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OPTIMUM CALCULATION OF TILT ANGLES AND COMPONENTS OF STANDALONE PHOTOVOLTAIC SYSTEM TO HARVEST SOLAR ENERGY

AMEEN SARHAN ABDULLAH AHMED

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By

AMEEN SARHAN ABDULLAH AHMED

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May 2018

Chair: Associate Professor Hashim Hizam, Ph.D.
Faculty: Engineering

Recently, there has been renewed interest in PV system worldwide because of high demand for green energy resources as an alternative to conventional energy resources, which contribute to the enormous amount of greenhouse gasses and a resultant global warming in the earth atmosphere.

In under developing countries, there is a sharp shortage in electricity supply, PV system may prove to be adequate solution for supplying the required electrical load in such counties. However, the drawback of PV system is the high capital cost as compared to conventional energy sources. For lower energy cost and better performance, the components of PV system and its tilt angle must be designed optimally.

Yemen is under developing country suffering from shortage of electricity especially in remote areas. Nevertheless, Yemen receives abundant sunshine all year round, thereby making solar energy a promising alternative to conventional fuels. Moreover, there are many isolated and remote areas located far away from the national electrical grid and require a large fund to be integrated in the near future. Therefore, Standalone Photovoltaic (SAPV) system is an adequate solution for electrification in such area. However, one of the main obstacles of PV system compared to conventional energy sources is the initial high capital cost. So, for low-energy cost and enhanced performance, the size of the systemâĂŹs components, as well as PV array tilt angle, need to be designed optimally.

This study aims to optimize the annual, bi-annual, quarterly, and monthly tilt angles of PV panels for various cities in Yemen based on the model of Liu and Jordan for solar radiation on inclined surfaces. Moreover, an improved optimization method for sizing and configuration standalone photovoltaic (PV) systems is presented.

For simulation purpose, 22-year monthly average horizontal and diffused solar radiation and ground albedo data were obtained from NASA, and MATLAB software was utilized to optimize the tilt angle by maximizing the solar radiation on the PV panel. Optimization and configuration algorithm of sizing SAPV system is implemented using MATLAB and hourly meteorological data and load demand. Loss of load probability analysis is conducted to set the benchmark for determining all possible PV arrays and battery capacities. Then, the optimum design is proposed based on the lowest levelized cost of energy (LCE) and net present value (NPV).

Consequently, by applying the annual, bi-annual, quarterly, and monthly optimum tilt angles, the collected gain of the PV module increases by 2.86%, 8.52%, 8.61%, and 9.30%, respectively. Based on the calculated results, the tilt angle should be changed at least twice a year for improving the productivity of PV systems in Yemen and nearby countries. Regarding the 2.475 kW_p PV system, the results show that the net present value of the PV system for Yemen is 22224 USD, while the cost of energy generated by the proposed system is 0.403 USD/kWh at Loss of Load Probability (LLP) equal to 0.130%.

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

PENGIRAAN OPTIMUM KECONDONGAN SUDUT DAN KOMPONEN UNTUK SISTEM FOTOVOLTAIK BERDIRI SENDIRI UNTUK TUAIAN TENAGA SOLAR

Oleh

AMEEN SARHAN ABDULLAH AHMED

Mei 2018

Pengerusi: Hashim Hizam, Ph.D.
Fakulti: Kejuruteraan

Kebelakangan ini, sistem PV m erupakan di antara sumber alternatif tenaga diper- baharui yang mendapat perhatian yang sangat tinggi serta menjadi perhatian dunia eko- ran pertambahan pengeluaran gas rumah hijau yang mana mengakibatkan masalah kepanasan global serta peningkatan suhu dunia.

Yemen merupakan salah sebuah negara yang menerima sejumlah tenaga yang sangat besar daripada sumber matahari sepanjang tahun dan keadaan ini adalah sangat sesuai untuk pembinaan sistem tenaga solar bagi menggantikan tenaga yang berasaskan minyak. Tambahan pula, terdapat banyak kawasan yang masih tidak mempunyai grid talian elektrik kerana kedudukan kawasan-kawasan ini adalah jauh daripada grid talian kebangsaan dan kos untuk menyalur bekalan elektrik ke kawasan-kawasan tersebut amatlah tinggi dan tidak menguntungkan. Justeru itu, pembinaan Sistem Solar Fotovoltaik Bebas (SAPV) merupakan langkah terbaik bagi mengatasai masalah tersebut. Walaubagaimanapun, kos permulaan bagi penyaluran bekalan elektrik berasaskan sistem solar agak tinggi jika dibandingkan dengan pembekalan elektrik secara konvensional. Oleh yang demikian, kerja-kerja merekabentuk sistem solar tersebut perlu dijalankan dengan teliti serta mengambil kira kesemua aspek termasuk jenis dan komponen berkaitan, kesesuaian sudut kecondongan bagi kedudukan panel solar serta lain-lain komponen yang terlibat bagi menghasilkan rekabentuk yang paling optimum untuk mendapatkan bekalan elektrik yang maksima daripada sistem solar tersebut.

