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CUSTOM NEURAL NETWORKS MODELLING FOR SEMITRANSPARENT THIN FILM PHOTOVOLTAIC

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By

SABRI YASAMEEN HUSSEIN SABRI

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

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DEDICATION

This thesis is especially dedicated to:
To my Parents,
To my Family,
To my Brothers and Sisters,

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

CUSTOM NEURAL NETWORKS MODELLING FOR SEMITRANSPARENT THIN FILM PHOTOVOLTAIC

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July 2018

Chairman : Associate Professor Wan Zuha b. Wan Hasan, PhD
Faculty : Engineering

Thin-Film solar module of cadmium telluride (CdTe) is one of the Semi-transparent PV (STPV) that can be employed in a wide application range as a means to sunlight permeability while supplying solar electrical energy with some shading which also preferable in hot areas. The power generated by solar photovoltaic (PV) is highly affected by the weather environment. The prediction of a PV harvested energy and the system performance requires an accurate and reliable modelling as a formula and simulation design before installation. Silicon-based PV module with specifications equivalent to that for the STPV for comparison purposes. The proposed approach analyses the empirical data of a Thin-Film STPV module of CdTe type towards modelling. A developed Custom Neural Network (CNN) has been functioning for modelling the PV generated power based on laboratory and in-situ measurements. Experiments for different PV panel installation topologies have been conducted for performance analysis. Several standard single independent variable fitting modelling equations have been addressed as a basic modelling for I-V and P-V characteristic curves such as; Polynomial, Exponential, and Gaussian as parametric models. The developed CNN modelling has been implemented on both; I-V, P-V characteristic curves, and to simulate the power pattern of the PV module by adopting three factors; a minimum number of the hidden neurons, the use of all measured data for training the network weights, and linear output activation function, these factors were examined to reduce the complexity of solving the network equations. Silicon-based PV has been used in all modeling stages to validate the proposed methodology. The simulation has been performed by the MATLAB-Simulink environment. The result highlights the limit at which the STPV starts generating power via comparing with its equivalent silicon-based PV module. The proposed CNN modelling has the best goodness-of-fit than other relative models, and it is verified by the comparison between the measured and modelled outcomes which shows reasonable R-square

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value. The experiments have been conducted on different Thin-Film STPV modules; 48W and 40% transparency, 62W and 20% transparency, and 72W and 10% transparency. The results show that for a single module, the daily harvested energy is =190.01Wh, while that double module is= 218.48Wh, which satisfies the analysis of the single module measurements and that each individual thin film module can only generate power at a high certain level of irradiance. The results of the proposed CNN attain a correlation coefficient of 0.986 and show different fitting accuracy depends on several factors for each individual method. The proposed approach can facilitate the modelling strategy for other types of PV modules.

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

PEMODELAN RANGKAIAN NEURAL CUSTOM UNTUK PHOTOVOLTAIC FILEM TIPIS SEMI-TELUS

Oleh

SABRI YASAMEEN HUSSEIN SABRI

Julai 2018

Pengerusi : Profesor Madya Wan Zuha b. Wan Hasan, PhD
Fakulti : Kejuruteraan

Modul solar Filem-nipis yang diperbuat daripada Kadmium Telluride *(CdTe)* adalah salah satu PV Separa-lutsinar *(STPV)* yang boleh diaplikasikan secara meluas sebagai cara untuk kebolehtelapan cahaya matahari, di mana dalam masa yang sama membekalkan tenaga elektrik solar dengan kesan teduhan yang bersesuaian di kawasana beriklim panas. Cuaca persekitaran memberi kesan langsung terhadap kuasa yang dihasilkan oleh fotovoltaik solar (PV). Jangkaan tenaga yang mampu diahasilkan daripada PV dan prestasi sistem memerlukan pemodelan yang tepat dan boleh dipercayai sebagai reka bentuk formula dan simulasi sebelum pemasangan. Modul PV berasaskan silikon dengan spesifikasi bersamaan dengan STPV digunakan untuk tujuan perbandingan. Pendekatan yang dicadangkan menganalisis data empirikal modul filem-nipis STPV jenis Kadmium Telluride (CdTe) bagi tujuan pemodelan. Rangkaian Saraf Tersuai (CNN) yang dibangunkan telah berfungsi untuk memodelkan kuasa PV yang dihasilkan berdasarkan pengukuran di makmal dan lapangan. Eksperimen untuk topologi pemasangan tunggal dan multi-lapisan telah dijalankan untuk menganalisis prestasi sistem. Beberapa piawaian persamaan pemodelan persamaan pembolehubah bebas tunggal standard telah diatasi sebagai pemodelan asas untuk lengkung ciri I-V dan P-V seperti; Polinomial, Eksponen, dan Gaussian sebagai model parametrik. Pemodelan CNN yang telah dibangunkan telah dilaksanakan pada kedua-dua lengkung ciri I-V dan P-V, serta mensimulasi corak kuasa modul PV dengan menggunakan tiga faktor; bilangan minimum neuron tersembunyi, penggunaan semua data yang diukur untuk latihan beban rangkaian, dan fungsi pengaktifan output linear. Faktor-faktor ini dikaji untuk mengurangkan kerumitan dalam menyelesaikan persamaan rangkaian. PV berasaskan silikon telah digunakan dalam semua peringkat pemodelan untuk mengesahkan metodologi yang dicadangkan. Simulasi telah dilakukan menggunakan persekitaran MATLAB-Simulink. Hasilnya menyerlahkan batas di mana STPV mula menjana kuasa dengan membandingkan dengan modul PV silikon yang bersamaan. Pemodelan CNN yang

