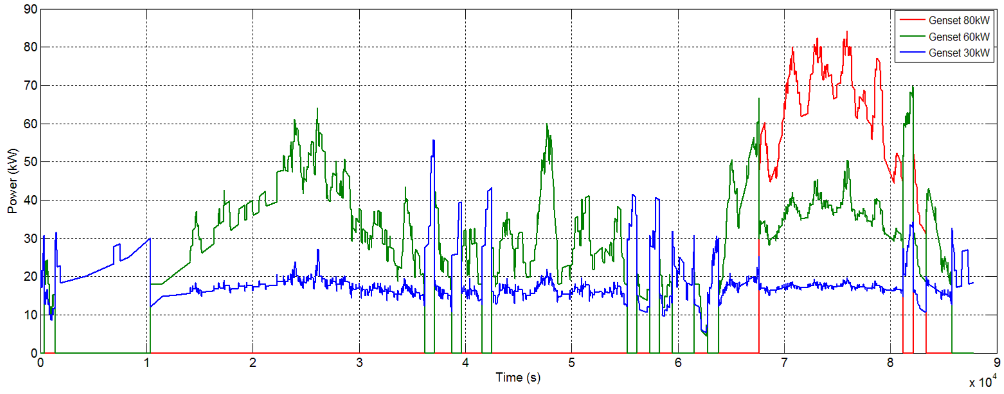

Figure 5-24: 2nd load profile for each genset for 88kW PV using primary control only

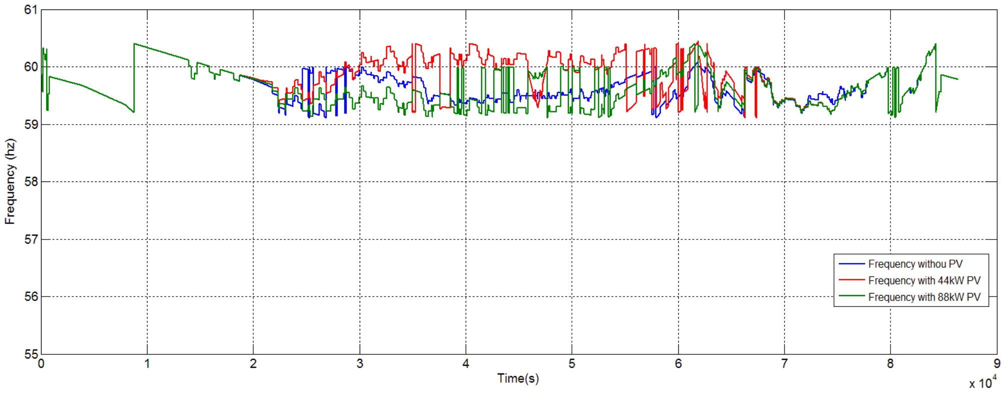

Figure 5-25: Frequency for 2nd load profile with multi PV power using primary control only

Table 5-2 shows that genset cycling is increased whenever the PV power increases or the load demand decreases. This will reduce the life time cycle of the gensets. From Figure 5-15 and Figure 5-21, the variation of efficiency increased when the power is decreased and the minimum value happens when the power goes lower than 42kW when the 60kW is working in minimum efficiency region. On the other hand, the relation between the power and efficiency is reduced compared to the single genset case. The load demand always is in the working range as shown in Figure 5-14 and Figure 5-20 and the average efficiency is increased.

The frequency ~~is~~ varies depending on the load as shown in Figure 5-19 and Figure 5-25 but it is still in the range of 60 ±1 Hz.

Table 5-2: Multi-genset without supervisory controller

	Load Profile 1									**Load Profile 2**								
PV Peak Power	0 kW			44kW			88kW			0 kW			44kW			88kW		
Fuel Consumption (L)	793.5			690.9			581			577.1			466.3			367		
Efficiency (%)	32.7			32.55			32.76			32.66			32.9			32.62		
Cyclic	1	1	4	1	1	11	1	1	10	1	4	10	1	5	17	1	13	5
Working percentage per Day (%)	100	100	82	100	100	69.3	100	100	42.8	100	87.8	52.6	100	87.4	23.36	100	79.7	16
Energy Total (MWh)	2.778			2.407			2.036			2.017			1.641			1.281		
Mean Frequency (HZ)	59.5			59.62			59.6			59.66			59.83			59.64		
STD	0.225			0.28			0.257			0.27			0.33			0.32		

b. With supervisory controller

The supervisory control which includes ED problem solver is responsible to share the power between the working gensets to increase the total efficiency of the system as shown in chapter 3. Two cases are discussed, first without DSM and second with DSM.

- <u>Case 1 : multi-genset without DSM :</u>

This case will illustrate the benefit of ED method base on reduction of fuel consumption and increasing the efficiency.

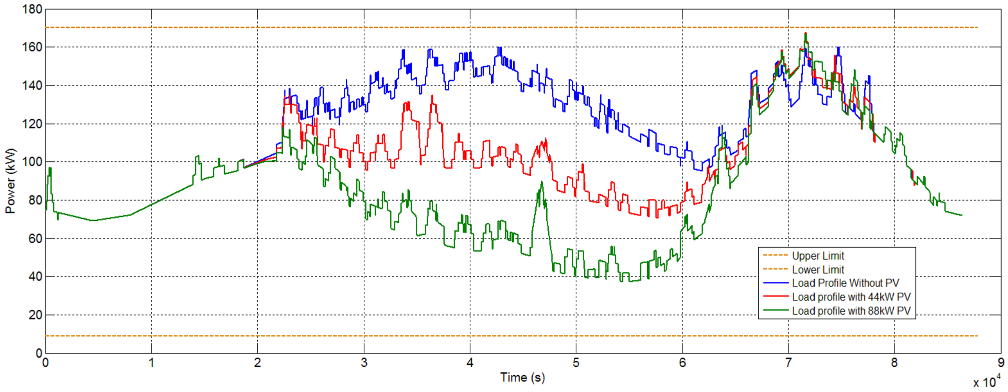

Figure 5-26: 1st load profile for multi penetration level of PV power without using DSM

