UNIVERSITI PUTRA MALAYSIA

MAXIMUM POWER POINT TRACKING USING ARTIFICIAL NEURAL NETWORK FOR PHOTOVOLTAIC STANDALONE SYSTEM

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By

RAZIEH KHANAKI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

April 2014

Dedicated to my parents, beloved brothers and sisters

Abstract of thesis presented to the Senate of Universiti Putra Malaysia
in fulfilment of the requirement for the degree of Master of Science

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April 2014

Chairman: Mohd Amran Mohd Radzi, PhD
Faculty: Engineering

Solar energy has drawn much attention in recent years because of high demand for green energy resources. Electrical power can be generated by using semiconductors in photovoltaic (PV) cells to convert solar irradiance into DC current. Each PV module has its own optimum point at which the power delivered from the PV is at its maximum value. Since the initial cost for using PV is high, it is essential to make the PV module to work at its maximum power point. Thus, an algorithm named as maximum power point tracking (MPPT) has been introduced. These algorithms by controlling the duty cycle of a converter which is inserted between the PV module and the load make the PV to work at its maximum power point (MPP). Since the characteristics of PV module are dependent on atmospheric conditions of solar irradiance and cell temperature, conventional MPPT methods fail to find the MPP under rapidly changing of solar irradiance. Artificial intelligence methods have drawn much attraction in recent years due to their capability of handling uncertainty and nonlinearity conditions.

In this work, an improved MPPT using Artificial Neural Network (ANN) has been presented. The control unit is comprised of two stages where at the first stage, ANN finds the voltage and current at which the maximum power is delivered, and at the second stage, another algorithm by developing the mathematical equation in related to input impedance, output impedance and duty cycle of the boost converter, tracks the MPP independent from the load, under changing condition of solar irradiance and cell temperature.The overall system consists of a PV module, a DC-DC boost converter, a control system and a resistive load. Also, a digital signal processor is used to generate the pulse width modulation signals for the driver of the converter. The proposed MPPT system is simulated using MATLAB. The results are compared with the results of the perturbation and observation (P&O) method under low and high solar irradiances; and slowly and rapidly changing of solar irradiance. Furthermore, the results of the proposed method are compared with results of the previous ANN MPPTs in two aspects of ANN outputs, and PV MPPT performance.

The simulation and experimental results show that for both high and low solar irradiances, the proposed ANN method has smaller trackingtime, less power oscillation at steady-state, and higher efficiency than P&O MPPT with different step-

sizes. Simulation results for different loads of 20 Ω, 33 Ω, and 40 Ω show that the proposed MPPT has efficiency between 99.96-100%, for different irradiances between 300-1000 W/m^2. In term of ANN output, the percentage error between the expected power and power predicted from ANN in this work is 0-0.119 %, which is more accurate than the previous ANN MPPT works with error percentage of 0.05-3.66 %. In term of MPPT performance, the proposed MPPT has efficiency of 99.97% for low irradiance of 200 W/m^2 and temperature of 31.9^{O}C, which shows better performance as compared to ANN MPPT using PI controller which has efficiency of about 84% for low irradiance.

As conclusion, the proposed ANN MPPT has high precision in finding the optimum points, as compared to previous ANN works. Furthermore, it tracks the MPP independent from the load, with high efficiency as compared to P&O with different-step sizes and ANN MPPT using PI controller.

Abstak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENJEJAKAN TITIK KUASA MAKSIMUM MENGGUNAKAN RANGKAIAN NEURAL BUATAN UNTUK SISTEM FOTOVOLTAN BERDIRI SENDIRI

