POWER DISPATCH OF HYBRID PHOTOVOLTAIC-GENSET SYSTEM USING HEURISTIC BIO-INSPIRED APPROACH

CHUA HOCK GUAN

A thesis submitted in

fulfillment of the requirements for the award of the

Degree of Master in Electrical Engineering

Faculty of Electrical and Electronic Engineering

Universiti Tun Hussein Onn Malaysia

SEPTEMBER 2013

ABSTRACT

Malaysia is advancing into solar energy as a replacement of alternative source of an electrical energy production to meet the escalation load demand due to the strategic equatorial region. Hybrid *PV-Genset* system are developed to generate power as it can be fitted into its local geography and other condition according to specification. However, this does not guarantee that the hybrid system generates power optimally because weather conditions (solar insolation, temperature and others) changes periodically and influences the power generation and dispatch. Therefore, under these circumstances the hybrid system does not operate optimally and lead to over stress the system components resulting a higher maintenance cost due to frequent wear and tear. Particle Swarm Optimisation (*PSO*) is implemented into two non-linear optimisation areas such as the *PV* power tracker system and the power dispatch controller. The required bio-inspired algorithm searches the best potential optimal state for the maximum *PV* power generation as well as determining the suitable power dispatch arrangement of the small scale hybrid *PV-Genset* system. Fuzzy Logic Controller (*FLC*) and logic gate are used as a battery monitor for the power dispatch controller depending on the capability and availability. The hybrid *PV-Genset* system modelling was simulated using two types of tropical weather conditions (sunny and rainy). As an outcome, the obtained simulation results and series of analysis are conducted using MATLAB/SIMULINK environment. Through the analysis and results, the contribution of each hybrid system component operates at the optimum level and hybrid power is dispatch to the load based on the hybrid *PV-Genset* system capability.

ABSTRAK

Disebabkan oleh rantau strategik khatulistiwa, Malaysia meningkatkan penghasilan tenaga solar sebagai pengganti sumber alternatif pengeluaran tenaga elektrik untuk memenuhi permintaan beban elektrik. Sistem hibrid *PV-Genset* dicipta dan dipasang mengikut spesifikasi yang sesuai dengan geografi tempatan serta keadaan lain untuk penjanaan kuasa elektrik. Walau bagaimanapun, ini tidak menjamin bahawa penjaaan kuasa elektrik oleh sistem hibird beroperasi pada tahap yang optimum kerana perubahan cuaca (radiasi solar, suhu dan lain-lain) mempergaruhi penjanaan dan penghantaran kuasa. Jikalau operasi ini berterusan, sistem hibrid tidak akan beroperasi secara optimum dan ini menyebabkan tekanan ke atas komponen sistem dan mengakibatkan kos penyelenggaraan yang tinggi kerana kerosakan yang kerap. Particle Swarm Optimisation (*PSO*) digunakan di dalam dua bahagian pengoptimuman bukan linear seperti sistem pengesanan kuasa *PV* dan pengawal penghantaraan janakuasa. Algortima bio-inpirasi akan mencari keadaan optimum untuk meningkatkan penjanaan kuasa sistem *PV* serta menentukan susunan sistem hibrid yang berskala kecil bagi penghantaraan kuasa. Pengawal Logik Kabur (*FLC*) dan get logik digunakan sebagai pengawal batteri untuk pengawal penghantaran kuasa bergantung kepada keupayaan dan kemampuan batteri. Simulasi permodelan sistem hibrid *PV-Genset* mengunakan dua jenis keadaan cuaca tropika (cerah dan hujan). Keputusan simulasi yang diperolehi melalui penggunaan perisian MATLAB/SIMULINK. Melalui analsis dan keputusan, sumbangan setiap komponen serta penghantraan kuasa hibrid beroperasi pada tahap yang optimum bergantung pada permintaan beban berdasarkan kepada kemampuan sistem hibrid *PV-Genset*.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

w	Weight (unitless)
b	Bias (unitless)
m^2	Meter square
t	Time (*min or s*)
h	Hour
$°C$	Celsius
R^2	Coefficient of determination
Ah	Ampere Hour
Wh	Watt Hour
η	Discharging Rate
P (+)	Positive
N (-)	Negative
G	Irradiance/Insolation (kw/m^2)
I	Current (A)
J	Joule
P	Power (W)
$P_{PV\ Optimal}$	Optimal Photovoltaic Power (W)
P_{pv}	Photovoltaic Power (W)
P_{LEF}	Load Power (W)
P_B	Battery Power (W)
P_D	Diesel Generator Power (W)

P_t	Total Power Generated (*W*)
T	Temperature (°*C or K*)
V	Voltage (*V*)
W	Watt
RM	Ringgit Malaysia
G_{MEAS}	Measured Irradiance/Insolation
G_{EST}	Estimated Irradiance/Insolation
V_{MPP}	Voltage at Maximum Power Point
P_{MPP}	Maximum Power Point
I_{MPP}	Current Maximum Power Point
V_{OC}	Open Circuit Voltage
I_{PV}	Photovoltaic Current
AC	Alternating Current
AI	Artificial Intelligence
ANN	Artificial Neural Network
DC	Direct Current
DFC	Dynamic Filter/Capacitor
DG	Diesel Generator
DP	Dynamic Programming
DSM	Demand Side Management
F	Fuel Consumption
FIS	Fuzzy Inference System
FLC	Fuzzy Logic Controller
GA	Genetic Algorithm
Genset	Generator set
GPF	Green Power Filter
GUI	Graphical User Interface
Ms	Module in Series
Mp	Module in Parallel

MAPE	Mean Absolute Percentage Error
MAE	Mean Absolute Error
MLP	Multilayer Perceptron
MOPSO	Multi Objective Particle Swarm Optimisation
MPT	Maximum Power Tracking
MPPT	Maximum Power Point Tracker
NMSE	Normalised Mean Square Error
PI	Proportional Integral
PSO	Particle Swarm Optimisation
PV	Photovoltaic
PVA	Photovoltaic Array
PVDB	Photovoltaic-Diesel-Battery
RBF	Radial Basis Function
RMSE	Root Mean Square Error
SDL	Solar Data Logger
SFC	Specific Fuel Consumption
SOC	State of Charge
UMPSO	Uniform Design and Inertia Mutation Particle Swarm Optimisation
UTHM	Universiti Tun Hussein Onn Malaysia
UPS	Uninterruptable Power Supply
VSI	Voltage Source Inverter

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

Hybrid *PV-Genset* system is one of the most common integrated power generation system used in most countries. Furthermore, it is known for its reliable off-grid/stand-alone power supply. This chapter provides the general information of this research with brief explanation in each section. The respective sections are divided as project background, problem statement as well as the objective and scope of this research.