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dicadangkan mempunyai kebaikan yang terbaik daripada model relatif lain, dan ia disahkan oleh perbandingan antara hasil yang diukur dan model yang menunjukkan nilai R-square yang munasabah. Hasilnya menunjukkan bahawa untuk modul tunggal, tenaga penuaian harian adalah = 190.01Wh, manakala bagi lapisan multi ialah = 218.48Wh, yang memenuhi analisis pengukuran modul tunggal dan setiap modul filem nipis masing-masing hanya boleh menghasilkan kuasa pada paras yang tinggi dalam sinaran. Hasil CNN yang dicadangkan mencapai koefisien korelasi sebesar 0.986, dan menunjukkan ketepatan pemasangan yang berbeda bergantung pada beberapa faktor untuk setiap metode individu. Pendekatan yang dicadangkan ini boleh memudahkan strategi pemodelan untuk modul PV jenis lain.

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

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TABLE OF CONTENTS

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LIST OF TABLES

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LIST OF FIGURES

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LIST OF ABBREVIATIONS

PV	Photovoltaic
STPV	Semi-transparent PV
CdTe	Cadmium Telluride
ANN	Artificial Neural Network
CNN	Custom Neural Network
STC	Standard Test Conditions
I	Current (Amp)
V	Voltage (Volt)
P	Power (Watt)
Voc	Open Circuit Voltage
Isc	Short Circuit Current
T	Temperature ^{0}C
G	Irradiance (W/m^2)
RMSE	Mean Squared Error
R	Correlation coefficient
MPP	Maximum Power Point
E_{irrd}	Input energy (Wh)
E_out	The quantity of energy output (Wh)

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CHAPTER 1

INTRODUCTION

1.1 Background

PV module represents the fundamental power conversion unit of a PV generator system. Installing PV modules on part of the greenhouse roof area can be a strategy when crops require moderate shading in the high-insolation regions. Unlike simple shading nets or reflective coatings, appropriate shading and electricity production can be realized concurrently in a greenhouse with installed PV. However, excessive shading by enlarged PV panels on the greenhouse roof conflicts with the sunlight requirements of crops below

The output characteristic of the PV module depends on the solar insolation and the cell temperature [1]. The wide acceptance and utilization of the photovoltaic (PV) generation of electric power depend on reducing the cost of the power generated and improving the energy efficiency of PV systems. The additive transparent PV technology can similarly modify the glass transparency, but the no transmitted light would be utilized for power generation. CdTe cells are a type of the semiconductor thin film that has the permission for lower production costs. Semitransparent PV (STPV) thin film CdTe type of technology has done the highest production level of all the thin film technologies. Although thin-film photovoltaic (PV) modules have been in production for decades, the characterization of their performance analyzed under a synthetic light. The Standard Test Conditions (STC) take in the light intensity of a clear summer day and the module temperature of a clear winter day. These measurement conditions clearly do not represent the real operating conditions of PV devices at the site of installation. The increase in temperature or decrease solar irradiance has a dominant effect on PV modules' performance in a module PV, which that way significantly reduces the produced power [2]. Modeling of PV modules is one of the major components responsible for proper functioning of PV systems. However, the estimation of models is affected by various intrinsic and extrinsic factors, which ultimately influence the behavior of current and voltage. Therefore, perfect modeling is essential to estimate the performance of PV modules in different environmental conditions. In recent years, the researchers worked generally to introduce some advances on PV model parameters under various operating conditions. One of the tools that could serve to model the power system is the artificial neural network. Nowadays, significant growth has been made in neural network knowledge, thus enlarging the range of potential applications in different areas due to the black box functionality of the neural network. ANN can offer very good mapping if taught properly.