Oleh

RAZIEH KHANAKI

April 2014

Pengerusi: **Mohd Amran Mohd Radzi, PhD**
Fakulti: **Kejuruteraan**

Tenaga suria telah menarik perhatian banyak dalam beberapa tahun kebelakangan ini kerana permintaan yang tinggi untuk sumber tenaga hijau. Kuasa elektrik boleh dihasilkan dengan menggunakan semikonduktor dalam sel fotovoltan untuk menukar sinaran suria kepada arus DC. Setiap modul fotovoltan mempunyai titik optimum sendiri yang mana kuasa yang dibekal dari fotovoltan adalah ada nilai maksimumnya. Oleh itu, algoritma yang dinamakan sebagai penjejakan titik kuasa maksimum telah diperkenalkan. Algoritma ini dengan dikawal oleh kitaran tugas penukar yang dimasukkan antara modul fotovoltan dan beban membuatkan fotovoltan berkerja pada titik kuasa maksimumnya. Oleh sebab ciri modul fotovoltan bergantung kepada keadaan atmosfera, kaedah penjejakan titik kuasa maksimum konvensional gagal mencari titik kuasa maksimum di bawah perubahan cuaca yang pantas. Kaedah kepintaran buatan telah menarik perhatian banyak dalam beberapa tahun kebelakangan ini disebabkan oleh keupayaan kaedah ini mengendalikan keadaan ketidakpastian dan ketaklelurusan.

Dalam kerja ini, penjejakan titik kuasa maksimum yang diperbaiki menggunakan rangkaian neural buatan telah dibentangkan. Unit kawalan terdiri daripada dua peringkat yang mana pada peringkat pertama, rangkaian neural buatan mencari dan menempatkan voltan dan arus di mana kuasa maksimum dibekalkan, dan pada peringkat kedua, algoritma lain dengan membangunkan persamaan matematik yang dikaitkan kepada galangan masukan, galangan keluaran dan kitaran tugas penukar penggalak, menjejak titik kuasa maksimum bebas daripada beban, di bawah perubahan keadaan cuaca terhadap sinaran suria dan suhu sel. Keseluruhan sistem terdiri daripada modul fotovoltan, penukar penggalak DC-DC, sistem kawalan dan beban rintangan. Pemproses isyarat digital digunakan juga untuk menjana isyarat pemodulatan lebar denyut untuk pemacu penukar penggalak. Sistem penjejakan titik kuasa maksimum yang dicadangkan disimulasi menggunakan MATLAB. Keputusannya dibandingkan dengan keputusan kaedah usikan dan cerapan yang paling popular di bawah perubahan sinaran suria rendah dan tinggi, dan perubahan sinaran suria yang perlahan dan pantas. Tambahan pula, keputusan diperolehi dibandingkan dengan keputusan penjejakan titik kuasa makismum rangkaian neural buatan sebelum ini dalam dua aspek, iaitu keluarannya dan pretasi penjejakan titik kuasa maksimum fotovoltan.

Keputusan kerja simulasi dan eksperimen menunjukkan bagi kedua-dua sinaran suria tinggi dan rendah, kaedah yang dicadangkan mempunyai masa penjejakan yang kecil, kurang ayunan kuasa pada keadaan mantap, lebih kuasa purata, dan mencapai kecekapan lebih tinggi berbanding penjejakan usikan dan cerapan dengan saiz langkah berbeza. Keputusuan simulasi untuk beban berlainan 20 Ω, 33 Ω, dan 40 Ω menunjukkan bahawa penjejakan yang dicadangkan mempunyai kecekapan antara 99.96-100%, bagi sinaran berlainan antara 300-1000 W/m^2. Daripada segi keluaran rangkaian neural buatan, ralat peratus antara kuasa jangkaan dan kuasa tekaan daripada rangkaian neural buatan dalam kerja ini adalah 0-0.199 %, yang lebih tepat berbanding kerja penjejakan lepas dengan ralat peratus 0.05-3.66%. Daripada segi prestasi penjejakan, penjejakan yang dicadangkan mempunyai kecekapan 99.97% untuk sinaran rendah 200W/m^2 dan suhu 31.9^{O}C, yang menunjukkan prestasi yang lebih baik berbanding penjejakan menggunakan pengawal PI yang mempunyai kecekapan kira-kira 84% untuk sinaran rendah.

Kesimpulannya, penjejakan titik kuasa maksimum rangkaian neural buatan yang dicadangkan mempunyai ketepatan yang tinggi dalam mencari titik optimum, berbanding rangkaian sebelum ini berfungsi. Tambahan pula, ia menjejaki titik kuasa maksimum bebas daripada beban, dengan kecekapan tinggi berbanding usikan dan cerapan dengan saiz langkah berbeza dan penjejakan rangkaian menggunakan pengawal PI.

ACKNOWLEDGEMENTS

First, I would like to express my gratitude to the creator deity of the universe, for helping me to complete this research.