1.1 Project background

Interests on conserving and minimising the impact on the environmental issues are increasing as ideas on developing green technology for power generation application have attracted the attentions of many countries. Solar photovoltaic (*PV*) system generates pollution-free electricity and its solar energy is available at no cost, as compared to the conventional generation system that using fossil fuel. The advantage of solar energy is sustainable and eco-friendly. However, harnessing its energy leads to a major drawback due to the inconsistency as it fluctuates in nature. Climatic condition and fluctuation of solar insolation and temperature are the major setbacks for *PV* generator system. Therefore, integration with a diesel generator is required to curb the issue of inconsistency power supply from the *PV* generator. Nonetheless, it is not only to obtain a reliable and stable power supply but also to meet the high load demand at various operating conditions [1].

Power capacity of a diesel generator is available in wide range, from one kilowatt to several hundred kilowatts. Furthermore, it is widely use in either small or medium range size of power generation as an electrical energy production scheme [2]. Diesel generator is meant to operate during high load demand period simultaneously charging the storage battery to reach the highest generation efficiency and to reduce the fuel consumption [3].

Typically, hybrid *PV-Genset* system is often known as an alternative off-grid power supply, conventional generation system and islanded power supply. In order to design this hybrid system scheme, factors like weather condition, operation and maintenance has to be considered. Hence, the design and control operation of the system is constructed in such a way to adapt with the large number of non-linear variable components [4]. Most of the proposed empirical operation rules in the hybrid system can be said reasonable, however they are not suitable for optimal operation rules in regard to generator fuel consumption [3]. This is because the control operation rule does not determine the optimal operation of the diesel generator during low load demand.

Hybrid *PV-Genset* power generation performance is dependent on factors like cell temperature, fault level of *PV* array, output power, insolation level, operation and fuel consumption of diesel generator. Solar insolation level defines as the solar radiation energy received on the given surface area and recorded during a given time. In *PV* system, a constant cell temperature with a higher insolation level results higher generation on power and voltage. If cell temperature rises, this lowers the open circuit voltage. The power output increases with a steep gradient which is almost proportional to the solar insolation at a constant cell temperature, however the power output decreases when the cell temperature increases. Other adverse performance of the *PV* arrays could be affected by aging of the system, dust and mechanical damage [5]. As for diesel generators, it is recommended to operate at a higher load demand for better efficiency performance and lower fuel consumption as to prevent internal glazing of the generator combustion chamber. In addition, the results of the frequent stop and start of the diesel generator leads to high maintenance cost due to wear and tear of the diesel generator engine.

Likewise, a method is required to optimise the power generation of the *PV* system under these intermittent weather and condition. As solar insolation varies with time, such as year, month and hour, the insolation level needs to be forecasted in order to make full use of the solar energy. A power tracker approach is required in the *PV* system as it can track the potential optimal power at any operating condition. Moreover, a power management with a proper dispatch strategy is essential to dispatch the power of a hybrid system to its load. Therefore, this research presents a method on optimal power tracking and power dispatch strategy for the hybrid *PV-Genset* system using bio-inspired approach. The general overview of this research is illustrated in a block diagram shown as in Figure 1.1.

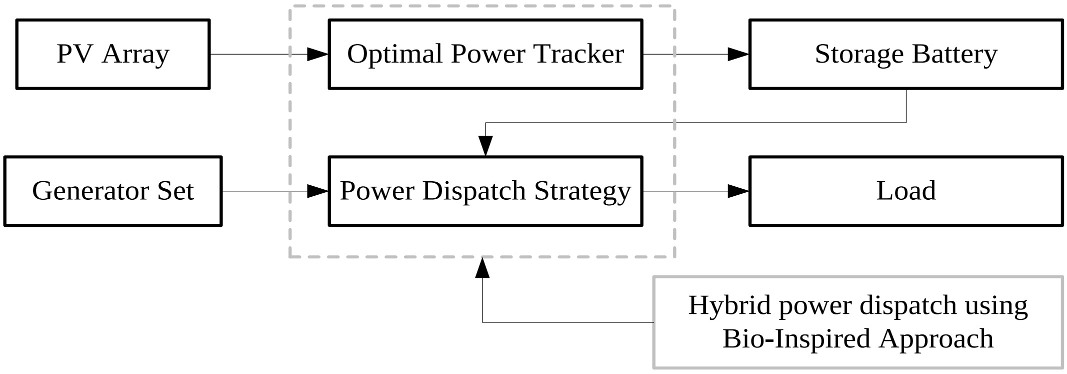

Figure 1.1: Overview of main component in hybrid *PV-Genset* system using bio-inspired approach for power dispatching

1.2 Problem statement

The integrated scheme of the hybrid *PV-Genset* system utilises more than one power sources as its reliability is depends on the diesel generator as a compensator to the inconsistent *PV* array (*PVA*) [2]. Thus being well known of its advantages, it is important to operate the hybrid *PV-Genset* system with optimal power at unforeseen operating condition with extended operational life, less cost and power efficient [1-4] by using an effective optimal power tracker method along with a proper dispatch control algorithm.

The power generated of the *PVA* panels can be optimised using a bio-inspired optimal power tracker. This approach improves the efficiency of the *PV* panel power generation at the inconsistent solar insolation and temperature condition. However, the optimal power tracker need to be comprehended the behavioural pattern of the solar energy as to increase the solar insolation level at specific location and throughout the year [5]. The behavioural pattern of the solar insolation can be familiarised by utilising the forecasting method which can provides a set of prediction data for the possible forthcoming solar insolation.

Power dispatch strategy refers to a control system with a management approach of supplying consistent power depending on the system components ability [6]. It can be improved by using a suitable control algorithm and power dispatch strategy depending on the area of deployment and requirement by managing the distribution of the generated power supply to the load depending on the hybrid systems power generation capability and load demand. Although control algorithms for the power dispatch are offered either in empirical operation rules or classical optimisation methods [3-4], yet it is not so simple and straightforward to attain [4] especially regarding to fuel consumption of the diesel generator [3].Without a proper power cost optimisation method and a dispatch strategy, the power generated from the hybrid *PV-Genset* system is not fully utilise and consequently leads to battery wear [6] and the hybrid system lifecycle will be shortened [7-8]. Furthermore, not many hybrid *PV-Genset* systems highlight the problem of optimal power tracker in conjunction with a power dispatch strategy capability under various and unpredicted operating situations. However, most researchers emphasise more on the optimum operation strategies and the optimum sizing of the components [9].

