UNIVERSITI PUTRA MALAYSIA

MATHEMATICAL MODEL FOR EFFECTS OF TROPICAL TEMPERATURE ON PERFORMANCE OF PHOTOVOLTAIC GENERATORS

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MATHEMATICAL MODEL FOR EFFECTS OF TROPICAL TEMPERATURE ON PERFORMANCE OF PHOTOVOLTAIC GENERATORS

By

IR. MOHAMMAD EFFENDY YA'ACOB

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirement for the Degree of Doctor of Philosophy

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DEDICATION

First and foremost, I would like to praise Allah The Al-Mighty,The Most Gracious and The Most Merciful for enlightening my way and directing me with continuous enthusiasm through each and every stage of my study.

I would like to dedicate and express my full appreciation to my chairman ofsupervisory committee, Associate Professor Dr. Hashim Hizam, and both of my co-supervisors Dr. M. Amran M. Radzi and Associate Prof. Dr. Mohammad Hamiruce Marhaban for their encouragement and support throughout my research work. It has been my honor and privilege to work under their supervision. My thanks also goes to Dr Tamer Khatib and Dr Mohd. Bakri Adam as the research collaborators for their strong comment, guidance and insight based on their expertise in PV system design and statistical analysis which are invaluable to me.

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Abstract of the thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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IR. MOHAMMAD EFFENDY YAACOB

March 2014

Chairman: Hashim Hizam, Ph.D.
Faculty: Engineering

Based on the presently practised method, Photovoltaic (PV) manufactures estimate the total energy generated from a collection of PV system based on a collection of PV modules datasheet by considering that such data incorporatesthe pertinent percentage of energy conversion capability. The module efficiency estimated in this method does not reflect the collective efficiency of a complete PV generator system. Due to factors such as cost, equipment, space and bulkiness of the system setup, normally a PV generator system cannot be tested in laboratories based on Standard Testing Conditions (STC). Hence the generation capability and the efficiency are solely extrapolated by per PV module characteristics. Moreover, the common customer trend for PV system requires more than a single module to be installed at their place.However, related to the issue, there has been little discussion about PV array temperature characteristics especially when it is installed in the tropics.

The standard approach of defining the efficiency of a photovoltaic cell strongly depends on the cell temperature, T_c which is calculated using a reference value of the Nominal Operating Cell Temperature (NOCT). Field analysis of a period of ten consecutive months comprising three different PV generator configurations, STC rated at 1 kWp with 12,190 data sets on the 15 minute intervals are the backbone of this work. Rapid fluctuating environmental data flow are the triggering factor to be monitored at site. It consists of both online and ground platform interface via Data Acquisition and Real-Time Monitoring (DART) systemto capture measurement from multiple input sources and analyse in synchronize mode.The crucial part in this study considers dominant influential factors of temperature which are the surface and bottom sides of each PV paneloperated in fluctuating climatic conditions.

Based on this issue, to cater for tropical condition, a new condition parameter with a new terminology “tropical Field Operation Cell Temperature (tFOCT)”is introduced.

This new condition calculates the PV cell temperature in the tropics with statistical justifications of Generalized Extreme Value Distribution (GEV).Furthermore, by using Multiple Linear Regression (MLR) technique, it is found that the Radiation (G) correlates the PV Power (P_{pv}) by the factor of 0.76 (in W/m^2) andcorrelates with tFOCT by the factor of 25.8 (in ^0C). Both factors have significant positive correlationsin enhancing the PV generator output.

This study also addresses some findings on the PV array electrical and thermal characteristics comprising five standard operating conditions based on the Sandia National Laboratory (SNL) model. It is found that Fixed Flat (FF) array projects the highest operating value with good regression fit and fairly acceptable correlations. The Tracking Flat (TF) PV Generator is suggested to be the most suitable PV generatorbased on the field performance analysis witha system efficiency of 10.78%.

The research contribution lies on the proposed tFOCT condition parameter, array temperature difference (ΔT), array temperaturemodels (T_{array}), array electrical/ thermal specifications, PV generator field performanceand the P_{pv} equation which is brought forward as reference for PV manufacturers and designers who intend to install their PV products in tropical-based countries.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah.