I would like to thank my supervisor Dr. Mohd Amran Mohd Radzi for being patient and guiding me all the way. It has been so pleasure to have him as supervisor. I am so grateful for his support, time, availability, encouragement and suggestions during my master program and for valued comments on this work. His dedication to his students is appreciable.

I would like to thank Prof. Mohd Hamiruce Marhaban for his support as my committee member.

I would like to thank my family, mother, father, brothers and sisters, especially my dear sister Marzieh for supporting me all the way.

I would like to thank all my friends who gave me encouragement during my master journey, especially Nima Khalili Samani for being with me all the way.

I would like to thank my friends in power electronic lab for their encouragement and giving useful suggestions.

I certify that a Thesis Examination Committee has met on 28th April 2014 to conduct the final examination of Razieh Khanaki on her thesis entitled "Maximum Power Point Tracking Using Artificial Neural Network for Photovoltaic Standalone System" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the relevant degree of Master of Science.

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This thesis was submitted to senate of Universiti Putra Malaysia and has been accepted as fulfilment of requirement for degree of Master of Science. Members of the Supervisory Committee were follows:

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Declaration by graduate student

I hereby confirm that:

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- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
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This is to confirm that:

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LIST OF ABBREVIATIONS

PV	Photovoltaic
MPP	Maximum power point
I-V curve	Current-voltage curve
V-P Curve	Voltage-power curve
DC	Direct current
DC-DC	Direct current to direct current
MPPT	Maximum power point tracking
ANN	Artificial neural network
DSP	Digital signal processor
P&O	Perturbation and observation
GaAs	Gallium arsenide
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
CIS	Copper indium selenide
KCL	Kirchhoff's current law
V_{pv}	Output voltage of the PV module
I_{pv}	Output current of the PV module
I_D	Diode current
I_{sh}	Shunt resistor current
I_{ph}	Photo current

I_o	Reverse saturation current
N_p	Number of cells in parallel
N_s	Number of cells in series
R_s	Series resistance
R_{sh}	Shunt resistance
q	Electron charge (1.602×10^{-19}C)
K	Boltzmann constant(1.38×10^{-23}J/K)
T	Temperature
^{O}C	Degree Celsius
I_{scr}	Short-circuit current of the PV at standard test condition
STC	Standard test condition
K_i	Short-circuit current temperature co-efficient
T_r	Reference temperature
G	Solar irradiance
G_r	Reference solar irradiance
I_{or}	Saturation current
E_{go}	Band gap energy
IGBT	Insulated gate bipolar transistor
MOSFET	Metal oxide silicon field effect transistor
D	Duty cycle of the converter
R_{in}	Input resistance of the converter

R_0	Output resistance
CCM	Continuous conduction mode
DCM	Discontinuous conduction mode
L	Conductor
C	Capacitor
F	Frequency
dV	Change of voltage caused by the perturbation of the MPPT
dP	Change of power caused by the perturbation of the MPPT
ΔV	Variation in voltage
ΔP	Variation in power
FLC	Fuzzy logic controller
INC	Incremental conductance (INC)
NB	Negative big
NS	Negative small
ZE	Zero
PB	Positive big
PS	Positive small
E	Error
ΔE	Change of error
ΔD	Change of duty cycle
AFLC	Adaptive fuzzy logic controller

MLP	Multilayer perceptron
RBF	Radial basis function
RNN	Recurrent neural network
$I_i^l(k)$	Input of the i^{th} node at the l^{th} layer in k^{th} sample
$O_i^l(k)$	Output of the i^{th} node at the l^{th} layer in k^{th} sample
$w_{ij}^l(k)$	Weight of the connection between the j^{th} node in the $l\text{-}1^{th}$ layer and the i^{th} node in the l^{th} layer
X^n	Input vector of radial basis Gaussian function
μ_j	Centre of radial basis function
σ	Scalar for presenting the width of the radial basis function
P_{pm}	Maximum power or optimum power
V_{pm}	Voltage at maximum power or optimum voltage
I_{pm}	Current at maximum power or optimum current
V_{oc}	Open circuit voltage
I_{sc}	Short circuit current
GA	Genetic algorithm
d(t)	Duty cycle of the converter at time t
d(t+1)	Duty cycle of the converter at time t+1
CCS	Code composer studio
PWM	Pulse width modulation

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

This chapter presents a general overview on solar energy as an alternative energy source for fossil fuel, followed by stating the problems arising when using this source. Aim and objectives of the work are then presented. After that, its scope and limitations are provided. Finally, outline of the thesis is given at the end of this chapter.