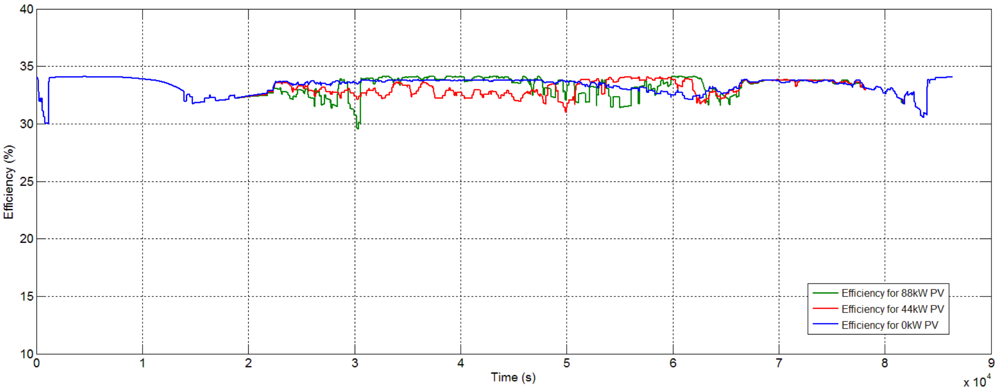

Figure 5-27: System efficiency for 1st load profile multi penetration level of PV power without using DSM