Therefore, the importance of this research is to curb the problem with an efficient simulation of a hybrid *PV-Genset* system with an optimal power tracker and a practical power dispatch controller in conjunction with the proposed dispatch strategy, control algorithm, method and approach. It will optimise the generated power from the renewable energy while hybrid power is dispatch to the load based on the hybrid system component capability.

1.3 Research objectives

The major objective of this research is to propose an integrated scheme for power utilisation and dispatching of the hybrid *PV-Genset* system with load. Its measurable objectives are as follows:

(1) To forecast the solar insolation using artificial intelligence (*AI*).

(2) To develop a control strategy for the hybrid *PV-Genset* system along the storage battery that will manage, dispatch and supply the hybrid power to the load.

(3) To analyse the operation and the performance of the proposed hybrid *PV-Genset* system.

1.4 Research scopes

It is too vast for any single research work under a given time frame to cover all the topics related to the optimal power dispatch of the hybrid *PV-Genset* system with random load. Therefore, this project will focus on certain parameters of the system.

(1) The data collection of the solar insolation, temperature and other data will be carried out at *UTHM* electrical power laboratory for a period of 12 hours, i.e from 7 am to 7 pm.

(2) The control module design will based on the inter-operation of hybrid *PV-Genset* system components capability and ability while effciently dispatch the generated hybrid power to the load demand.

(3) The analysis of the small scale hybrid *PV-Genset* system is conduct under sunny and weather condition.

1.5 Thesis outline

This subsection provides a general overview of the thesis compile chapters as it is elaborated in stages corresponding to the research work that has been done. The thesis is divided into seven chapters.

Chapter 1 highlights the introduction and importance of this research as a start. Along with the provided information, the collective facts for the problem statement are discussed, followed by the research objective, scopes, thesis outline and summary.

Chapter 2 elaborates the theory, basic concept, implementation and previous works of the solar insolation forecasting using Artificial Neural Network (*ANN*) approach. The gather information helps to understand and identify the suitable *ANN* network selection for solar insolation forecasting.

Chapter 3 discusses about the theory, application and previous works done by the other researches related to the hybrid *PV-Genset* system. The background studies helps to elaborate and understand the possible improvement of the hybrid system in detail.

Chapter 4 explains the implementation of the optimal power tracker using *ANN* and Particle Swarm Optimisation (*PSO*). The approach begins with the explanation of the artificial neural network used as solar insolation forecast. Then, the forecasted data is implemented to search the optimal photovoltaic power using particle swarm optimisation algorithm. MATLAB is used as a simulation tool in both approaches.

Chapter 5 describes the modelling of the hybrid *PV-Genset* system using optimal power dispatch controller using Fuzzy Logic Controller (*FLC*) and *PSO*. The hybrid system modelling is developed for offline simulation using the approaches given in Chapter 4. Each system component and the dispatch strategy are given in details. MATLAB-SIMULINK is used as a simulation tool to verify the hybrid

PV-Genset system modelling.

Chapter 6 expounds the simulation results, analysis and discussion of the hybrid *PV-Genset* system. This chapter discusses the characteristic behaviour on how the hybrid system adapts with the various operating conditions. Each hybrid system component is analysed and reviewed using a define parameters.

Chapter 7 presents the research conclusion and recommendation for future works. This chapter concludes the research work along with some future recommendations for further improvement.

1.6 Research contribution

This research has proposed and developed a bio-heuristic based power optimisation approach for hybrid *PV-Genset* system under intermittent weather and various operating condition. The bio-heuristic approach optimises the power generation of the *PV* system corresponding to the weather condition and optimally dispatches the hybrid power to load by managing the optimal configuration of the hybrid power system. The proposed approach has the following features:

(a) New methods

The Artificial Neural Network (*ANN*) based solar insolation forecast and Particle Swarm Optimisation (*PSO*) based optimal power tracker and optimal power dispatch are the newly methods that has been used and considered in the hybrid *PV-Genset* system development.

(b) Non-complex algorithm for non-linear power optimisation application

The optimisation algorithm that have been applied (*PSO*) are simple, non-complicated and easy to compute for the non-linear power optimisation problems based on the objective function selection.

(c) Simulation for system testing

The system modelling provides a practical simulation hybrid *PV-Genset* system testing for any related studies on power optimisation and hybrid power generation performance.

1.7 Summary

The synopsis of this chapter emphasises on the introduction for the whole research done. The research background is elaborated by highlighting the advantages and drawbacks of the hybrid *PV-Genset* system. It is followed by the explanation on the potential obstacles occurred during the operation of the hybrid *PV-Genset* system. The objective and scopes are asserted to specify the goals and the limitations of the research work. Thesis outline explains the general overview of each chapter for the ease of the reader to aid the clarity of the research work. Finally, the research contribution expounds the benefit of this proposed methodology and approach to the existing application.

CHAPTER 2

SOLAR INSOLATION FORECASTING USING ARTIFICIAL NEURAL NETWORK (*ANN*)

2.1 Introduction

This chapter provides detail information of the previous research and works regarding to solar insolation forecasting using Artificial Neural Network (*ANN*). The previous research and work will be reviewed, summarised and justified. The outcome of this chapter will specify the suitable *ANN* topology for the solar insolation forecast used in this research. The subsequent subsection in this chapter highlights the importance, the basic concept of *ANN* and the current approach for solar insolation forecasting using *ANN*.

2.2 Solar insolation forecasting

Malaysia is one of the tropical countries in South East Asia and is blessed with abundance of sunlight. The country experienced only two monsoon seasons and approximate 6 hours of sunshine per day due to its strategically situated on the equatorial region [10]. The average scale of solar insolation receives in Malaysia is ranging between 4.21 kWh/m^2 to 5.56 kWh/m^2 [10]. As for the ambient temperature, it remains almost uniformly through the year as it average scale ranging between 26 °*C* to 36 °*C* [10]. Therefore hybrid *PV-Genset* system is a viable alternative in Malaysia for electrical production scheme with comprehensive study and research on climate conditions despites on the system cost.