Kajian kerja yang dijalankan adalah tertumpu kepada sudut kecondongan yang optimum bagi kedudukan panel solar di beberapa bandar di Yemen. Selain itu, kaedah pengoptimuman yang lebih baik terhadap kerja-kerja konfigurasi bagi sistem solar PV serta kapasiti sistem solar juga turut dijelaskan bersama kajian kerja yang dijalankan.

Bagi kerja-kerja simulasi, data selama 22 tahun yang diambil di awal tahun, pertengahan tahuan serta secara bulanan adalah diperolehi daripada NASA dan perisian MATLAB digunakan bagi menjalankan kerja-kerja simulasi tersebut iaitu bagi mendapatkan sudut kecondongan yang optimum bagi mendapatkan pancaran radiasi yang maksima di permukaan panel solar. Algoritma kerja-kerja konfigurasi sistem juga dijalankan dengan menggunakan perisian MATLAB bagi menentukan saiz atau kapasiti sistem solar PV yang berasaskan kepada data setiap jam serta kehendak maksima beban sebenar. Analisa terhadap kemungkinan kegagalan sistem solar PV dijalankan agar dapat dijadikan tentuukur atau garis panduan penetapan susunan solar PV dan kapasiti bateri yang diperlukan. Seterusnya kerja-kerja merekabentuk optimum diperkenalkan berasaskan kepada Kos Tenaga yang Paling Rendah (LCE) dan Nilai Had Semasa Bersih (NPV).

Dengan mengambil kira pengumpulan data yang dibuat secara tahunan, suku tahun serta data secara bulanan mengenai sudut kecondongan optimum bagi kedudukan panel solar. Didapati jumlah penerimaan pancaran radiasi di permukaan panel solar adalah masing-masing meningkat sebanyak 2.86%, 8.52%, 8.61%, dan 9.30%. Berdasarkan kepada pengiraan, sudut kecondongan kedudukan panel perlu disemak sekurang-kurangnya dua kali setahun bagi menambahbaik sistem penjanaan tenaga solar di Yemen dan kawasan-kawasan sekitarnya. Berdasarkan kepada kapasiti sSistem Solar PV di Yemen, didapati bahawa Nilai Had Semasa Bersih adalah sebanyak 22224 USD, manakala jumlah kos bagi penjanaan bekalan daripada sistem solar yang dicadangkan adalah sebanyak 0.403 USD/kWh dengan jangkaan 0.130% bagi faktor Kemungkinan Kegagalan Bebas Sistem Solar tersebut.

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Finally, my appreciation goes to all my colleagues in *CAPER*, you have been good companions and shared some knowledge among ourselves.

I certify that a Thesis Examination Committee has met on 16/05/2018 to conduct the final examination of Ameen Sarhan Abdullah Ahmed on his thesis entitled OPTIMUM CALCULATION OF TILT ANGLES AND COMPONENTS OF STANDALONE PHOTOVOLTAIC SYSTEM TO HARVEST SOLAR ENERGY 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 Master of Science.

Members of the Thesis Examination Committee were as follows:

Mohammad Lutfi Othman, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairperson)

Noor Izzri bin Abdul Wahab, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Hashimah Abdul Rahman, PhD
Associate Professor
University Technology Malaysia
Malaysia
(External Examiner)

RUSLI HAJI ABDULLAH, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 30 August 2018

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:

Hashim Hizam, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohammad Effendy Ya'acob, PhD
Senior Lecturer
Fculty of Engineering
Universiti Putra Malaysia
(Member)

ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
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Name of Chairman of Supervisory Committee: Assoc. Prof. Dr.Ir. Hashim Hizam

Signature: ____________________________
Name of Member of Supervisory Committee: Dr. Ir. Mohammad Effendy Ya'acob