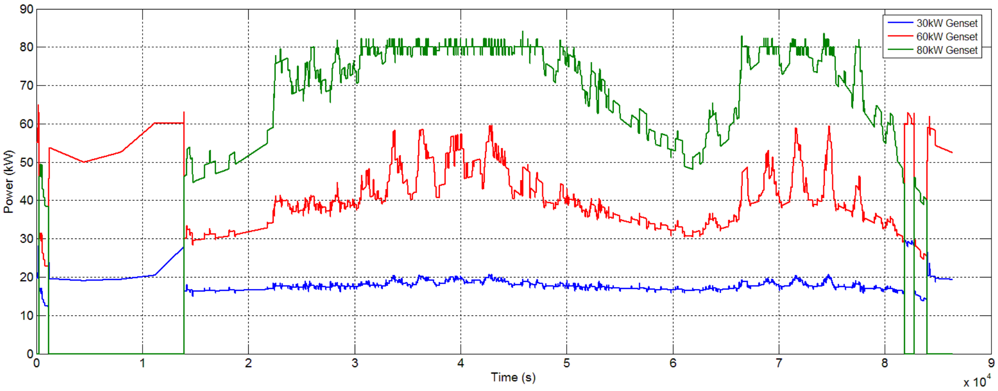

Figure 5-28: 1st load profile for each genset without PV without using DSM

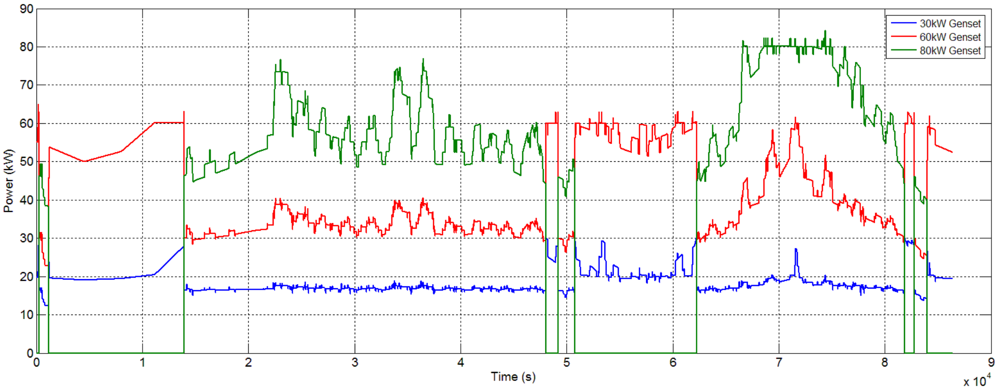

Figure 5-29: 1st load profile for each genset for 44kW PV without using DSM

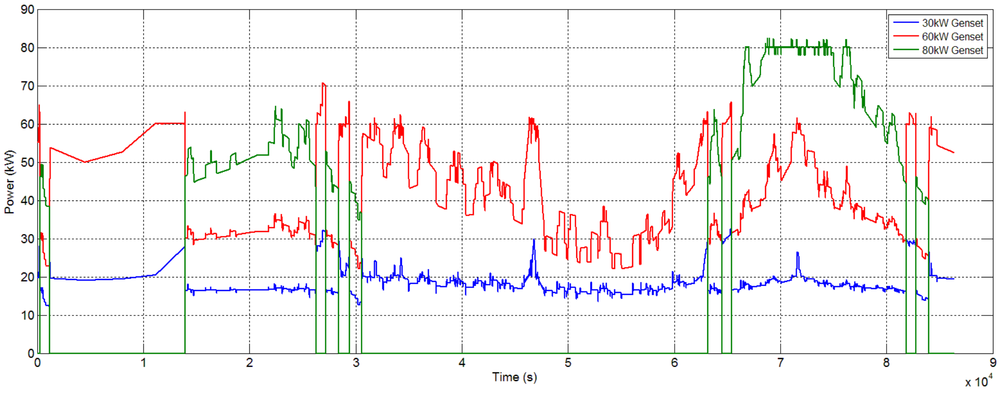

Figure 5-30: 1st load profile for each genset for 88kW PV without using DSM

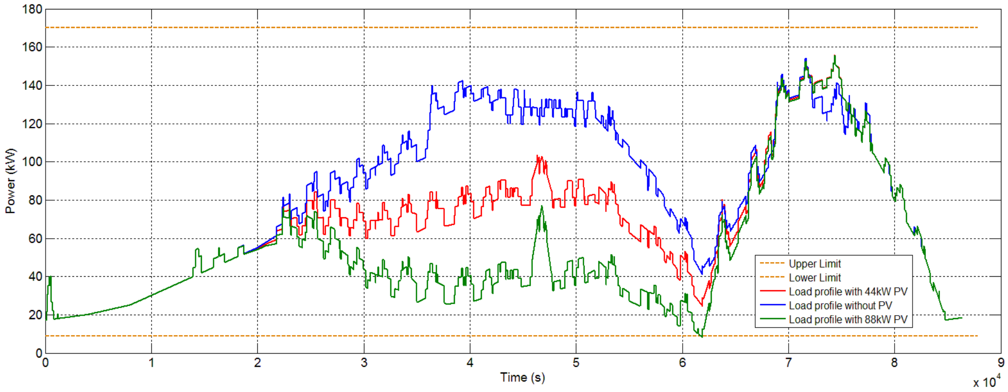

Figure 5-31: 2nd load profile for multi penetration level of PV power without using DSM

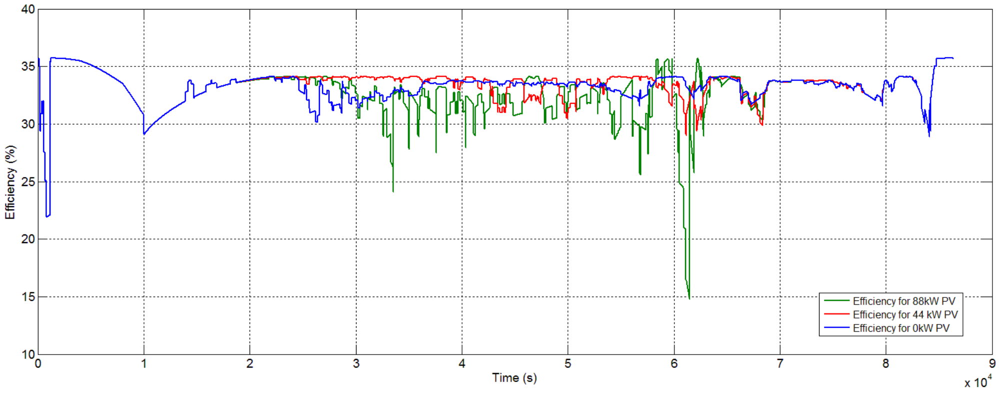

Figure 5-32: System efficiency for 2nd load profile multi penetration level of PV power without using DSM