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1.1.1 Mathematical Modelling

A mathematical model can be defined as an explanation of a system using mathematical theory and language. The modeling may help to clarify a system and to revise the effects of different elements, in addition, to make forecasts about the system behavior. In many cases, the value of a scientific field based on how well the mathematical models produced to match the theoretical side. The output power, current and voltage of PV array vary as functions of solar irradiation level, temperature and load current. Therefore the effects of these three quantities must be considered in the modeling of PV module. Accurate and simple mathematical models are usually required to estimate the performances of photovoltaic devices.

1.1.2 Curve Fitting Equations

Curve fitting is the process of constructing a curve or mathematical function that has the best fit to a series of data points possibly subject to constraints. Intensive parametric analysis for type of the solar PV module [3]. Curve fitting is one of the most powerful and most widely used analysis tools in Origin. Curve fitting examines the relationship between one or more predictors (independent variables) and a response variable (dependent variable), with the goal of defining a "best fit" model of the relationship. The curve fitting defines a convenient curve to fit the measured values and uses a curve function to analyze the relation between the variables. The purpose of curve fitting is to find a function *f(x)* for the input measured data (x_i, y_i) where i = 1, 2… n means the number of measurements. The function *f(x)* minimizes the distance, named residue, between the measured data and *f(x)*. Different fitting methods can estimate the input data to find the curve fitting model parameters [4]. Each method has its own criteria for evaluating the fitting residual in finding the fitted curve equations.

1.1.3 Custom ANN

An artificial neural network (ANN) is usually employed as a technology offering an alternative way to solve complex problems. In the last decade, significant progress has been made in neural network technology to expand the range of potential applications into different areas because of the black box functionality of neural.

Mathematically-based model of a solar cell, module is programmed to obtain desired output data taking into account ambient temperature, solar irradiance level, and load voltage, the increase in temperature or decrease solar irradiance has a dominant effect on PV modules' performance in a module PV, which that way significantly reduces the produced power [2]. A mathematical-based model can describe PV cell, module accurately using a complicated mathematical algorithm. Various algorithms have been developed according to the ANNs' purpose of usage. They can be preferred according to their convenience to the problem to be solved, and training

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speed [5]. ANNs are trained with known data and then tested with data not used in training. The training of all patterns of a training data set is called an epoch. The training set has to be a representative collection of input/output examples. Back-propagation training is a gradient descent algorithm. It tries to improve the performance of the neural network by reducing the total error by changing the weights along its gradient. Although training takes a long time, they make decisions very fast during operation. Therefore, they are used widely in modeling nonlinear systems, thanks to their ability to learn, to generalize, to tolerate the faults and to benefit from the faulty samples.

1.2 Motivations

Recently, semi-transparent photovoltaic (STPV) systems have been employed in a wide application range as resources to supply solar electrical energy with some sunlight permeability and shading. The generated electricity represents a major advantage over movable shading devices for adjusting the transmitted sunlight. Available commercial STPV modules comprise encapsulated crystalline/silicon PV cells between two layers of glass or a transparent plastic film. The energy efficiency improvement and the high utilization of renewable energy are important targets for sustainable green energy productions. Few experimental measurements of such PV types have been carried out. In a greenhouse application, the installation of two STPV prototypes in the greenhouse roof and the annual attained electrical energy for the greenhouse land area showed that these modules could be sufficient for such applications in high irradiation areas [6]. Thin-Film and organic STPV technologies are now being adopted as low-cost solutions for greenhouse applications because of their power generation and transparent, flexible properties [7]. For organic and Thin-Film STPV modules, the transparency replaces the normal PV area ratio to express the sunlight amount that is interspersed through the glazing. Their main drawback is that they cannot generate power on cloudy days or in winter. Building Integrated Photovoltaic (BIPV) is a new type of building material, which provides green energy as well as building preservation. Apart from generating electricity, BIPV modules can be customized in a different dimension, thickness, shape, and color [8].

Modeling is a very important part of any engineering project. Nowadays, with the use of computers and powerful software extremely complex systems can be simulated and their performance can be predicted and monitored. Availability of models of all PV system components (especially for the PV generator itself) at all stages of system development is very important in system sizing, cost analysis and monitoring. Moreover, such models may be tested together with other distributed system models in order to evaluate and predict the overall system performance.

1.3 Problem Statement

Semi-transparent Solar PV is the new technology that represents the wave of the future for new solar applications as a means to sunlight permeability while supplying

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solar electrical energy with some shading which also preferable in hot areas. Although transparency with electrical energy generation through the glazing is a great achievement as a green energy resource, it has different performance than that of the PV silicon (blind). Environmental conditions such as (solar irradiance and temperature) have a huge influence on the characteristics and performance of a PV module, with the change in the time of the day the power received from the Sun by the PV panel changes the prediction of a PV system performance requires a modeling that allows the prediction of transparent modules behaviour under different physical and environmental parameters.