Solar energy is utilised as electrical energy conversion production scheme for power generation purposes. This solar energy is also known as solar insolation as it is measured through the suns energy that shines on the surface of the earth during a particular time. Solar insolation data is important as it illustrates the pattern of the variation level and designates a potential location with the highest solar insolation [11]. Unfortunately, this data are not always available due to cost and difficulty constraints in measurement because there are existences of only few meteorology stations especially in remote areas. Hence, there is an alternative method on generating this data [12-14]. Due to the solar insolation pattern changes periodically and demand growth on solar energy, modelling and forecasting is essential. Likewise, solar insolation forecasting maximises the usage of solar energy [5] as it improve the operation control of solar energy harvesting and energy optimisation [12] in *PV* system.

Artificial Intelligence (*AI*) is a biological technique that is adopted from living creatures and has been applied in many areas in stand-alone and hybrid *PV* systems. *AI* such as *ANN* is one of the most common successful methods applied in modelling and forecasting of solar insolation data as to curb the non-linear meteorological condition [14]. Hence, *ANN* is effortless applied by most researchers on this application in order to study the changes of solar insolation throughout a potential location on solar energy. The following subsection explains further on the forecasting application using *ANN* in corresponding to the selected previous works of few researchers at different areas.

2.3 Artificial neural network (*ANN*) in solar insolation forecasting

ANN mimics the human brain biological nervous system [15]. There are five elements in an artificial neuron i.e. inputs, weights, summing function, activation function and output [15]. Each function of the *ANN* element imitates the four important biological operations of the human brain (synapses, dendrites, cell body and axon). These operations are receiving input signal from other neurons, combine them, execute the information process and produce an output result [12] as shown in Figure 2.1.

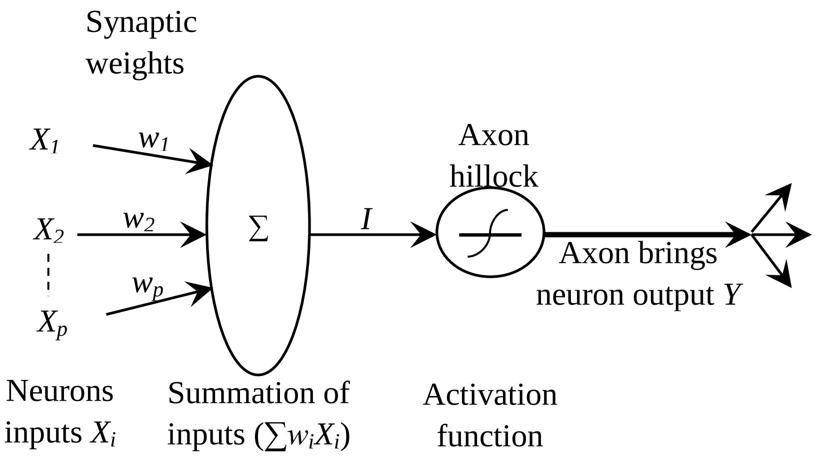

Figure 2.1: Operation of *ANN* architecture

ANN is classified by it network structure, training or learning algorithm and activation function. The structure comprises of an input layer, a few hidden layers and an output layer [16]. There are various types of *ANN* network structure available and Multilayer Perceptron (*MLP*) is one of them. *MLP* is used in many solar insolation forecast [5] as it is the cheapest method that uses a certain input parameters such as latitude, longitude, altitude and sunshine duration [11], sunshine ratio [12], mean daily solar irradiance, mean daily air temperature, day and month [13], sunshine accuracy and mean average temperature [11]. *MLP* is preferable in most solar insolation modelling and forecasting [13] due to its inherent capability of logical input-output mapping and its learning ability to perform a specific task. Besides *MLP* topology, Radial Basis Function (*RBF*) is another well-known topology which offers a better result than *MLP* restrictedly if there are more input parameters [11-12].

MLP network has different connection styles and learning algorithms as it is adapted to its structure and convergence time. There are two types of learning algorithm, supervised and unsupervised. With supervised learning, weights in the network are adjusted to produce the desired output. On the contrary, unsupervised learning does not depend on the target data to achieve the desired output as the aim is to find the core structure of the data [11]. One of the common supervised learning algorithms used is back-propagation algorithm [17]. Back-propagation algorithm is applied in the network design as it is to train the network subset data. Likewise, most insolation level forecast [11 - 17] uses back-propagation algorithm.

The activation function refers to the output relation of the network to the input based on the input activity level. Sigmoid function is widely used as activation function due to its non-linearity function whose output lies in between 0 and 1 [18]. It is used in between each hidden layers in the network structure. As the activation function is applied in the network, a new summary output neuron is obtained [15].

2.4 Previous research and works for solar insolation forecasting using *ANN*

Several studies for the solar insolation forecast using various types of topology have ensued. Table 2.1 shows the summary of the various *ANN* topology used from the ensued research.

M.Mohandes et. al. (2000) [11], compared the performance network of the monthly mean daily solar radiation falling on the horizontal surface using *RBF* network, *MLP* network and classical regression model. The input network parameters comprised of 41 different locations in Saudi Arabia. The results indicated that the *RBF* network produced better results than the *MLP* network as the average Mean of the Absolute Percentage Error (*MAPE*) for *RBF* is 10.1 while *MLP* is 12.6 [11].

Atsu S.S. Dorlo et. al. (2002) [12], initially estimate the clearness index and compared the solar radiation estimation performance of the eight different stations in Oman based on the long-term data by using *MLP* and *RBF* networks. Their results have concluded that both network performed well based on Root Mean Square Error (*RMSE*) as *RBF* error ranges from 0.83 $MJ/m^2/day$ to 10.08 $MJ/m^2/day$, while *MLP* error ranges from 1.01 $MJ/m^2/day$ to 9.41 $MJ/m^2/day$. Consequently, they concluded that the best *MLP* network which uses 3 hidden layers has the minimal mean and standard deviation of the root mean square errors. However, *RBF* network was selected due to less computation time compared to *MLP* network [12]. The network proposed in [11-12] provides a simple and practical approach for solar insolation forecast using sets of long-term data.