1.1 General Overview on Solar Energy

Energy demands in all around the world are increasing, and looking for alternative energy resources seems essential. In order to find unlimited energy sources, a lot of research works have been done, mostly on renewable energy sources such as biomass, geothermal, hydro, fuel cells, wind and solar (Bratt, 2011), (Bennett, Zilouchian, & Messenger, 2012). Solar energy has drawn much attention in recent decades for some reasons such as environmental benefits of having no noise and pollution, being renewable for human future, and being independent source of energy since it comes directly from sun irradiance (Xiao, 2003). Despite all advantages mentioned above for solar energy, there are some drawbacks for this energy resource such as high capital cost and low efficiency. To make solar energy become economical, it is essential to increase its efficiency (Pandey, Dasgupta, & Mukerjee, 2008).

Solar energy which comes from the sun in the form of solar irradiance, can be converted into the electricity by use of the photovoltaic (PV) technology (EL-Moghany, 2011), (Lobera, 2010). PV technology is a method that uses solar cells which are made of semiconductors, to absorb the solar energy and convert it into the electrical energy (Raihana, 2008). Solar cells can produce a low power, so they are usually connected in series or parallel arrangement and form PV modules to produce high power (Safari & Mekhilef, 2011). PV modules have a non-linear characteristic with a unique maximum power point which is dependent on the weather conditions of solar irradiance and module temperature as well as the load connected to it. In PV applications, it is desirable to find and track this maximum power point in order to draw maximum energy. Maximum power point trackers are so used to make the PV module work at its maximum power point (Pandey et al., 2008).

1.2 Problem Statement

When a PV module is directly connected to a load, the mismatch between the PV module and the load prevents the system to work at its maximum power point (MPP) (J. Appelbaum, 1987). In fact the operating point of the load is located at the intersection of I-V or P-V curves of the PV module and the load, which is not usually maximum power point as plotted in Figure 1.1 (Balakrishna, Nabil, Rajamohan, Kenneth, & Ling, 2006).

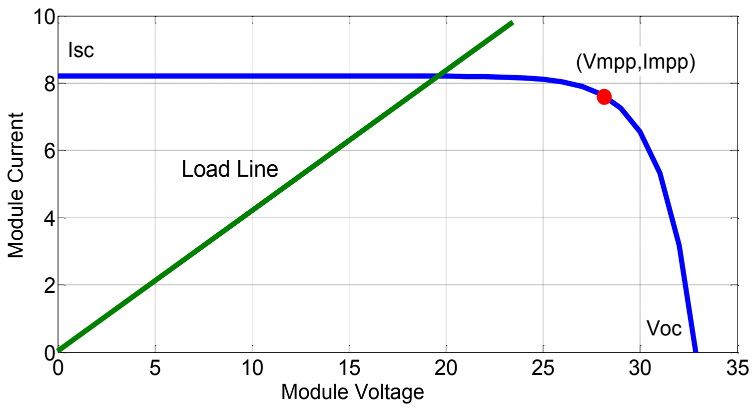

Figure 1.1. Typical I-V characteristics of a PV module in steady-state operation
(source: Balakrishna et al., 2006)

Furthermore, the non-linear output characteristics of the PV module and consequently the MPP is dependent on the weather conditions such as irradiance from the solar and cell temperature as shown in Figure 1.2 (Brito, Galotto, Sampaio, de Azevedo e Melo, & Canesin, 2013).

