UNIVERSITI PUTRA MALAYSIA

GENETIC ALGORITHM-BASED ARRANGEMENT OF PHOTOVOLTAIC MODULES IN ARRAYS FOR MISMATCH LOSS MITIGATION

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By

SAMAD SHIRZADI DEH KOHNEH

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

May 2015

DEDICATION

I would like to dedicate my thesis to my beloved family

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

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Chairman: Jasronita bt. Jasni PhD
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Photovoltaic (PV) arrays which are the main part of PV generators consist of PV modules and PV modules are composed of PV cells. Such a modular nature is a blessing when it provides flexibility in system sizing but is a curse when it combines with inequality of PV modules and causes the so-called mismatch power loss. Recent investigations have reported this type of mismatch losses from 1% to 10%. The conventional techniques to minimize mismatch losses are distributed maximum power point tracking (MPPT), array reconfiguration and module sorting technique. Module sorting techniques which sort modules in arrays by one characteristic parameter are superior among all conventional solutions. This study proposes a new method for arranging modules in arrays using a genetic algorithm (GA) to find the arrangement with lowest mismatch losses and highest output power. Some data sets of modules are generated through a stochastic process and organized in different arrays. These data sets are used to carry out several simulations in MATLAB. These simulations cover calculation of mismatch losses at standard test circumstance (STC) and also energy yield under the GA based arrangement as well as the sorting techniques. Results prove that the proposed arrangement of modules in arrays reduces mismatch losses and subsequently improves the energy yield more effectively than what conventional sorting techniques do. The GA based arrangement is also validated with other data sets of modules that are collected from 3 practical arrays. Results of participation of these practical data sets also support the superiority of the GA based arrangement over sorting techniques. Comparison between best sorting technique and the GA based arrangement turned out that the GA based arrangement recovers daily energy ranging from 50 Wh to 320 Wh and monthly energy ranging from 1010 Wh to 6240 Wh depending on the array size. Similar comparison for the practical arrays shows an annual recoverable energy ranging from 6.35 kWh to 11.8 kWh and up to 278 kWh for an array with defective modules.

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

SUSUNAN MODUL FOTOVOLTA DALAM TATASUSUNAN BERASASKAN ALOGARITMA GENETIK BAGI PENGURANGAN KERUGIAN TIDAK SEPADAN

Oleh

SAMAD SHIRZADI DEH KOHNEH

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Koleksi fotovolta (PV) yang merupakan bahagian utama penjana PV terdiri daripada modul PV dan modul PV pula terdiri daripada sel-sel PV. Ianya sesuatu yang menakjubkan apabila sifat modular menyediakan fleksibiliti dalam sistem ukuran tetapi adalah sesuatu yang tidak disenangi apabila ia bergabung dengan ketidaksamaan modul PV dan menyebabkan apa yang dikenali sebagai kehilangan kuasa tidak sepadan. Kajian terkini telah melaporkan bahawa jenis kerugian tidak sepadan ini adalah dari 1% ke 10%. Teknik-teknik biasa yang digunakan untuk mengurangkan kerugian tidak sepadan diagihkan melalui pengesanan titik kuasa maksima atau maximum power point tracking (MPPT), konfigurasi yang pelbagai dan teknik penyusunan modul. Teknik penyusunan model yang menyusun modul dalam jajarannya melalui satu parameter ciri adalah lebih baik dari semua penyelesaian konvensyional. Kajian ini mencadangkan satu kaedah baru menyusunatur modul dalam jajarannya menggunakan satu algoritma genetik (GA) untuk mencari susunan yang mempunyai kerugian tidak sepadan terendah dan dengan kuasa output tertinggi. Beberapa set data modul dijana melalui satu proses stokastik dan disusunatur dalam pelbagai tatacara. Set-set data ini digunakan untuk menjalankan beberapa simulasi dalam MATLAB. Simulasi-simulasi ini merangkumi perkiraan kerugian tidak sepadan pada keadaan ujian berpiawai atau standard test circumstance (STC) dan juga hasil tenaga di bawah susunan berasaskan GA dan juga teknik-teknik penyusunan. Keputusan menunjukkan bahawa jajaran modul yang disarankan berjaya mengurangkan kerugian tidak sepadan dan seterusnya memperbaiki lagi hasil tenaga dengan lebih berkesan dari teknik-teknik penyusunan konvensyional. Susunan berasaskan GA ini juga turut disahkan dengan set-set data modul yang lain yang dikumpul dari 3 jajaran yang praktikal. Keputusan penyertaan set-set data yang praktikal ini turut memberi sokongan kepada kelebihan jajaran berasaskan GA berbanding dengan teknik-teknik susunan yang lain. Perbandingan di antara teknik susunan yang terbaik dan susunan berasaskan GA menunjukkan bahawa susunan berasaskan GA memulihkan tenaga harian berjulat dari 50 Wh ke 320 Wh dan tenaga bulanan berjulat dari 1010 Wh ke 6240 Wh bergantung kepada saiz susunan. Perbandingan yang serupa susunan praktikal menunjukkan satu pemulihan tenaga tahunan dari 6.35 kWh sehingga 11.8 kWh dan sampai kepada 278 kWh untuk pelbagai susunan yang mempunyai modul-modul yang rosak.