Adel Mellit and Alessandro Massi Pavan, (2010) [13], implemented and tested using *K-fold* cross validation method in 24 solar irradiance forecast as to improve the *MLP* network generalisation capability in four different experiments under sunny and rainy weather. The *K-fold cross validation* method splits the data into *K* number of subsets during each activity in training, validation and testing. In each subsets of the cross validation step for each activity, a single subset is remained as the test set while the rest as training sets. The cross validation process reiterates the *K* number of time and subsets. As their results, the coefficient of determination, (R^2), for sunny weather ranges from 0.95 to 0.99 while cloudy weather ranges from 0.92 to 0.97. In addition, the effectiveness of the forecast network is compared with the grid connected photovoltaic plants which give a good correlation of determination result of 0.90. Thus, the result shows that the Mean Absolute Error (*MAE*) is less than 5% and the correlation coefficient ranges from 90% to 92% [13]. The approach used in [13] proposed a good network generalisation indication for each execute activity by portioning the sets of data in each *K* number of subsets and times where the training set is validated with a test set. Nevertheless, it is not vital as the network generalisation capability can be improved using various numerical tool such as Levenberg-Marquardt and Bayesian regularisation which is defined in the MATLAB neural network toolbox.

Melit, Shaari, H.Mekki and N.Khorissi, (2008) [14], introduced a low cost real time forecasting application using a reconfigurable Field Programming Gate Array (*FPGA*) hardware (Xilinx and VirtexII) and Hardware Description Language (*VHDL*) to forecast the daily solar radiation based on *ANN* architecture. The performance of each written program environment using *VHDL* and MATLAB for the back-propagation *MLP* network forecaster simulation is compared to determine the results accuracy. In MATLAB simulation, the best architecture obtained results is 98% and the coefficient of determination comprised of a single layer with 9 neurons. Whereas using *VHDL* environment, the data is coded in 18 bits fixed point and simulated in (MODELSIM) which gives an acceptable result. As a conclusion, they remark a good agreement between the data simulated from MATLAB and *VHDL* simulation environment [14]. This approach introduces a great potential for practical real time solar radiation forecast hardware development using *FPGA* at a minimum cost.

Özgür, Humar, Ali and Muammer, (2010) [15], proposed a standard back-propagation and back-propagation with momentum training algorithm in daily solar radiation prediction in Turkey. The network topology consists of 5 inputs, a hidden layer with 10 neurons and an output. Therefore number of iteration and coefficient of determination, R^2, results from both standard and momentum back-propagation is 15000, 0.9870 and 7500, 0.9821 respectively. The result shows that the momentum back-propagation computes faster and better correlation than the standard back-propagation. In contrast, the *MAE* and *RMSE* result of a standard back-propagation outpaced the momentum back-propagation by 1.02% and 0.8% difference. Therefore, they concluded that the standard back-propagation gives a better result with slow computational time than the momentum back-propagation as the Mean Relative Error (*MRE*) concluded with 8.96% and 10.12% each [15]. Table 2.1 shows the summarise comparison of the model. It is noted that the proposed classical back-propagation method with or without momentum offers the fundamental background of *ANN* and the ability to be utilised in the solar radiation prediction application. Although the prediction results are convincing, yet this approach can be improved using a different network topology and numerical tools.

Table 2.1: Summarised comparison of the standard and momentum back-propagation

Statistical measurement	**Standard Back-Propagation**	**Momentum with Back-Propagation**
No. of iteration	15000	7500
R^2	0.987	0.9821
MRE	8.96%	10.12%
Δ *MAE*	1.02%	
Δ *RMSE*	0.8%	

Mónica Bocco, Gustavo Ovando and Silvina Sayago, (2006) [16], developed a *MLP* back-propagation type neural network to estimate the solar radiation at Córdoba, Argentina. Three layers network and five neurons in the hidden layer is use to simulate 8 types of forecast result models, *M1-M8*. Figure 2.2 shows the neural network structure of the multilayer perceptron type of model M1. The estimation result indicates the root mean square error ranging between 3.15 MJ/m^2d to 3.88

MJ/m^2d^1. The 14 hours cloudiness records of the *M6-M8* models result a pertinent error in estimation in each model.

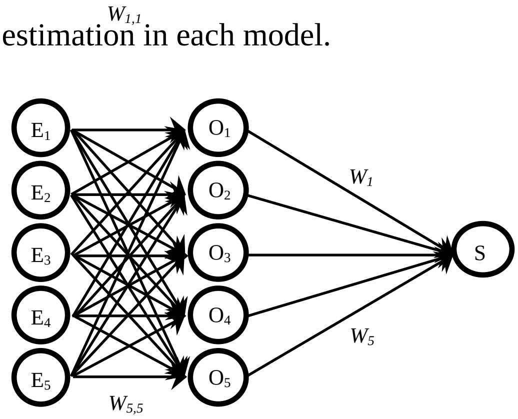

Figure 2.2: Scheme of a neural network of the multilayer perceptron type (Model M1)

On contrary, the temperature and precipitation information of the *M3* and *M4* model result a greater error in the estimation and the difference are irrelevant to each model. *M1* and *M2* obtained the best estimation results as the model present a better adjustment. In the *M1* model observation result, the underestimation percentage reaches 15% when the daily radiation exceeds 25 $MJ\ m^{-2}\ d^{-1}$ through an analysis dispersion diagram of the observed and estimated value as it shows a seasonal behaviour pattern correctly to those of the observed ones [16].

Table 2.2 shows the summarised topology used for the discussed solar insolation forecast.

Table 2.2: Summarised network topology for solar insolation forecasting application

Author(s)	Year	Network topology and field
Mohandes, Balghonaim, Kassas, Rehman & O.Halawani [11]	2000	Comparison of *RBF* and *MLP* network for monthly mean daily solar radiation estimation in Saudi Arabia
Atsu, Joseph & Ali [12]	2002	Comparison of *RBF* and *MLP* network for monthly solar radiation estimation of 8 different locations in Oman
Mellit & Alessandro [13]	2010	*MLP* network with cross-validation method for 12 hours solar irradiance forecasting
Mellit, Shaari, Mekki & Khorissi [14]	2008	Application of *MLP* network in FPGA hardware for real time solar radiation prediction
Solmaz, Humar, Ali & Muammer Özgören,[15]	2010	Application of classical network topology such as standard back-propagation and back-propagation with momentum for daily solar radiation prediction in Turkey.
Mónica, Gustavo & Silvina [16]	2006	*MLP* feed forward network for daily solar radiation estimation in Argentina

From the collected information and discussion, the methods from [11 and 12] are adopted for this forecasting method. It is decided that the best network topology use for solar insolation forecast for this research is feed forward multilayer perceptron with a back-propagation training algorithm. This approach shows a potential and viability for evaluating solar energy possibilities. However, due to constraints in obtaining proper sets of long term data, this approach provides a non-complex forecasting application which requires non-compulsory selective range of input parameters as it is suitable for the objectives requirements. Besides that, the proposed topology has the capability to learn the complex input-output relationship which could be challenging for other model with conventional algorithmic approach.