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LIST OF ABBREVIATIONS

ANN	Artificial neural network
$AGCE$	Average generation cost of energy (USD)
ACS	Annualized cost of the system (USD)
AI	Artificial Intelligent Method
ATC	Total annualized cost (USD)
ACC	Annualized capital costs (USD)
ARC	Annualized replacement costs (USD)
$A(O\&M)C$	Annualized operation and maintenance costs (USD)
ASV	Annualized salvage values (USD)
CRF	Capital recovery factor
CRF	Capital recovery factor
C_B	Possible battery capacity (Wh)
DOD	Allowable battery depth of discharge (%)
E_o	Eccentricity correction factor
ELF	Equivalent loss factor
E_{Deff}	Deficit energy (Wh)
f	Annual inflation rate
FL	Fuzzy logic
GA	Genetic algorithm
$GANN$	General artificial neural network
$G(t)$	Solar irradiation (W/m^2)
G_{STC}	standard test conditions for solar radiation (W/m^2)
$\bar{H}_\beta$	Daily global solar radiation on tilted surface ($kWh/m^2/day$)
$\bar{H}_b$	Daily beam solar radiation on horizontal surface ($kWh/m^2/day$)
$\bar{H}$	Daily global solar radiation on horizontal surface ($kWh/m^2/day$)
$\bar{H}_d$	Daily diffuse solar radiation on horizontal surface ($kWh/m^2/day$)
$\bar{H}_r$	Daily reflected solar radiation on horizontal surface ($kWh/m^2/day$)
I_β	Hourly global solar radiation on inclined surface (W/m^2)
$I_{b\beta}$	Hourly beam solar radiation on inclined surface (W/m^2)
$I_{d\beta}$	Hourly diffuse solar radiation on inclined surface (W/m^2)
$I_{r\beta}$	Hourly reflected solar radiation on inclined surface (W/m^2)
I_g	Hourly global solar radiation on horizontal surface (W/m^2)
I_d	Hourly diffuse solar radiation on horizontal surface (W/m^2)
I_{sc}	Solar constant (W/m^2)
I_o	Hourly extraterrestrial solar radiation on horizontal surface (W/m^2)
I_{output}	Charge controller rating current (A)
I_{charge}	Charging current (A)
ICC	Initial capital cost of the PV system (USD)
i	Real interest rate
i'	Nominal interest rate (the rate at which you could obtain a loan)
$LPSP$	Loss of power supply probability
LLP	Loss of load probability
$LOLE$	Loss of load expected
LCE	Levelized cost of energy (USD/kWh)
M_t	Indicative of the clearness of the sky
n	Day of the Year

NPV	Net present value (USD)
N_{pv}	Number of PV module in an array
N_{CC}	Number of charge controllers
N_{BP}	Number of battery parallel strings
PV	Photovoltaic
P_{pv}	Output power produced by a PV module (W)
P_{load}	Load power (W)
P_{STC}	Maximum power production for a PV module under the standard test condition (W)
PV_{max}	Maximum output power of the PV array (W)
P_{CC-max}	Maxium output power of the charge controller (W)
P_{inv}	Inverter power rating (W)
r_b	Ratio of hourly global solar radiation on an tilted surface to that on a horizontal surface
r_d	Ratio between hourly diffuse solar radiation on a horizontal surface to that on an inclined surface
r_r	Ratio of hourly reflected solar radiation on an inclined surface to that on horizontal surface
$\bar{R}_b$	Ratio of average daily global solar radiation on an tilted surface to that on a horizontal surface
$\bar{R}_d$	Ratio between diffuse solar radiation on a horizontal surface to that on an inclined surface
$\bar{R}_r$	Ratio of reflected solar radiation on an inclined surface to that on horizontal surface
R_S	System lifetime
RC	Replacement cost of PV system (USD)
R_{comp}	Lifetime of the system component $(year)$
R_{rem}	Remaining life of the component $(year)$
R_{rep}	Replacement cost duration $(year)$)
SAPV	Standalone Photovoltaic sytem
SFF	Sinking fund factor
S	Salvage value of system components (USD)
SOC	Battery sate of charge (%)
T_c	PV cell temperature (C^o)
TEL	Total energy loss (Wh)
TS	Tabu search
T_{STC}	Standard test conditions for ambient temperature (C^o)
V_{DC}	DC voltage operation (V)
V_B	Battery voltage (V)

Greek Latters

ϕ	Latitude $(^o)$
β	Tilt angle $(^o)$
β_{opt}	Optimum tilt angle $(^o)$
δ	Declination angle $(^o)$
δ_c	Declination angle at characteristic day $(^o)$

ω_s	Sunset hour angle (^{o})
$\omega_s{}'$	Sunrise hour angle (^{o})
γ	temperature coefficient of the PV module power P_{pv}
η_{cc}	Charge controller efficiency
η_{wire}	Wire efficiency
η_{inv}	Inverter efficiency
η_{Batt}	Battery efficieny
$\eta_{Batt,RT}$	Battery round-trip efficiency
ρ	Ground Albedo
Γ	Day angle

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Recently, there has been renewed interest in green energy sources worldwide as an alternative to conventional energy resources. This is due to the fact that green energy resources are renewable, environmentally friendly and entailing insignificant maintenance compared to conventional energy sources (Thomas et al., 1999; Razykov et al., 2011). In the country with abundant solar energy, energy conversion via photovoltaic (PV) technology is the most attractive compared to other available renewable resources.