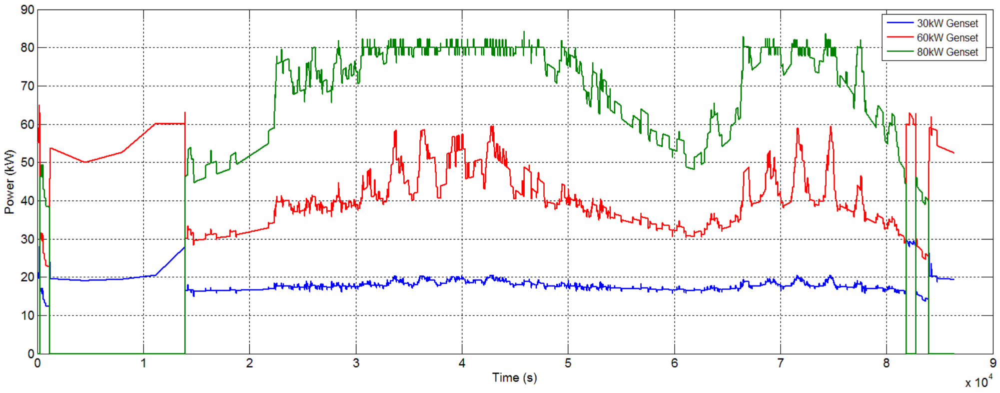

Figure 5-33: 2nd load profile for each genset without PV without using DSM

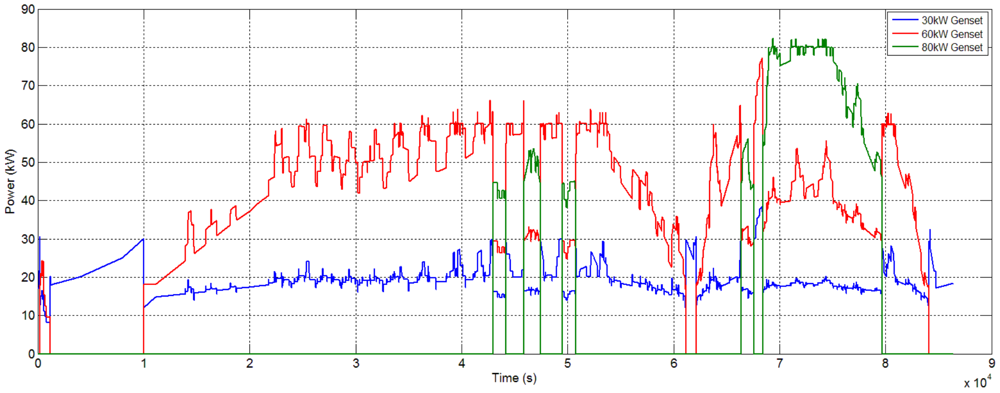

Figure 5-34: 2nd load profile for each genset with 44kW PV without using DSM

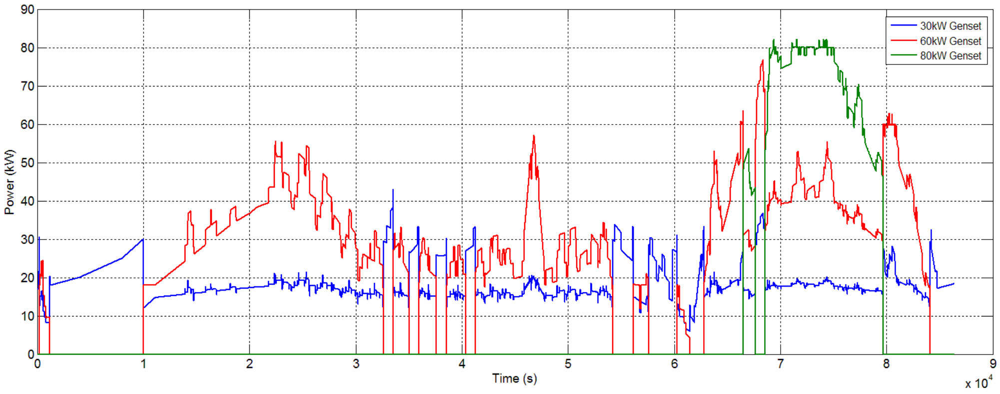

Figure 5-35: 2nd load profile for each genset for 88kW PV

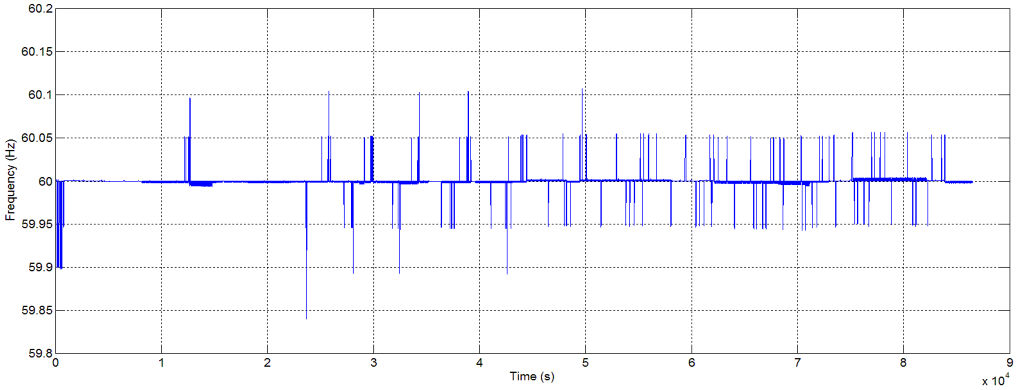

Figure 5-36: Frequency for both load profiles without using DSM

As shown in Table 5-3, and comparing to Table 5-4 , the system is now more optimised. The effect of the power on the efficiency is reduced comparing to the case of primary controller only. The working percentage per day is decreased and cycling is decreased. The frequency is regulated to 60 Hz by the supervisor controller. These improvements have a positive effect of the life time and overhaul cost.

Table 5-3: Multi-genset without DSM

	Load Profile 1									**Load Profile 2**								