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This thesis was submitted to the Senate of 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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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

arr	Array
BL	Bridge-Link
DMPPT	Distributed Maximum Power Point Tracking
DC	Direct Current
FF	Fill Factor
GA	Genetic Algorithm
IEA	International Energy Agency
Irr	Irradiation
I-V	Current-Voltage
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
mod	Modules
mp	Maximum Power
MML	Mismatch Losses
MF	Mismatch Factor
OC	Open Circuit
ph	Photo-generated
PMX	Partially Mapped Crossover
PV	Photovoltaics
P-V	Power-Voltage
SC	Short Circuit
SP	Series-Parallel
STC	Standard Test Circumstance
TCT	Total-Cross-Tied

Symbols

σ_{η}^{2}	Variance of variations in the max-power current
σ_{ξ}^{2}	Variance of variations in the max-power voltage
α	Temperature coefficients of the I_{sc}
β	Temperature coefficients of the V_{OC}
$\bar{I}$	Nominal value for current
$\bar{V}$	Nominal value for voltage

CHAPTER 1

INTRODUCTION

1.1 Background

The growing global desire for energy can be understood by taking a look at the International Energy Agency (IEA) Key World Energy Statistics that states a yearly energy consumption of 140’000TWh for the world in 2006 and predicts it to increase up to 224’000TWh in 2030 (Freris & Infield, 2008). Considering such an energy demand, the finitude of fossil fuels (Shafiee & Topal, 2009), and environmental issues (Gieré & Stille, 2004; Kasting, 1998), curiosity of human beings about renewable energy resources seems justifiable. Among various types of renewable sources sun has specific position since there are different technologies to harvest the energy that is delivered from sun.

Sun radiation carries heat and light together. Solar thermal systems use the sun heat, solar photovoltaic/thermal systems use a combination of sun heat and sunlight (Huang, Lin, Hung, & Sun, 2001; Tripanagnostopoulos, 2007; Tripanagnostopoulos, Nousia, Souliotis, & Yianoulis, 2002) and PV systems which are subject of this study use the sunlight. When PV industry was born with the invention of first solar cell at American Bell Laboratory in 1954 (Quaschning, 2009), it was difficult to predict its worldwide installed capacity to increase from 5 GW in 2005 up to 40 GW in 2010 (IEA, 2011). Such a remarkable development shows the commercial and technological prosperity of PV industry. Current PV generators are different in terms of technology, size and connectivity to the main power grid.
There are different technologies to convert photo-energy to electrical energy, such as mono-crystalline, poly-crystalline, thin film or amorous silicon, hybrid panels, organic panels (Brabec, Scherf, & Dyakonov, 2014) and others. Each technology has advantages and drawbacks. For example mono-crystalline has higher conversion efficiency and higher price in comparison with thin film, but thin film has the best performance in climates with high temperature among all technologies (Parida, Iniyan, & Goic, 2011).