PV system converts sun energy into electricity directly by utilizing advanced technology to manufacturing efficient solar cell, which is the key component of a PV system (Xiao, 2004). The PV system can be categorized into three main types: standalone, grid-connected and hybrid PV system (Khatib et al., 2013a). The standalone PV system (SAPV) is consists of DC_DC converter, battery storage bank, power inverter and particular load such as home appliances (Hankins, 2010).

In the installation and design of PV system, the installer should have knowledge of design process starting maximum utilization and variation of solar radiation falling on PV panel. As the amount of solar radiation received by a solar panel is mainly affected by its orientation and tilt angle, local solar radiation, as well as the property of ground reflection (Reddy et al., 2013). Furthermore, for lower energy cost and better performance, the components of PV system and its tilt angle have to be designed optimally.

Studying issues related to Standalone PV system design and installation is a vital solution for electrical shortage in different places around the world which are rich with solar energy resources. For example, Yemen is a country located in the Middle East whose geographical coordinates are between $13^o - 16^o$ North latitude and $43.2^o - 53.2^o$ East longitude. Due to the location of Yemen in the worldâĂŹs solar belt, it receives an abundance of sunshine all the year around, for that the use of solar energy as an alternative to conventional fuels is more feasible. Table 1.1 shows the monthly average of solar energy and ambient temperature for various locations in Yemen. The table also shows that the annual daily average solar insolation is 6.3 $kWh/m^2/day$, with a peak value in May (7.24 $kWh/m^2/day$) and a minimum value in December (5.21 $kWh/m^2/day$). The annual daily average ambient temperature is 26.05 C^o to 29.71 ^oC, and the minimum value in January is 20.75 ^oC.

Table 1.1: 18-year (1987–2005) Monthly Averaged Insolation Incident on a Horizontal Surface and Air Temperature Various Locations in Yemen (NASA, 2017)

Month	Insolation ($kWh/m^2/day$)	Air Temperature (^oC)
January	5.32	20.75
February	5.92	22.28
March	6.54	24.52
April	6.95	26.93
May	7.24	29.71
June	7.02	30.66
July	6.65	29.37
August	6.53	28.19
September	6.54	28.06
October	6.35	26.29
November	5.70	24.07
December	5.21	21.81
Annual Average	6.33	26.05

1.2 Problem Statement

The tilt angle is one of the most critical factors that considerably influences the amount of solar radiation received by a flat surface. The ideal method to optimize the slope of a solar surface is using an active sun tracker. But due to the latter increases, the solar system's capital and maintenance cost as well as consumes energy during tracking, adjusting the tilt angle monthly, three-month, six-month or fixed at optimum value may be more practical than using an active sun tracker (Kazem et al., 2013; Khatib et al., 2012a). Moreover, the difficuly of maintenance of sun tracker in remote areas.

However, the unpredictable and uncertain nature of solar energy remains a challenge to PV systems, and the variations of solar energy and load demand distribution may not match the intended level of availability. Although oversizing may address the reliability problem, it may lead to a high capital cost. Therefore, optimally sizing PV system components is essential to a reliable and cost-effective PV system. Sizing optimization is performed by determining the capacity of the PV array, charge controller, storage battery, and the inverter to solve the formulated bi-objective techno-economic optimization problem based on optimal trade-off between the cost and availability of the system (Abbes et al., 2014; Zhou et al., 2010). Meanwhile, meteorological data of solar radiation and ambient temperature have a significant influence on the optimization and performance of PV systems. Consequently, extensive studies regarding such meteorological variables should be considered for the optimum design of PV systems (Khatib et al., 2013b; Thevenard and Pelland, 2013).

Many countries around the world, especially developing countries, such as Yemen, are currently experiencing electricity shortage; the annual energy consumption per capita in Yemen is approximately 0.22 MWh (International Energy Agency, 2014). Yemen is underdeveloped country where about 66% of the populations (17.3 million) live in rural areas, and about 41% of them (7.08 million) live without access to electricity (The World Bank, 2014). Extension of the power grid to these areas is not economically feasible. Moreover, conventional solutions provided by diesel generators are costly due to the high cost of fuel and maintenance as well have disadvantages such as loud noise and more importantly, environmental issues.