PV Power Peak	0 kW			44 kW			88 kW			0 kW			44 kW			88 kW		
Fuel Consumption (L)	777.8			679.6			573.1			567.8			460.2			364		
Efficiency (%)	33.37			33.09			33.2			33.19			33.33			32.88		
Cyclic	1	1	4	1	1	6	1	1	8	1	3	5	1	4	6	1	10	3
Working percentage per Day (%)	100	100	81	100	100	66.3	100	100	40	100	86.8	49.7	100	85.7	19	100	75.7	14.2
Energy Total (MWh)	2.777			2.406			2.036			2.017			1.641			1.281		
Mean Frequency (HZ)	60			60			60			60			60			60		
STD	0.001			0.001			0.001			0.001			0.001			0.001		

Case 2 : multi-genset with DSM:

This case will illustrate the benefit of using DSM, by means of frequency control, to reduce cycling of the gensets and increase the average efficiency.

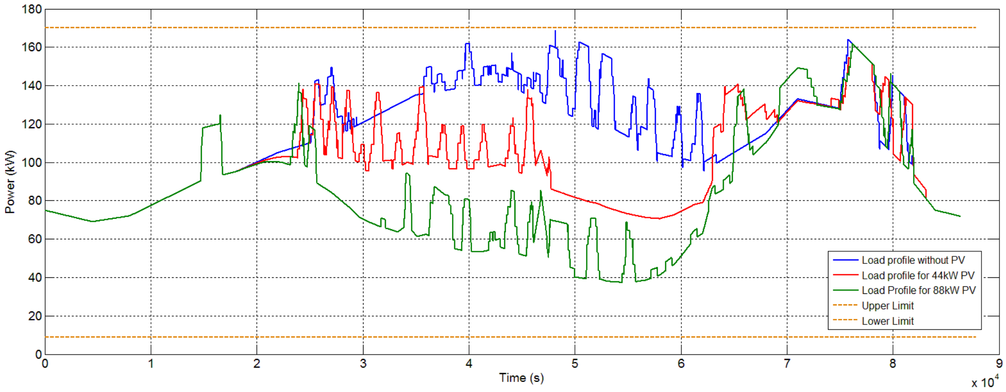

Figure 5-37 : 1st load profile for multi penetration level of PV power using DSM

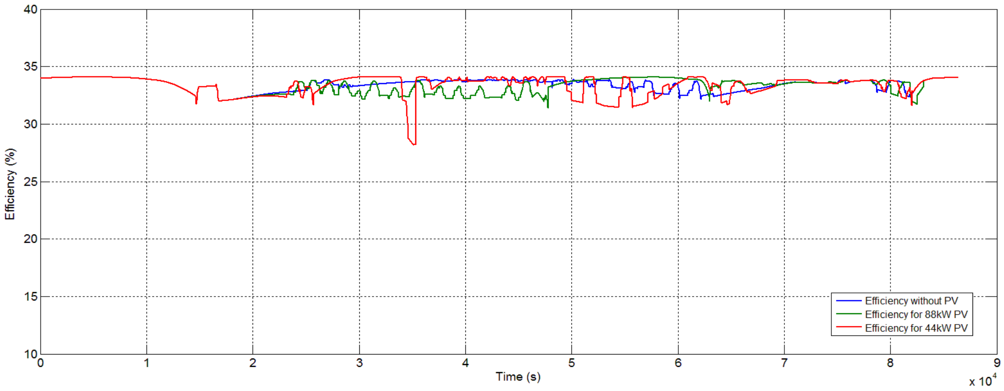

Figure 5-38 : System efficiency for 1st load profile multi penetration level of PV power using DSM