2.5 Summary

Within this chapter, the importance, the basic concept of *ANN* and the existing approach for the solar insolation forecasting using *ANN* are discussed. The chapter begins with the significance of solar insolation forecasting using *ANN* as the enhancement for solar energy utilisation. This approach offers a simpler and viable forecasting method compare to other conventional computation method especially for non-linear meteorological condition. Besides that, each function in the *ANN* network component is elaborated in term of its task. Investigation on the preceding solar insolation forecast approach are ensued and justified to its methodology, *ANN* topology and application. Through the justification of each ensued preceding approach, *MLP* network with back propagation technique is selected for solar insolation forecast application. The develop design of the *MLP* network will be discuss further in Chapter 4.

CHAPTER 3

HYBRID *PV-GENSET* SYSTEM AND POWER DISPATCH STRATEGY

3.1 Introduction

This chapter delivers substantial materials on the existing development and previous research of the hybrid *PV-Genset* system. Within this chapter, there are two main sections comprise of the hybrid system construction and the power dispatch strategy. Both sections will describe, justify and summarise of its existing operation and previous development of this system. The outcome of these sections emphasises on the explanation of each system component, the various connection topologies and the power dispatch strategy of the hybrid system.

3.2 Hybrid *PV-Genset* system

The hybrid *PV-Genset* system satisfies the electricity demands to the consumers while conserving the nature, the environment and the system itself. In general, hybrid *PV-Genset* system is the integrated *PV* system with another form of fossil fuel driven power generation system as back-up supplementary power generation, such as diesel generator. As to ensure a consistent supply of electrical power at all time, rechargeable storage batteries are also integrated into the hybrid system [19].

Hybrid *PV-Genset* system is usually ideal for remote applications such as communication stations, military installations and rural areas. However, the operation of the hybrid *PV-Genset* system must be able to adapt in its local geography and other specifics to supply the electricity demand needs [19].

A hybrid *PV-Genset* system can be identified either stand-alone or grid-connected system. In remote and rural areas, stand-alone hybrid system would assist in expanding the electricity access in the isolated region. Therefore, stand-alone *PV* hybrid system is most often found on island. As for grid connected system it is connected to a large independent grid typically for public electricity grid and feed the power back into the main grid. This is also known as decentralised electricity generation [20].

Likewise in many cases of hybrid *PV-Genset* system, it offers a clean and more cost-effective efficient power than sole diesel generator system. Ultimately, it serves to fully utilise the available solar energy for electrical power generation and to reduce fuel consumption of the diesel generator. As a result, renewable energy is a preferable solution for either grid-connected or stand-alone system [20]. Thus, the following subsection aids to elaborate the further understanding and the previous works of the components, connection topologies and power dispatch strategy used in the hybrid *PV-Genset* system.

3.2.1 Hybrid *PV-Genset* system components

Hybird *PV-Genset* system consists of photovoltaic array system (*PVA*), battery storage system and generator set. These are the main components that provide electrical power to the load. In order to operate efficiently, all of these components must withstand under all conditions. Power condition unit such as switching power converters and inverters are also important as it is used to accommodate the variable nature of power output and prevent malfunction of the hybrid system. These components will be explained further in Chapter 5. Hence in this subsection, the theory of various system development and arrangement for different approaches along with other researches previous work is explained.

3.2.1.1 Photovoltaic array (*PVA*) system development and arrangement

Solar cells are the fundamental element of the photovoltaic system (*PV*) which converts sunlight or solar energy directly to electricity. A solar cell consists of a positive and negative (*P-N*) junction formed in a semiconductor material [21]. They are much similar to any solid-state electronic devices such as diode, transistors and integrated circuits. Generally, solar cells are manufactured into *PV* modules for practical operations [22]. Various semiconductor materials give a different efficiency and cost. Thus, silicon is one the most common semiconductor material used in solar cells. There are several types of solar cells made from silicon such as mono-crystalline silicon (*c-Si*), poly-crystalline silicon (*poly-Si*) and amorphous-silicon [21].

Solar cells comprise of *P-N* junction that are fabricated into a thin wafer or layer of silicon material. During the dark, the current-voltage (*I-V*) output characteristics of a solar cell has an exponential characteristics same as diode [21]. When the solar cells is exposed to solar energy, it creates photons with energy greater than the semiconductor band gap energy causing an electron-hole pair where the electrons are knocked loose from the atoms in material. These electrons are carried away under the influence of the internal electric fields of the *P-N* junction and create current proportional to the incident radiation. During the short circuited solar cell, the current flows in the external circuit while as for open circuited solar cell, the current is shunted internally by the intrinsic *P-N* junction diode. Therefore, these diode characteristics set the open circuit voltage characteristics of the cell.

During electron-hole pairs are formed, the electron charges reach to the neighbouring junction, causing the electric field in the depletion region push the holes into the positive side (*p-side*) and push the electrons into the negative side (*n-side*) as shown in Figure 3.1. Each of the *p-side* and *n-side* accumulates holes and electrons creating a voltage in between the load and conducts current. If the electrical contacts are attached to top and bottom of the cell, the electrons drift out from the *n-side* into the connecting wire, through the load and back to the *p-side* as shown in Figure 3.1 [22]. Since wire cannot conduct holes, the electrons move around the circuit. Therefore, the positive current flows in the opposite direction of the electrons where the current goes from the *p-side* to the load and back into the *n-side*. In general, the conventional current flows in the opposite direction from the electrons.

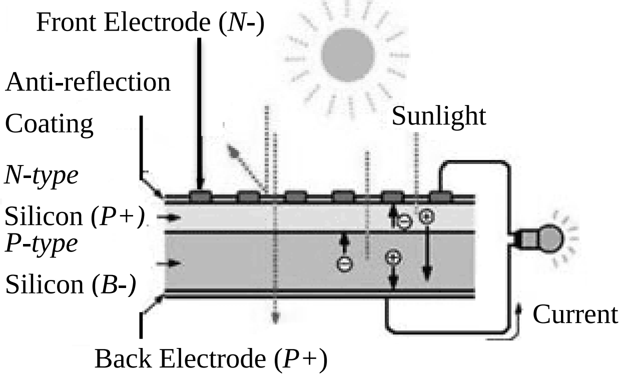

Figure 3.1: Illustration of the *p-n* junction in the solar cell of the *PV* system

In electrical energy production schemes, solar cells are mass-produced into photovoltaic modules which are integrated into *DC* power-producing unit configuration. Typically, many *PV* systems development uses solar panels, where it is the physical connection of modules with supports to form arrays [22]. Figure 3.2 shows that *PV* system has various categories, starting from cells to arrays.