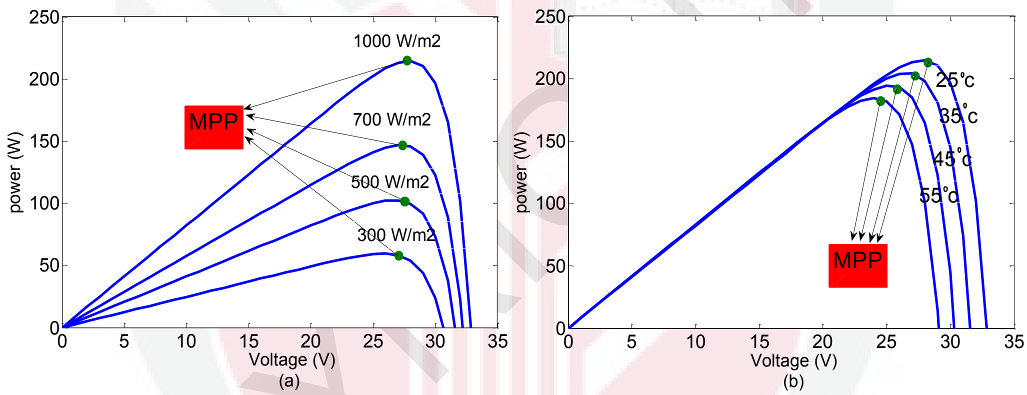

Figure 1.2. P-V characteristics of a PV module and location of the MPP for (a) different irradiances at 25^{O}C, and (b) different temperatures at irradiance of 1000W/m^2

Figure 1.2 (a) shows the shifts of the MPP on the voltage-power curve with change in the irradiance at a constant temperature, and Figure 1.2 (b) represents MPP shifts with change in the module temperature at a constant irradiance. In reality, an increase in solar irradiance leads to increase in module temperature, so tracking of MPP gets even more complicated (Xiao, 2003).To overcome problems mentioned above, a power conditioner such as a DC–DC converter is usually used as interface between the PV module and the load, and together with a maximum power point tracking (MPPT) controller, used to control the duty cycle of the converter, makes the PV module to work at its MPP (Duru, 2006). Figure 1.3 shows a typical MPPT control system.

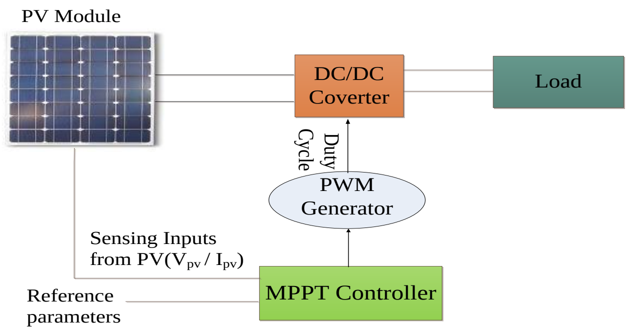

Figure 1.3. Typical MPPT control system

Different MPPT algorithms have been developed previously which are different in complexity, implementation, sensors required, precision, costs etc. (Esram & Chapman, 2007). One of the most important factors in evaluating the MPPTs is the dynamic response under rapidly changing of the solar irradiance. Conventional MPPTs such as perturbation and observation (P&O) and incremental conductance (INC) algorithms fail to find the MPP when the solar irradiance changes suddenly and some of them get confused by tracking the MPP in a wrong way. Another problem comes along with slowly changing of the solar irradiance. MPPTs with this drawback fail to find the exact MPP. Furthermore, oscillation around the MPP in this condition causes fluctuation at steady-state response which leads to power loss and lots of energy dissipation in long term (Hussein, Muta, Hoshino, & Osakada, 1995), (Liedholm, 2010), (X. Zhang, 2011), (Kumar, Dharmireddy, Raja, & Moorthi, 2011).

In recent years, several ANN MPPTs have been developed for changing weather conditions of solar irradiance and cell temperature (Ramaprabha & Mathur, 2011), (Xu, Shen, Yang, Rao, & Yang, 2011), (Ramaprabha, Mathur, & Sharanya, 2009), (Elobaid, Abdelsalam, & Zakzouk, 2012). In some works, only two sensors of irradiance and temperature are used, and ANN by sensing the irradiance and temperature, delivers the exact duty cycle required for the converter. In these works, the effect of the load is not considered and they are designed for a constant load. In other works where four sensors of irradiance, temperature, voltage and current are used; after ANN finds the optimum points, another controller makes the PV module to work at this point. Most of the previous ANN MPPT algorithms use an ANN to find the optimum points of voltage and current or maximum power at the first step, then by using a PI controller in the second step and changing the duty cycle of the converter, make the PV module to work at its maximum power point. With these algorithms, although the performance of the MPPT has improved as compared to traditional methods of perturbation and observation (P&O) and incremental conductance (INC) methods, the controller gain parameters need retuning for different loads and different conditions of solar irradiance and consequently cell temperature (Ramaprabha, Balaji, & Mathur, 2012), (Veerachary, Senjyu, & Uezato, 2003), (Mohamed, Elshaer, & Mohammed, 2012). With this drawback in these MPPTs, finding another algorithm which independent from the load to track the maximum power point of the PV module under different conditions of solar irradiance and cell temperature seems essential.