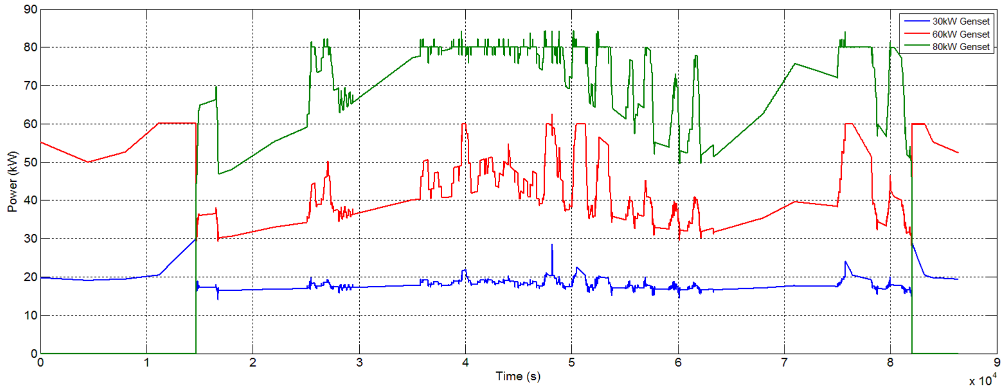

Figure 5-39: 1st load profile for each genset without PV using DSM

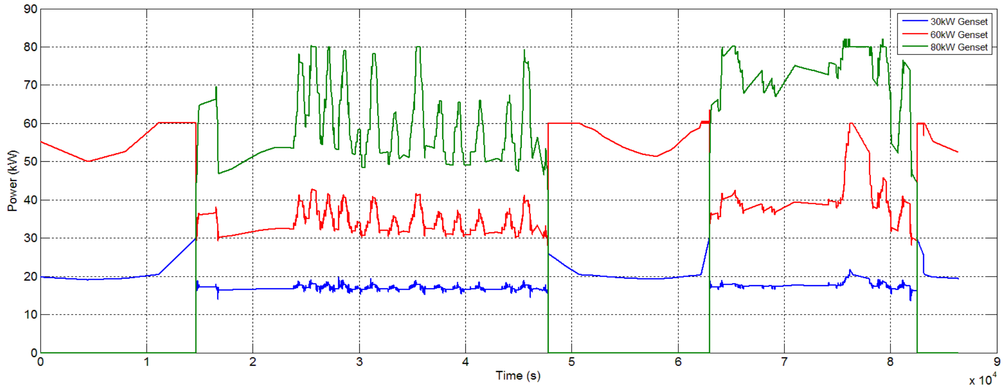

Figure 5-40: 1st load profile for each genset for 44kW PV using DSM

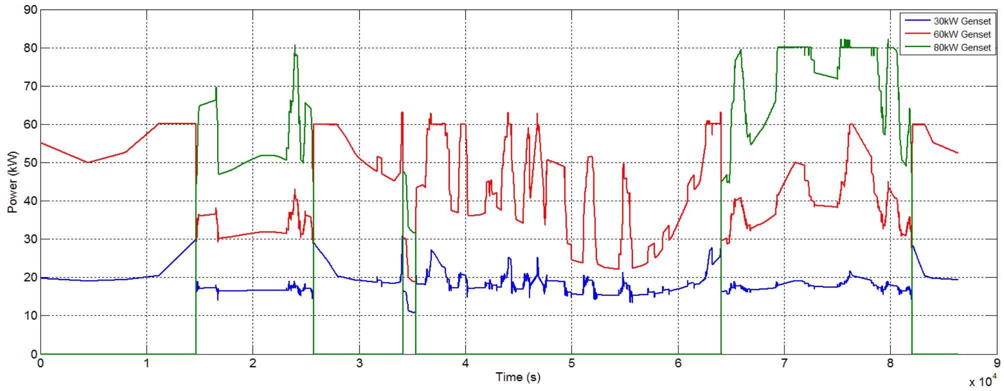

Figure 5-41: 1st load profile for each genset for 88kW PV using DSM

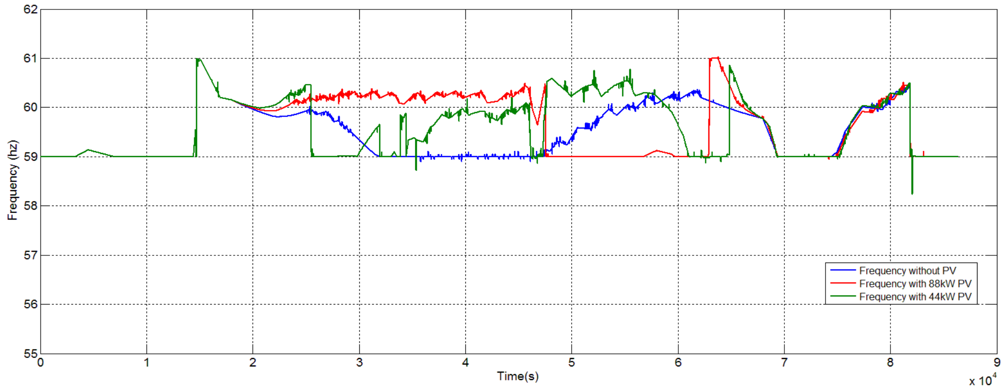

Figure 5-42: Frequency for 1st load profile multi PV power using DSM

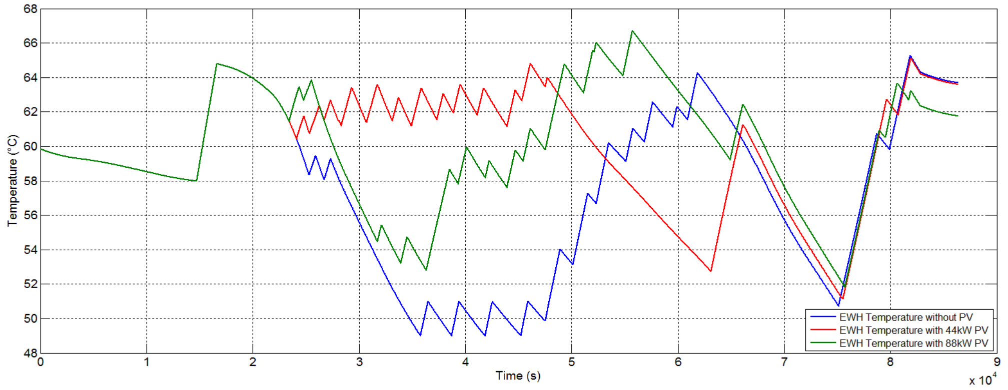

Figure 5-43: EWH temperature for multi PV power using DSM for 1st load profile

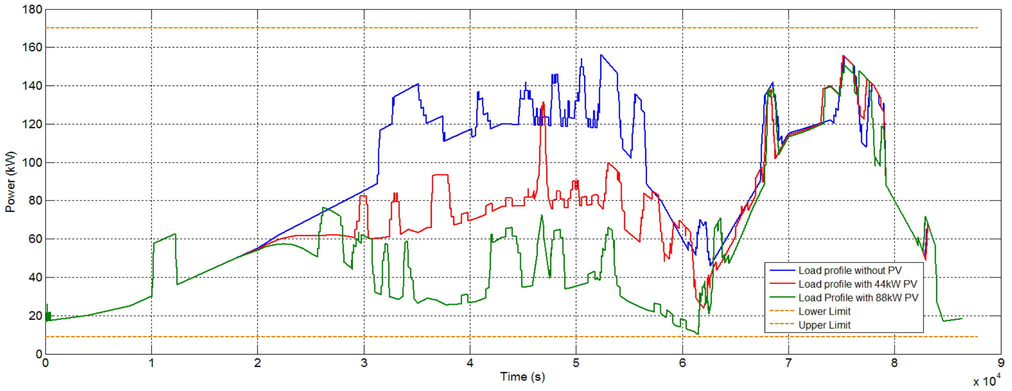

Figure 5-44: 2nd load profile for multi penetration level of PV power using DSM

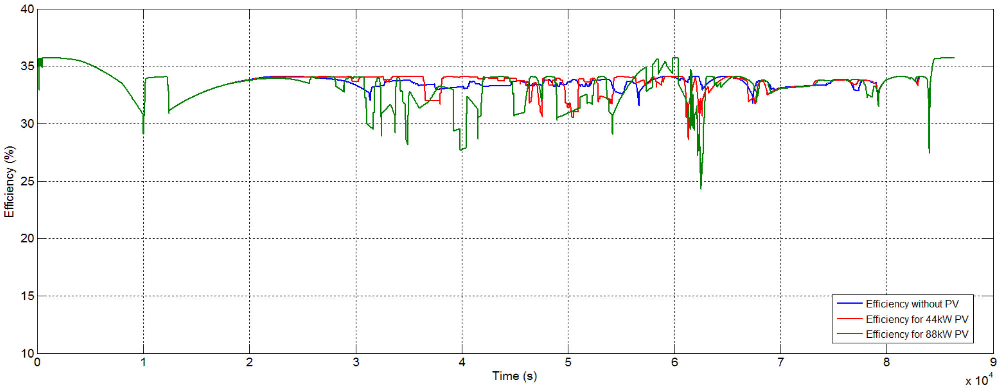

Figure 5-45: System efficiency for 2nd load profile multi penetration level of PV power using DSM