Yemen is a country with abundant sunshine all year around; PV systems are clean, environment-friendly and secure energy sources, which may prove to be an adequate solution for supplying the required electrical load. However, the drawback of PV system is the high capital cost as compared to conventional energy sources and uncertainty of solar energy source. Currently, in order to design the PV system efficiently, many research works are carried out focusing on the maximization of harvesting solar energy by PV panel and optimization of PV system components as well concerning the economics and reliability aspects.

To our knowledge, no work has been conducted to determine the optimum tilt angle of PV panel in Yemen. Moreover, sizing of SAPV system's components has been done based on the intuitive method which leads to high capital cost and unreliable PV system. Therefore, by considering all advantages and drawbacks of previous work related to sizing components of SAPV system around the world, an improved optimization algorithm is developed which can be applied not only for Yemen but, also for any location around the world.

1.3 Aims and Objectives of the Study

The main aim of this study is to present recommendations for size optimization of a SAPV system installed in Yemen. These recommendations include the optimization of PV panel's tilt angle, PV array's size, the capacity of the storage battery, operation DC voltage, charge controller and power inverter rating, series and parallel connection of PV panels and batteries.

In order to achieve the aim, the objectives are listed as follows:

1. To identify the optimum tilt angle for PV module located in different Yemeni cities.

2. To develop a numerical algorithm which can determine the optimal sizing, connection and operation DC voltage of SAPV system in Yemen.

3. To determine the minimum cost for SAPV system components with satisfied reliability conditions.

1.4 Scope and Limitation

The research scope taken in this work starts with optimization of PV module tilt angles and components of SAPV system in Yemen. The considered locations in this work are based on seven main cities in Yemen in case of tilt angle optimization. In actual, there are 39 cities divided into 22 governorates. The main important note for dealing with selected cities is the high density of population in these cities. Also, these cities represent more than two-third of Yemen area. So other cities are located near to these seven cities, and the difference in latitude and longitude values is small.

In recent years, different optimization algorithms have been presented based on different techniques by utilizing daily or monthly average load and meteorological data. This study proposed numerical techniques with hourly load and meteorological data as inputs for sizing of SAPV system components.

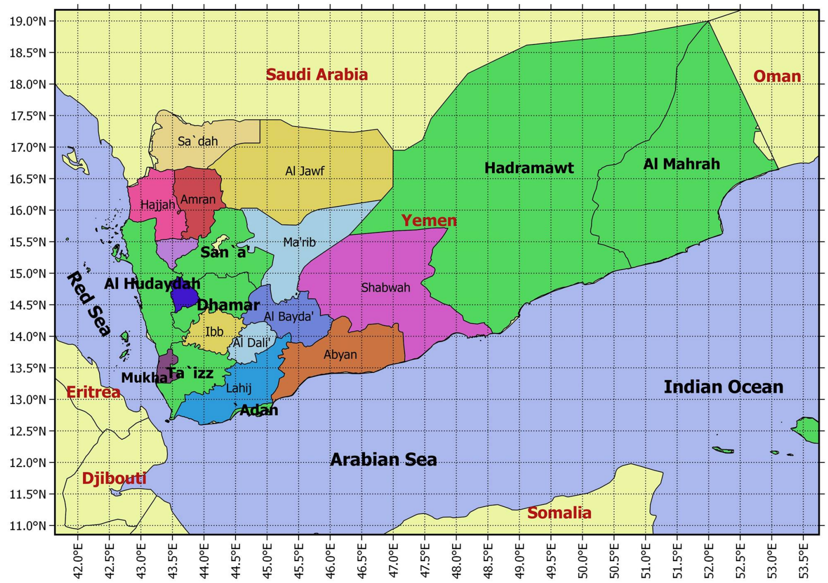

Figure 1.1: Republic Of Yemen Map

1.5 Thesis Organization

In this study, various important issues related to optimization of SAPV system's components and PV module's tilt angle are discussed and presented in five chapters as follows:

Chapter 1 introduces a brief background and research motivation. The problem statement, aims, objectives, scope, and limitations as guidelines to complete this thesis are also covered in this chapter.

Chapter2 reviews the theoretical background and existing work related to tilt angle optimization and sizing of SAPV system components.

Chapter 3 describes some necessary theories related to modeling of solar radiation on tilted surface, SAPV system's components. Moreover, the description of suggested methodology is discussed in this chapter.

Chapter 4 highlights the simulation results for optimization of PV panel's tilt angles and sizing of stand-alone PV system's components. Finally, the optimization results of proposed sizing algorithm by comparing with other studies are presented in this chapter.

Chapter 5 summarizes the finding results and recommends the outlines for future works.

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