From the standpoint of independency on the main power grid, PV systems are classified as stand-alone and grid-connected types. Stand-alone PV systems are developed to maintain load demands that are situated far from the power utility so these systems supply the loads in closely surrounding areas. Grid-connected systems are designed to inject power to the utility power grid. Stand-alone PV systems are sized according to the load demand, while grid-connected PV systems are scaled in accordance with the availability of the primary energy source (Kaundinya, Balachandra, & Ravindranath, 2009).

Size of PV generators range from small scale residential roof mounted PV systems to large scale PV farms. First residential application of PV systems in a systematic way was found in USA (Green, 1982). According to the 2010 Solar Market Trends Report, the average-sized of a residential PV system is 5.7 kW-DC (Speer, 2012). Large scale PV installations (that are referred to as PV farms), were as large as about 1 MW at the beginning of the 21st century. But currently there are much larger systems installed such as the 60 MW PV farm in Spain or the 40MW PV farm in Germany (Komoto, 2009). These PV installations are distinctly larger than the residential ones.

For a typical PV generator, sort of components are required to work together to generate an appropriate form of electrical energy that is used in domestic, industrial, agricultural and other applications out of sun radiation. These components are mainly PV arrays that convert photo-energy to electrical energy in DC form which is variable in terms of voltage and current, a DC-DC converter that stabilizes the DC voltage and leads the PV array to work optimally, an inverter that converts electrical energy of DC form to AC form and a storage device that preserves electrical energy to be used when sun radiation is lower than minimum required level. Storage device is a necessity of stand-alone PV systems that work independently from the main power grid (Hansen, Sørensen, Hansen, & Bindner, 2001) where as it can be eliminated in grid connected PV systems that are connected to the main power grid consistently (Ropp, 1998).

There are technical challenges for PV generators as complex systems and every challenge is an opportunity for study and probable development. One of the challenges arises from the modularity of PV arrays and the inequality of PV modules.

A PV array consists of series and parallel combination of PV modules. The same way PV modules are composed of PV cells (see Figure 1.1). This modular nature of PV systems is advantageous when it helps to wire the system up to desirable level of current, voltage and power. But the fact that PV modules with the same brand and same ratings are not exactly identical turns the modularity of PV systems to be disadvantageous when it causes sort of power losses known as mismatch losses which are recognized by several research works (Bucciarelli Jr, 1979; Chouder & Silvestre, 2009; Picault et al., 2010). Since PV modules are fabricated in the factory, further investigation and modification in cell level requires damaging the module encapsulation. So investigation and mitigation of mismatch losses among cells inside modules is of PV module manufacturers' interest whereas such an investigation among modules in arrays is of system operators and installers' interest. This work deals with mismatch losses among modules at array level.

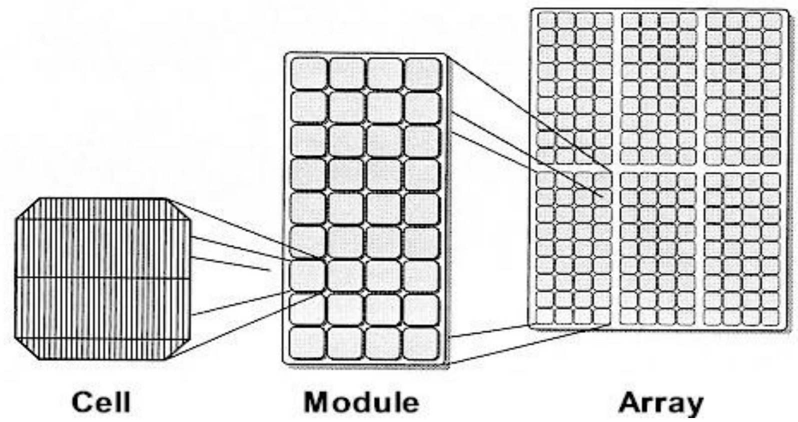

Figure 1.1: Modularity of PV systems

A group of modules of the same brand and same nominal ratings are not exactly identical. Their differences are understood by comparing and contrasting their characteristic parameters such as fill factor (FF), maximum power (P_{MPP}), current at maximum power (I_{MPP}), voltage at maximum power (V_{MPP}), short circuit current (I_{SC}) and open circuit voltage (V_{OC}). Difference in modules characteristic parameters is called I-V mismatch, since it results in different electrical performances. I-V mismatch comes from either temporary or permanent sources as classified in Figure 1.2.