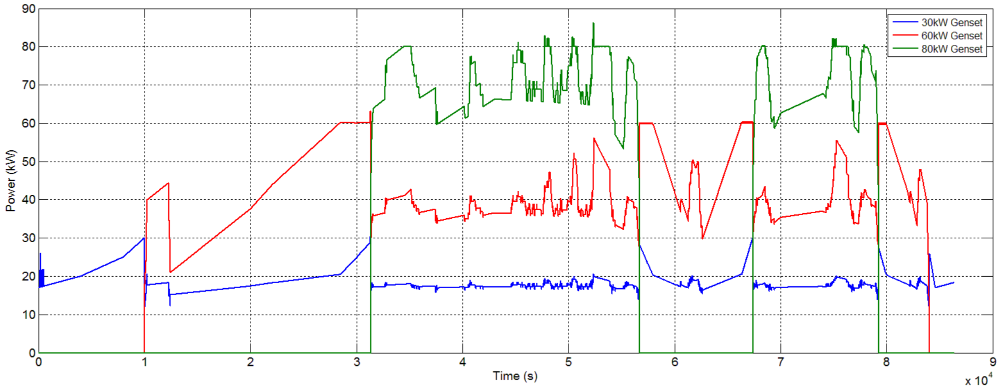

Figure 5-46: 2nd load profile for each genset without PV using DSM

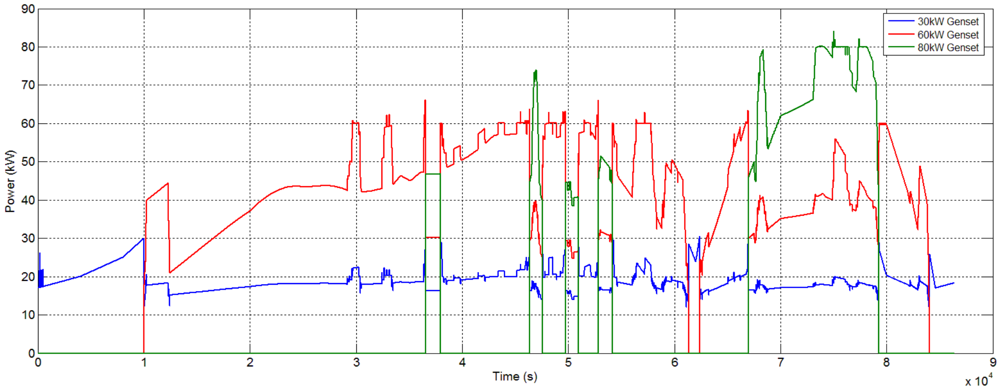

Figure 5-47: 2nd load profile for each genset for 44kW PV using DSM

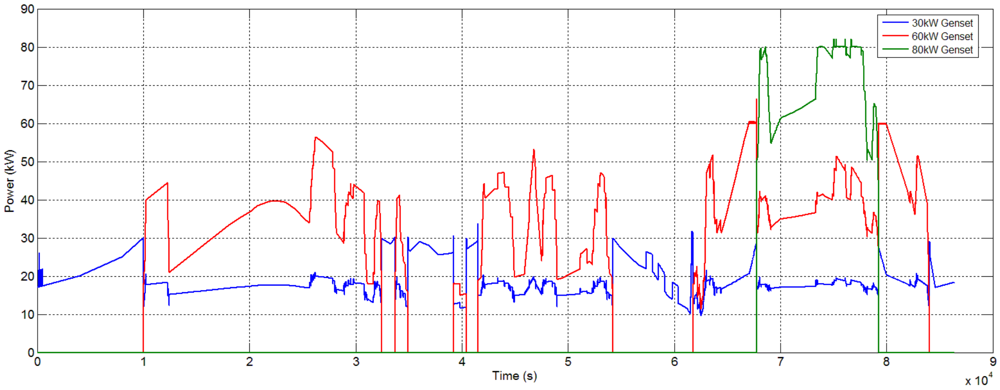

Figure 5-48: 2nd load profile for each genset for 88kW PV using DSM

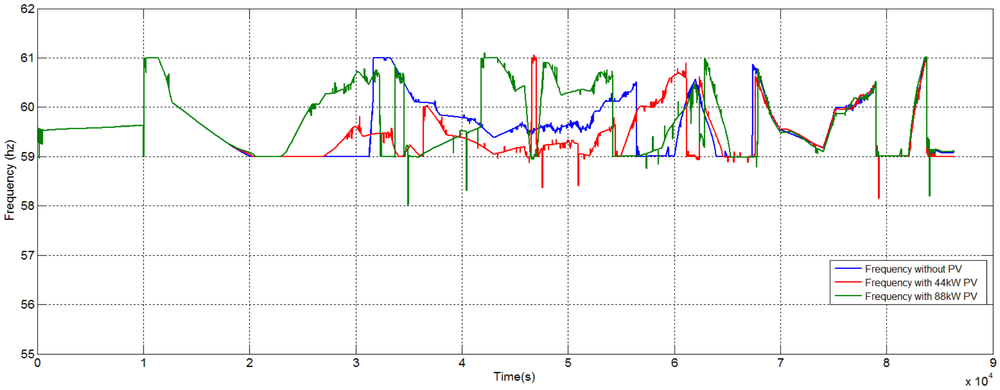

Figure 5-49: Frequency for 2nd load profile multi PV power using DSM

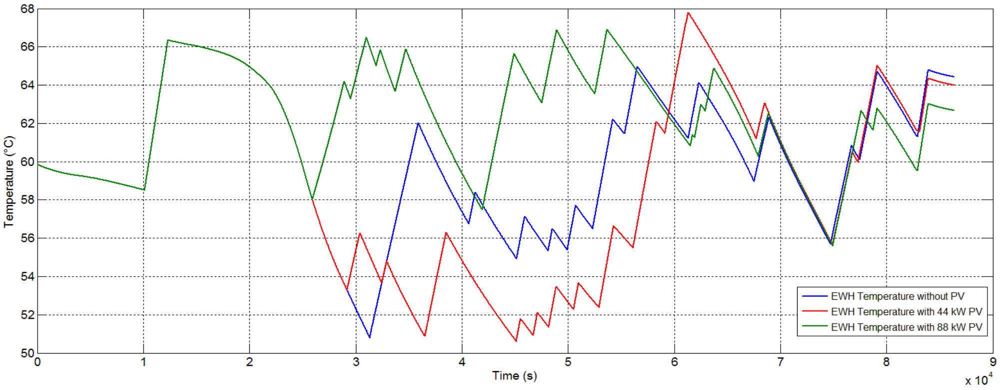

Figure 5-50: EWH temperature with multi PV power using DSM for 2nd load profile

From Table 5-4 comparing to Table 5-3, the fuel consumption is reduced in all cases, especially in the case of the 2nd load profile with 88kW PV where the reduction of fuel consumption reaches 1%. The main advantage of applying DSM is reducing the cycling of the gensets and their working percentage per day.

The frequency in DSM system varies independently of the load, this variation occurs because the DSM controller uses the frequency as one-way communication signal with EWH to increase or decrease the load when needed.