MODELMATEMATIKBERDASARKANIMPAKSUHUTROPIKA KE ATASPRESTASI JANAKUASA PHOTOVOLTAIC

Oleh

IR. MOHAMMAD EFFENDY YA'ACOB

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Pengerusi : Hashim Hizam, PhD
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Berdasarkan kaedah amalan kini, sektor pembuatan Photovoltaic (PV) menganggarkan jumlah tenaga yang dijana hanya merujuk kepada koleksi modul PV melalui data spesifikasi dan dihitung dengan peratusan yang berkaitan keupayaan penukaran tenaga. Ia menunjukkan bahawa kecekapan modul yang dianggarkan dalam kaedah ini tidak mencerminkan kecekapan kolektif sistem penjana PV yang lengkap. Disebabkan faktor seperti kos, ruang, peralatan dan konfigurasi sistem yang besar, biasanya sistem janakuasa PV tidak boleh diuji dalam makmal berdasarkan Kondisi Pengujian Piawai (STC). Oleh itu keupayaan Janakuasa dan kecekapannya diekstrapolasi semata-mata dari setiap karektor modul PV yang digunakan. Selain itu, amalanpengguna sistemPVmemerlukanlebih daripada satu modulPVyang akan dipasangdi tempatmereka.Walaubagaimanapun, berkait dengan isu di atas, hanya terdapat sedikit penyelidikan berkaitan karektor suhu tatasusunan PV terutama di kawasan tropika.

Pendekatan piawai untuk menentukan kecekapan sel PV amat bergantung pada suhu sel, T_c yang dikira menggunakan nilai rujukan Suhu Nominal Operasi Sel (NOCT).Analisis untuktempoh sepuluhbulan berturut-turutyang terdiri daripada tiga Janakuasa PV pelbagai konfigurasi, 1 kWp pada kadaran STC dan mencapai 12,190 set data berselang 15 minit adalah tulang belakang kerja penyelidikan ini. Berdasarkan aspek penting merakam perubahan data alam sekitar secara berkesan, sistem pemantauan di tapak,telah menggunapakai dua kaedah iaitu pemantauan dalam talian dan pemantauan di tapak projek. Rekodpengukuran daripada pelbagai sumber dan analisis dalam mod seragam dapat dilaksanakan melalui sistem Pemerolehan Data dan Pengawasan Keadaan dalam Masa Sebenar (DART). Bahagian utama hasil penyelidikan ini memfokuskan kepada faktor berpengaruh oleh suhu dominan iaitu suhu bahagian atas dan bahagian bawah panel janakuasa PV yang beroperasi dalam keadaan iklim turun naikyang ketara.Walau bagaimanapun, keadaan ini mungkin berbeza-beza bergantung kepada jenis zon iklim di mana dalam kajian ini, untuk suhu

tropika, satu istilah baru yang dipanggil Suhu Operasi Sel LapanganTropika (tFOCT) telah diperkenalkan dengan justifikasi statistikSebaran Nilai Ekstrem Teritlak (GEV).

Denganaplikasi teknikRegresi Linear Berbilang(MLR), didapati bahawa sinarancahaya matahari (G) mempunyai hubungkait terhadap kuasa (P_{pv})dengan faktor0.76(dalamW/m^2) dan juga berkait secara langsungdengansuhu tFOCTdengan kadar25.8(dalam^0C) di mana kedua-duafaktor ini mempunyaikorelasipositif dalammeningkatkanhasil keluaranpenjanaPV.

Selain itu, hasil penemuan tentang karektor elektrikal dan termaluntuk PV array parameter adalah diperincikan yang merangkumi lima keadaan operasi piawai berdasarkan model Makmal Kebangsaan Sandia(SNL). Kajian ini mendapati Pipih Tetap PV (FF) mempunyai nilai operasi tertinggi dengan faktor regrasi dan korelasi yang munasabah.Berdasarkan analisis prestasi lapangan, kajian ini mencadangkan Pipih Penjejakan PV (TF) sebagai Janakuasa PV yang paling sesuai dengan kecekapan system penjana pada kadar 10.78%.

Sumbangan penyelidikan bagi kajian ini berpaksikan kepada cadangan kondisi parameter tFOCT, perbezaan suhu tatasusunan PV (ΔT), model suhu tatasusunan PV(T_{array}),spesifikasi elektrikal / termal, prestasi lapangan bagi Penjana PV dan persamaan P_{pv}. Adalah diharapkan hasil penyelidikan ini akan menjadi salah satu sumber rujukan bagi pengeluar dan perekabentuk PV yang bercadang memasang produk PV mereka di negara-negara beriklim tropika.

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I certify that a Thesis Examination Committee has met on 20 March 2014 to conduct the final examination of Ir. Mohammad Effendy Yaacobon his thesis entitled "A Mathematical Model for Effects of Tropical Temperature on Performance of Photovoltaic Generators" 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 Doctor of Philosophy.

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

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Declarationby Graduate Student

I hereby confirm that:

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