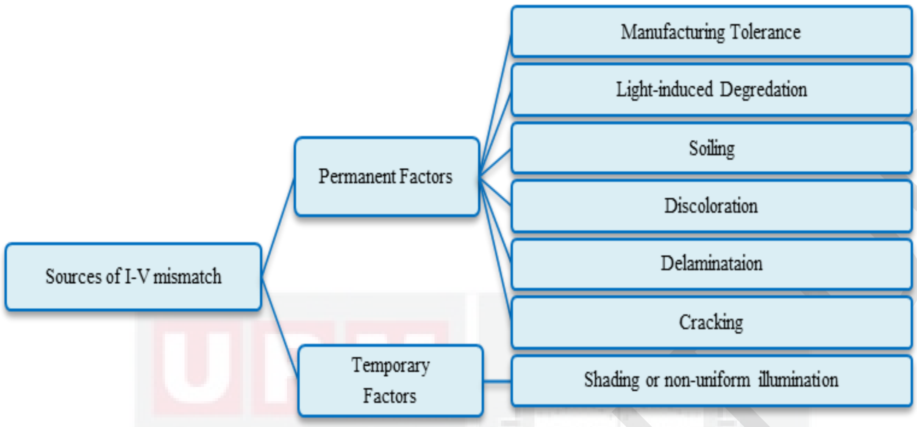

Figure 1.2: Classification of factors that cause mismatch losses

Shading or non-uniform illumination might happen by fallen leaves of trees, scattered clouds moving over the PV array, shadow of an object situated around the PV array or another reasons (Sonnenenergie D., 2008). This factor can temporarily result in mismatch losses in an array of modules, whereas there are other factors which permanently cause mismatch losses such as manufacturing tolerance, light-induced degradation, discoloration, soiling, delamination and cracking. Referring to datasheet of PV modules are currently available in the market, it is found that despite all advancements of PV modules production technology, there still exists a manufacturing tolerance of ±3% to ±5% in their rating P_{MPP}, I_{MPP} and V_{MPP}. Light-induced degradation, discoloration, soiling and delamination are all matters of aging (Smith, Jordan, & Kurtz, 2012). Cracking in cells is a module defect that can happen during shipment, installation or further happen due to hail (Ton, Tillerson, McMahon, Quintana, & Zweibel, 2007) so it also can be considered as a matter of aging. All these permanent factors cause dispersion in PV module characteristic parameters. This variation in module characteristic parameters is the root of mismatch losses (Reis, Coleman, Marshall, Lehman, & Chamberlin, 2002; Zilles & Lorenzo, 1992). This work focuses on finding a solution for mismatch losses occurs due to all permanent factors. Thus, hereinafter term mismatch losses addresses the mismatch power loss coming from permanent factors and term mismatch refers to permanent I-V mismatch in PV modules.

It should be pointed out that aforementioned permanent factors (excluding manufacturing tolerance) have another impact on the PV array performance that is always studied separately entitled “performance degradation”. Performance degradation is not a subject of this study. Performance degradation is measurable by comparing the performance parameters of an aged PV system to its fresh condition (Quintana, King, McMahon, & Osterwald, 2002) whereas mismatch losses is measurable by comparing array output power to the summation of individual modules output power.