1.3 Aim and Objectives

The main aim of this work is to design a MPPT controller using ANN algorithm for PV boost DC–DC converter which tracks the MPP independent from the load, under changing weather condition of solar irradiance and cell temperature. The proposed method eliminates the need for PI controller which needs retuning for different conditions of load, solar irradiance and consequently cell temperature. In order to achieve this aim, the specific objectives are listed below:

i. To design an ANN MPPT controller for changing weather condition of solar irradiance and cell temperature that is independent from the load.
ii. To simulate and evaluate performance of the MPPT controller with the PV module.
iii. To experimentally validate performance of the MPPT controller with PV module in laboratory.

1.4 Contributions of Work

In this work, an ANN MPPT with a new controller in the second step is introduced which independent from the load, to track the maximum power point under changing weather condition of solar irradiance and cell temperature. Simulation and experimental results for an ANN MPPT have been presented for different weather conditions of solar irradiance and cell temperature, and the results have been compared with the simulation and experimental results of perturbation and observation (P&O) method with different step-sizes. Furthermore, a comparison is conducted between the proposed ANN method and previous ANN MPPT methods in two aspects of ANN output and ANN MPPT performance. The main contributions of this work are as below:

i. To develop a new equation in related to input impedance, output impedance and duty cycle of the boost converter, which independent from the load, to track the MPP identified by the ANN, under changing condition of solar irradiance and cell temperature.
ii. To show that ANN method with a good design and training is precise in finding the MPP.
iii. To show that ANN MPPT, with new controller in the second step, has high performance in tracking the MPP.
iv. To verify that ANN MPPT is independent from level of the solar irradiance, and acts the same for both high and low solar irradiances.

1.5 Scope and Limitations

This thesis aims at simulating and implementing an ANN based MPPT which well suits for varying condition of solar irradiance and cell temperature. A specific single poly-crystalline PV module is applied as the PV source, a DC–DC boost converter is developed as the power conditioner, and the whole system is simulated, implemented and tested for a resistive load under natural sunlight. Although design of the controller in this work is independent from the load, a resistive load of 33Ω is applied for simulation and experimental set ups. However, the simulation results for various loads are also presented as well to verify the independency of the controller from the load value. The effect of partial shading is out of the scope of this thesis.

Since the previous ANN MPPT works have not discussed some conditions such as rapidly and slowly changing of solar irradiance, the comparison in these conditions is conducted with commonly used P&O method. Furthermore, because of unpredictable condition of solar irradiance, comparing the simulation and experimental results under rapidly and slowly changing of irradiance was not possible. Thus, the comparison between simulation and experimental works is only done for low and high level of solar irradiance.

1.6 Outline of Thesis

Chapter 2 describes an overview on photovoltaic including solar cell, different types of solar cells, and characteristics of solar cells and PV modules. After that, review on PV DC–DC converters will be carried out especially related to PV applications; and DC–DC boost converter, its operating modes and design equations will be presented. Finally, different MPPT techniques are explained and further analyzed.

Chapter 3deals with methodology which contains two main parts: modeling in MATLAB-SIMULINK and hardware implementation. At first, the SIMULINK based models of the PV module, boost converter, ANN based controller and the overall PV system will be illustrated. Next, implementation of the designed PV system containing PV module, boost converter, required sensors and their circuits, and digital signal processor (DSP) for MPPT will be described.

In Chapter 4, firstly simulation results which contain both transient and steady-state responses and discussions for the proposed method and comparison with P&O method, dynamic response comparison of two methods under rapidly and slowly changing of solar irradiances, simulation results for different loads under different solar irradiances, and evaluation of the proposed method for changing load condition are presented. Secondly, experimental results present high and low solar irradiance performance for both proposed and P&O methods; and also performance of the proposed method under changing solar irradiance, and comparison of simulation and experimental results are given. Finally a comparison is conducted between the results obtained with the proposed ANN method and the previous ANN methods in two aspects of ANN outputs and ANN MPPT performance.

Chapter 5 contains conclusion and recommendation for future work. The references and appendices are attached at the end of the thesis.

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