Table 5-4: Multi-genset with DSM

	Load Profile 1									**Load Profile 2**								
PV Power Peak	0 kW			44kW			88kW			0 kW			44kW			88kW		
Fuel Consumption (L)	774.8			675			569.1			562.5			456.5			360.7		
Efficiency (%)	33.4			33.5			33.5			33.75			33.52			33.3		
Cyclic	1	1	2	1	1	3	1	1	4	1	2	3	1	3	6	1	6	2
Working percentage per Day (%)	100	100	78	100	100	61	100	100	35	100	85.7	43	100	84.5	20	100	69.2	13.2
Energy Total (MWh)	2.771			2.42			2.045			2.03			1.638			1.286		
Water Temp ℃	58			59			60.02			60.18			59.15			62.32		
Mean Frequency (HZ)	59.5			59.6			59.6			59.62			59.42			59.73		
STD	0.516			0.61			0.58			0.544			0.501			0.622		

To illustrate how the DSM works, Figure 5-50 shows the temperature for a single home EWH. From the midnight (0 second) until 10e3 second the heater will not work because the temperature in the EWH is more than the set point which is 59 °C. The set point comes from the DSM controller, over frequency, using droop relation as discussed in chapter 4. The DSM block selects this frequency to avoid adding a new genset as shown in Figure 5-46, Figure 5-47 and Figure 5-48 where only the 30kW genset is working. A new update for set point comes in at 10e3 second because a new genset will be on to follow the uncontrollable load. Because of the new genset will work in light load, the DSM increased the set point and made all EWH work, this action will increase the load by 45kW which will increase the system efficiency as shown in Figure 5-45. The set point, which is related to frequency, is decreased by DSM between 12e3 and 20e3 second to limit the energy that is consumed by the EWH.

Between t = 20e3 and 30e3 second, the EWH set point is fixed to minimum as shown in the case without PV in Figure 5-49 because the 2nd genset, which is rated at 60kW, is working close to its limit as shown in Figure 5-47. Moreover the efficiency now is high enough as shown in Figure 5-47 and the EWH temperature is approximately high as shown in Figure 5-50. For that, there is no need to turning on the EWH.

This complicated logic is repeated always in DSM controller which will guarantee that the system always be optimized without interference from a human operator.

Table 5-5 and Table 5-6 compare the results for system using DSM and without DSM.

The main conclusion from the results is that the use of DSM has a bigger impact for the light load profile. For both load profiles the cycling of the gensets is reduced and their efficiency is increased when using DSM.

Finally, because there is no information on the data sheets regarding the costs of turning on/off the gensets, overhaul cost and also on the additional cost of a controllable EWH unit the payback time of such a system cannot be calculated at this time.

Table 5-5: Comparison between DSM system and without DSM for 1st Load profile

	Consumption (L)			**Efficiency (%)**			**Cycling (#)**		
PV Power (kW)	**0**	**44**	**88**	**0**	**44**	**88**	**0**	**44**	**88**
With DSM	774.8	675	569.1	33.4	33.5	33.5	2	3	4
Without DSM	777.8	679.6	573.1	33.37	33.09	33.2	4	6	8
With Primary Control only	793.5	690.9	581	32.7	32.55	32.76	4	11	10

Table 5-6: Comparison between DSM system and without DSM for 2nd Load profile

	Consumption (L)			**Efficiency (%)**			**Cycling (#)**		
PV Power (kW)	**0**	**44**	**88**	**0**	**44**	**88**	**0**	**44**	**88**
With DSM	562.5	456.5	360.7	33.75	33.52	33.3	5	9	8
Without DSM	567.8	460.2	364	33.19	33.33	32.88	8	10	13
With Primary Control only	577.1	466.3	367	32.66	32.9	32.62	13	20	17

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Summary

This thesis focused on an alternative approach for enhancing the performance of a PV-diesel hybrid mini-grid system: The use of demand side management (DSM) to make the diesel gensets operate more frequently at points of high efficiency, despite variations in the load demand and PV power generation. Electric water heaters (EWHs) were found to be good candidates for this approach because of their power ratings and natural thermal energy storage capabilities. The use of the grid frequency for controlling the power consumed by the EWHs does away with the need for a dedicated communication channel with the supervisory controller.

The power vs. frequency droop control parameters and the recommended operating region of the diesel gensets were defined based on the diesel genset power ratings. DSM based on frequency variation was successful with the frequency range recommended in ISO standards for diesel based grids, which is between 59Hz to 61Hz. In addition to the diesel gensets, the characteristics and behaviour of photovoltaic (PV) power sources were studied.

The EWH parameters and its behaviour were discussed in this thesis. The EWH was modeled using matlab/simulink and a typical 24-hr water draw profile was used to compute the power consumed by a residential type EWH.

Parallel operation for diesel gensets is also discussed in this thesis. Two methods of sharing power between gensets which is the Primary controller only and Economic Dispatch (ED) were considered and compared under various operating conditions.

The simulation results show~~s~~ that when the rated power of the PV source increased or the load demand decreased, the efficiency of the system is decreased and genset cycling in increased. On the other hand, when using ED with DSM the impact of the load on the efficiency will reduce and the negative effect of reduction of power which is the cyclic and working percentage peer day for each genset will reduce too.

In addition, the results show~~s~~ that the average hot water temperature of the EWH can be kept within the recommended range, for client satisfaction, ensuring that such an approach is likely to be well received by the owners of the residential type EWHs.

This improvement will increase the efficiency, lifetime of gensets and also reduce the fuel consumption.

6.2 Future Work

For future work, there are many things that can be investigated to further assess the benefits of using DSM in a PV-diesel hybrid mini grid system.

First one is the real-time identification of how much frequency variation is required to get the desired variation in power demanded from the diesel power plant. It should be noted that variations in the water draw from the EWHs, which can vary significantly from system to system and cannot be controlled, can have a higher impact on the power consumed by the EWHs than that of the grid frequency, which has to be kept in a relatively narrow range. Besides, distribution systems usually include significant shares of induction motor based loads, whose power demand also varies with the grid frequency.

Another is the combined use of DSM with energy storage units such as batteries and flywheels. This should allow the reduction of the size and cost of the energy storage units, if used as the only energy management elements, as well as reduce the uncertainties in how much and how often one can make the diesel gensets operate at their high efficiency points.

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