1.2 Statement of the Problem

In practical PV generators, a central Maximum Power Point Tracker (MPPT) system is applied to lead the system to work at its' possible maximum power (Femia, Petrone, Spagnuolo, & Vitelli, 2012). In the presence of such a system all modules are supposed to work at their I_{MPP} and V_{MPP} which are not exactly identical for all modules as previously explained. Simply put, under a central MPPT, when two modules with different I_{MPP} are connected in series, they compromise to work at the lower I_{MPP} and similarly two modules with different V_{MPP} connected in parallel work at the lower V_{MPP}. Generalization of these conditions to a large array of PV modules connected in series and parallel, results in the following equation (Chamberlin, Lehman, Zoellick, & Pauletto, 1995):

$$MML\% = 100\left(\frac{\sum_i P_{MPP}^{mod,i} - P_{MPP}^{arr}}{\sum_i P_{MPP}^{mod,i}}\right) \qquad (1.1)$$

Where $MML\%$ is the percent of mismatch losses, $P_{MPP}^{mod,i}$ is the maximum power produced by ith module if it works independently, and P_{MPP}^{arr} is the output power of the whole array.

1.3 Significance of Study

Optimal operation is indeed a concern of any energy generator and PV generators are not exceptions. Since arrangement of PV modules in an array affects the system energy losses and system yield, finding the optimal arrangement of the modules that returns the lowest possible mismatch losses and highest possible energy yield is worthy of investigation.

The proposed solution to the mismatch losses that will be offered here concerns arranging modules in a PV array at the installation stage or after some time of exposure. It is further explained that the offered method is more effective on reducing the mismatch losses comparing to existing techniques. Since application of this solution is just a matter of PV modules rearrangement, it does not charge any significant cost to the system operators or system installers.

1.4 Objectives

According to the problem statement of the study that is explained, the suggested solution that is comprehensively elaborated in the methodology chapter should cover the objective of the study as clarified hereby:

- Mismatch Losses Minimization
    - Energy Yield Improvement
    - Applicability for Different Array Sizes

The main aim of this study is to minimize the mismatch power loss that accurse to the system under standard test circumstance (STC) that counts for 1000 W/m^{2}and 25°C. Application of PV generators is ubiquitous in areas with high level of irradiation which is close to STC. In addition, PV arrays generate most of their power at high irradiation level which is close to STC. These facts stand behind the significance of this objective.

Although PV arrays generate more power at high irradiation level but their generation continues as long as they receive the minimum required radiation. Thus energy yield improvement should be investigated to assure the effectiveness of the proposed solution under variety of radiation levels and temperatures. In other words, investigation of energy yield improvement of PV systems under suggested solution should prove the independency of the solution on the STC. This point is very important since modelling, simulations and calculations for approaching the proposed mismatch losses mitigation technique that are covered in the main objective are performed at STC.

Since, PV arrays sizes range from small residential installations ones to some megawatts PV farms, it is important to makes sure that the proposed solution works for different sizes of PV arrays. Hence adaptability of the proposed solution to different array sizes is also considered in this investigation.

1.5 Summary

Environmental issues and finitude of fusil fuels have motivated human to look for renewable and clean energy resources. Sun is a renewable energy source that provides heat and photo-energy. Attempts for harvesting energy from sun photo-energy have resulted in Photovoltaic industry. There are several challenges about well utilization of PV systems and mismatch power loss is one of them.

Regarding the permanent factors of mismatch losses that are classified in Figure 1.2 and based on the mechanism of mismatch losses that is briefly explained, this study tries to find a solution to the problem of mismatch losses among the PV module at array level that firstly reduces the mismatch losses more effectively than existing methods and secondly is as economical as them.

1.6 Thesis Organization

Second chapter reviews the relevant literature including the fundamentals of mismatch power loss in PV systems, the reported amounts for the mismatch losses, and the solutions that have been suggested or applied to the problem of mismatch losses so far. Third chapter starts with elaborating the hypothesis of the study and continues with explaining the methodology of the study. Requirements of the methodology are explained in advance and then steps of methodology are brought out in accordance with the objectives of the study. Forth chapter demonstrates the results of the study regarding each part of the methodology. Finally the conclusion and the future work are provided in the fifth chapter.

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