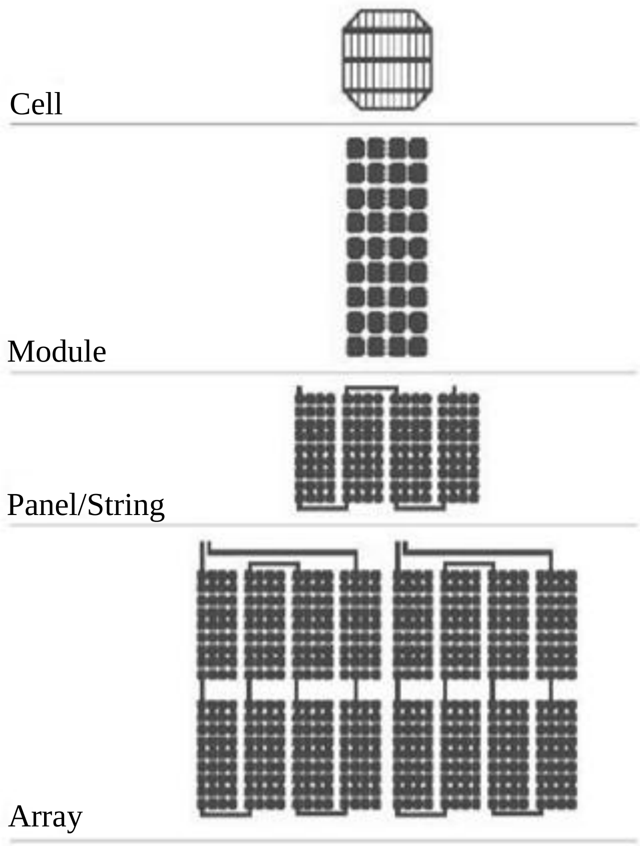

Figure 3.2: The Photovoltaic hierarchy from cell to array

Figure 3.3 illustrates how the *PV* modules are connected in arrays with *Mp* (Module in parallel) parallel branches each with *Ms* (Module in series) [23]. The arrangement of *PV* module portrays a vital task in terms of efficiency. Figure 3.4 shows three different types of arrangement donating various efficiencies. The *A* arrangement gives efficiency up to 97.2%, while *B* arrangement at 96.8% and *C* at 96.2% [23]. In this research, the *A* arrangement is use. Besides the *PVA* arrangement

REFERENCES

[1] Kamaruzzaman, Mohd. Yusof and Mohd. Azhar (2005). Performance of a Photovoltaic Diesel Hybrid System in Malaysia: ISESCO Science and Technology Vision. Vol. 1, 2005, pp. 37-39.

[2] Mohamed Rashed, A.Elmitwally and Sahar Kaddah, (2008). New control approach for a PV-Diesel autonomous power system. Electric Power System Research 78, 2008, pp. 949-956.

[3] Yasuharu Ohasawa, Shin-ichi Emura and Kenji Arai, (1993). Optimal Operation of Photovoltaic/Diesel Power Generation System by Neural Network, 1993. IEEE, pp. 99-103.

[4] Rodolfo and José L. , (2004). Design and control Strategies of PV-Diesel System using Genetic Algorithms: Solar Energy 2005, Vol 79, No.2, pp. 33-46.

[5] Momoh,J.A. , Wang,Y. , and Eddy-Posey, F. , (2004). Optimal Power Dispatch of Photovoltaic System with Random Load. Power Engineering Society General Meeting, IEEE, 2004 10-10 June 2004, Vol. 2, pp. 1939-1945.

[6] C.Dennis Barley and C.Byron Winn, (1996). Optimal Dispatch Strategy in Remote Hybrid Power Systems. Elsevier Science: Solar Energy Vol.58, No.4-6, 1996, pp.165-179.

[7] M.Ashari and C.V. Nayar, (1999). An Optimum Dispatch Strategy Using Set Points for A Photovoltaic (PV)-Diesel-Battery Hybrid Power System. Elsevier Science: Solar Energy Vol.66, No.1, 1999, pp. 1-9.

[8] M.Ashari, C.V.Nayar and W.W.L. Keerthipala, (2001). Optimum Operation Strategy and Economic Analysis of a Photovoltaic-Diesel-Battery-mains Hybrid Uninterruptible Power supply. Elsevier Science: Renewable Energy Vol.22, 2001, pp. 247-254.

[9] G.C.Seeling-Hochmuth, (1997). A Combined Optimisation Concept for the Design and Operation Strategy of Hybrid-PV Energy System. Elsevier Science: Solar Energy Vol.61, No.2, pp. 77-87.

[10] Ayu Wazira Azahari, Kamaruzzaman Sopian, Azami Zaharim and Mohd Al Ghoul, 2008. A New Approach for Predicting Solar Radiation in Tropical Environmentusing Satellite Images-Case Study of Malaysia. WSEAS Transactions on Environment and Development, Issue 4 Vol.4, April 2008, pp. 373-378

[11] M.Mohandes, A.Balghonaim, M.Kassas, S.Rehman and O.Halawani, (2000). Use Radial Basis Function for Estimating Monthly Mean Daily Solar Radiation. Elsevier Science: Solar Energy Vol.68, No.2, 2000, pp. 161-168.

[12] Atsu S.S. Dorlo, Joseph A. Jervase, Ali Al-Lawati, (2002). Solar Radiation Estimation using Artificial Neural Networks. Elsevier Science: Applied

Energy, 2002, pp. 307-319.

[13] Adel Mellit and Alessandro Massi Pavan, (2010). A 24-h Forecast of Solar Irrandiance using Artificial Neural Network: Application for Performance Prediction of a Grid-connected PV Plant at Trieste, Italy. Elsevier Science: Solar Energy, 2010, pp. 807-821.

[14] Mellit, S.Shaari, H.Mekki and N.Khorissi, (2008). FPGA-based Aritificial Neural Network for Prediction of Solar Radiation Data from Sunshine Duration and Air Temperature. Region 8 Sibircon, IEEE, 2008, pp. 118-123.

[15] Özgür Solmaz, Humar Kahramanli, Ali Kahraman and Muammer Özgören, (2010). Prediction of Daily Solar Radiation using ANNS for Selected Provinces in Turkey. International Scientific Conference 19-20 November, 2010, Gabrovo, pp. 450-456.