Some works present ANNs models specifically dedicated to model the power system and the hourly power generation forecasting in PV plants [9] [10] . All those ANN-based modeling provides accurate model architecture regardless of the complexity of that structure which in turns exhibit difficulties [11], when trying to solve the model mathematically and present a power formula.

Due to the intermittency and randomness of solar photovoltaic (PV) power, it is difficult for system operators to dispatch PV power stations. In order to find a precise expectation for power pattern of PV power generation, conventional models have taken into consideration the irradiance, temperature, humidity, and wind speed data for forecasting, but these predictions were always not accurate enough under extreme weather conditions. The power pattern of STPV has been modeled in the previous related studies [12] [13] via Neural Network, but all of those researchers didn’t offer a mathematical formula expressing this pattern of a PV system.

The proposed approach analyzes a PV of both normal Silicon-based and Thin-Film solar (CdTe)-type module and develops a custom neural network (CNN) for modelling its generated power expressed by its mathematical formula.

1.4 Objectives

The aim of this work is to study, design, and simulate an accurate architecture using a custom neural network with MATLAB functions based on lab and field-based experimental measurements of an STPV module. The study objectives:

- To investigate and analyze the STPV behavior under different and random weather conditions.
- To develop a custom neural network architecture model as a solution to facilitate deriving the modelling equations for the P-V characteristics and the generated power of a PV module.

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- To formulate the power of STPV based on the proposed model for different weather conditions such as solar irradiance and temperature, and analyze its performance when subjected to shading conditions.

1.5 Scope of Research

This research investigates, analyzes, and develops a mathematical model for the STPV Thin-Film from the experimentally measured data and compare its performance with its equivalent Silicon blind PV. The work also presents an algorithm for the daily real-time prediction model for the power generated from a PV system. This thesis presents various techniques, challenges and directions in modelling new semi-transparent PV module, as a part of a future promotion in building construction as such modules would use as a multi-function part, as a power generator and a glazier. Special design considerations are needed for PV systems. Environmental conditions have a huge influence on the characteristics and performance of a PV module. Therefore, it is imperative to have an accurate model at one's disposal as it aids in the testing and development of optimal power converters together with their associated control algorithms. Because the efficiency of PV generators is relatively low, it requires accurate models to ensure that designs can be easily tested for performance through simulations.

The standard mathematical fitting equations (such as Polynomial Models, Exponential, and Gaussian Models) addresses to see their effectiveness on modeling the I-V and P-V characteristic curves for silicon PV and STPV by approximating the experimentally measured data.

Both laboratory and field-based experimental measurements are considered to study the STPV P-V and I-V characteristics and their feasibility of providing a base for finding the mathematical model expression for such type of PV modules.

Developing a Custom Neural Network by considering; all measured data, a minimum number of neurons, and linear activation function for the output layer, to provide a robust mathematical formula interpreting the system behavior.

Comparing the STPV Thin-Film with its equivalent silicon-based PV to examine the electrical power output with the light intensity during a time period of one day, and also to study the performance and the efficiency of the Thin-Film PV under the influence of weather conditions.

The work also validates the results due to the measurements and modeling algorithm with MATLAB simulation to formulate STPV behavior by the developed CNN.

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1.6 Contributions

The key contributions of this paper are as follows:

- Customizing the ANN architecture to synthesize its topology for providing an output formula through solvable nonlinear algebraic equations. This is accomplished by; acquiring data with a high rate of sampling, normalizing the data set, selecting one hidden layer with no more than 6 neurons and a non-linear activation function, and using output neurons with linear activation function.
- Predicting the output power and formulate the performance of a PV system with mathematical equations derived from the proposed CNN.
- Proposing an approach analyzes a Thin-Film solar cadmium telluride (CdTe)-type module and developing a model for its behavior.

1.7 Research layout

After discussing the main research aspects and the main topology of the whole system, the remainder of the document is laid out as follows:

Chapter Two summarizes the literature review of the research trends like the current mathematical modeling for the silicon-based PV solar system as well as discusses the energy usage, monitoring, and design.

Chapter Three discusses the main research hypothesis, the algorithm of the system which is based on the STPV Thin-Film module. It also addresses the intensive parametric analysis of the STPV Thin-Film module of cadmium telluride (CdTe) type and its performance throughout the measurements that conducted at UPM University in the engineering faculty, Malaysia.

Chapter Four discusses all the research outcome results of the simulation and experimental phases in details.

Chapter Five Summarize the general conclusions of the thesis and the recommendations for future research.

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