[16] Mónica Bocco, Gustavo Ovando and Silvina Sayago, (2006). Development and evaluation of neural network models to estimate daily solar radiation at córdoba, Argentina. Pesq.agropec.bras, Brasilia, V.41, n.2, 2006, pp.179-184.

[17] Adnan Sözen, ErolArcaklioğlu, Mehmet Özalp, (2004). Estimation of solar potential in Turkey by artificial neural network using meterological and geographical data. Elsevier Science: Energy Conversion and Management 44, 2004, pp. 3033-3052.

[18] K. S. Reddy and Manish Ranjan, (2003). Solar resources estimation using artificial neural networks and comparison with other correlation models. Elsevier Science: Energy Conversion and Management 44, 2003, pp. 2519-2530.

[19] Chua Hock Guan, (2010). Optimal Power Algorithm of Photovoltaic-Generator Set. Thesis, Universiti Tun Hussein Onn Malaysia.

[20] Peter Gevorkian, (2008). Solar Power in Building Design. The Engineer's Complete Design Resources. pp. 1-62.

[21] Djamila Rekioua and Ernest Matagne, (2012). Optimisation of Photovoltaic Power systems, Modelisation, Simulation and Control. London: Springer, pp. 3-29.

[22] Tomas Marrkvart, (2001). Solar Electricity, 2nd ed. Chichester, United Kingdom : John Wiley and Sons.

[23] Suresh A/L Thanakodi, (2009). Modelling and Simulation of Grid Photovoltaic system using Matlab/Simulink. Masters Thesis, Universiti Teknologi Malaysia.

[24] Jerzy Duda, (2007). A critical review of the newest biologically-inspired algorithms for flow shop scheduling problem. Task Quarterly 11 No 1-2, 7-19, 1 February, 2007.

[25] Kwang.Y. Lee, Mohd. A. El-Sharkawi, (2008). Modern heuristic optimisation techniques, Hoboken, New Jersey, United States: John Wiley and Sons.

[26] Abdul El-Shafy A. Nafeh, (2009). Fuzzy logic operation control for PV-Diesel-Battery hybrid hybrid energy system. The Open Renewable Energy Journal, 2, January 27, 2009, pp. 70-78.

[27] Adel M. Sharaf, Adel A. A. El-Gammal (2010). A hybrid PSO self-regulating VSC_SMC controller for PV-FC-Diesel-Battery renewable energy scheme

for buildings electricity utilisation. 4th Asia International Conference on Mathematical/ Analytical Modelling and Computer Simulations, IEEE, 2010, pp. 463-469.

[28] Boquan Zhang, Yimin Yang, Lu Gan, (2008). Dynamic control of wind/photovoltaic hybrid power system based on an advanced particle swarm optimisation. Industrial Technology (ICIT): IEEE conference, 21-24 April 2008, pp. 1-6.

[29] Mohd Badrul Hadi Che Omar, (2008). Estimation of economic dispatch (line losses) at generation side using artificial neural network. Thesis, Universiti Tun Hussein Onn Malaysia.

[30] Kennedy, J. and Eberhart, R.C., (1995). Particle Swarm Optimisation: Proceeding of the IEEE International Conference on Neural Networks. Perth, Australia: IEEE, 1995, pp. 1942-1948.

[31] Shi Yao Lim, Mohammad Montakhab and Hassan Nouri, (2009). Economic Dispatch of Power system Using Particle Swarm Optimization with Consideration Factor. International Journal of Innovation in Energy System and Power, Vol. 4 no.2, 2009, pp. 29-34.

[32] Yamille del Valle, G. K Venayaganoorthy, Salman Mohagheghi, Jean-Carlos Hernandez and Ronald G. Harley, (2008). Particle Swarm Optimisation: Basic concept variants and applications in power system. IEEE Transactions on Evolutionary Computation, Vol 12 no.2, 2008, pp 171-195.

[33] N. Phuangpornpitak, W, Prommee and S. Tia, (2010). A study of particle swarm technique for renewable energy power systems. International

Conference on Energy and Sustainable Development: Issues and Strategies 2010, 2nd-4th June 2010.

[34] Francisco M. González-Longatt, (2005). Model of Photovoltaic Module in MATLAB. 2nd American Student Congress of Electrical, Electronics and Computer Engineering (II CIBELEC), 2005, pp. 1-5.

[35] B.C.Kok, H.H. Goh and H.G Chua, (2012). Optimal Power Tracker for Stand-Alone Photovolatic System using Artificial Neural Network (*ANN*) and Particle Swarm Optimisation (*PSO*). Renewable Energy and Power Quality Journal (RE & PQJ), No.10, April 2012, RE-PQJ-10.

[36] Tyson DenHerder, (2006). Design and simulation of Photovoltaic super System using SIMULINK. Thesis, California Polytechnic State University, San Luis Obispo.

[37] Luis Castañer and Santiago Silvestre (2002). Modelling of Photovoltaic System using PSpice, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England: John Wiley and Sons.

[38] D. Yamegueu, Y. Azoumah, X. Py and N. Zongo (2011). Experimental study of electricity generation by solar PV/Diesel hybrid systems without battery storage for off-grid areas. Elsevier Science: Renewable Energy Vol. 36, 2011, pp. 1780-1787.

[39] Mo’ien Ali Ahmad Omar (2007). Computer – Aided Design and Performance Evaluation of PV-Diesel Hybrid System. Maters Thesis, An-Najah National University.

[40] Francisco Gonçalves Goiana Mesquita, (2010). Design Optimisation of Stand

Alone Hybrid Energy Systems. Masters Thesis, Univerdidade Do Porto.

[41] Adel El-Menchawy, Hasham Bassioni and Abdel-Aziz Farouk, (2011). Photovoltaic System in Existing Residential Building in Egypt. International Journal Scientific and Engineering: Research Vol 2, Issue 7, July 2011, pp. 1-10.

[42] Susan Schoenung, (2011). Energy Storage System Cost Update, A study for the DOE energy storage system program. Ph.d Report. Sandia National Laboratory Report, United States Department of Energy, April 2011, pp. 10-11.

[43] Kamaruzzaman Sopian, Azami Zaharim, Yusoff Ali, Zulkifli Mohd Nopiah, Juhari AB. Razak and Nor Salim Muhammad (2008). World Scientific and Engineering Academy and Society: Transaction on Mathematics Vol 7, Issue 4, April 2008, pp. 130-140