FORMULATION OF PHOTOVOLTAIC INVERTER WEIGHTED CONVERSION EFFICIENCY FOR EQUATORIAL CLIMATE

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ABSTRACT

The system energy yield (E_{sys}) is a performance indicator used by the installer to predict the energy output generated by a photovoltaic (PV) system. From the E_{sys} estimation, the return of investment (ROI) for the installation can be approximated. The E_{sys} equation consists of several elements, in which one of them is the PV inverter efficiency. The peak or maximum efficiency (η_{max}) value from the inverter data sheet is usually used, but this practice is inaccurate because the PV inverters rarely operate at the peak power. Alternatively, the weighted efficiency is more preferable as it essentially considers the power conversion characteristics of the inverter when subjected to varying solar irradiance. Currently, the European weighted efficiency (η_{EURO}) is the most recognized and widely accepted. This is because, historically, European countries (particularly Germany) used to be the largest exporter and consumer of PV inverters throughout the world. Since η_{EURO} is developed based on a specific European irradiance profile, it is suspected that its value may not be suitable for inverters installed in different climatic conditions, particularly the equatorial region. Thus, the first objective of this work is carried out to prove this hypothesis. A one-year dataset from a weather station located at Universiti Teknikal Malaysia Melaka is collected with adherence to the IEC 61724 Standard. This irradiance profile is injected into a PV array simulator (PVAS) and tested on four PV inverters with different sizes and technologies. It is found that the recalculated η_{EURO} does not conform to the value stated in the respective inverter's datasheet, thus confirming the above hypothesis. This finding inspires the formulation of a new weighted efficiency formula for the equatorial climate (η_{EQUA}). Three methods have been utilized, namely the IEC 61683 Standard, Response Surface Methodology (RSM) and Equatorial Irradiance-Duration Curve. The outcomes revealed that the last approach is the most practical solution to formulate η_{EQUA}. The newly developed formula is validated by the measured data from the field. It is demonstrated that the prediction of E_{sys} using η_{EQUA} closely matched the E_{sys} of a real 3 kW PV system, with only 0.16% difference between the two. It is envisaged that the usage of η_{EQUA} instead of η_{max} (or η_{EURO}) will results in more accurate E_{sys} and ROI predictions for PV system installed in the equatorial region.

ABSTRAK

Hasil tenaga sistem (E_{sys}) adalah petunjuk prestasi yang digunakan oleh pemasang untuk meramal keluaran tenaga yang dihasilkan oleh sistem fotovoltaik (PV). Daripada anggaran E_{sys}, pulangan pelaburan (ROI) untuk pemasangan dapat dianggarkan. Persamaan E_{sys} terdiri daripada beberapa elemen yang berbeza, di mana satu daripadanya adalah kecekapan penyongsang PV. Nilai puncak atau kecekapan maksimum (η_{max}) dari lembaran data penyongsang biasanya digunakan, tetapi amalan ini adalah tidak tepat kerana penyongsang-penyongsang PV jarang sekali beroperasi pada kuasa puncak. Sebagai alternatif, kecekapan berwajaran adalah lebih sesuai kerana pada dasarnya ia mengambil kira ciri penukaran kuasa penyongsang apabila mengalami sinaran matahari yang berubah-ubah. Pada masa kini, kecekapan berwajaran Eropah (η_{EURO}) adalah yang paling dikenali dan diterima secara meluas. Ini kerana, menurut sejarah, negara-negara Eropah (terutamanya Jerman) pernah menjadi pengeksport penyongsang PV terbesar di seluruh dunia. Oleh kerana η_{EURO} dibangunkan berdasarkan profil sinaran matahari yang spesifik di Eropah, adalah dicurigai yang nilainya mungkin tidak sesuai untuk digunakan dalam keadaan iklim yang berbeza, terutamanya kawasan khatulistiwa. Oleh itu, objektif pertama penyelidikan ini dijalankan adalah untuk membuktikan hipotesis ini. Data profil sinaran matahari selama setahun dari stesen cuaca yang terletak di Universiti Teknikal Malaysia Melaka telah dikumpul dengan mematuhi Piawai IEC 61724. Profil sinaran matahari ini digunakan dalam simulator susunan PV (PVAS) dan diuji pada empat penyongsang PV dengan saiz dan teknologi yang berbeza. Adalah didapati yang η_{EURO} yang dikira semula tidak sama seperti mana yang dinyatakan dalam lembaran data setiap penyongsang, lantas mengesahkan hipotesis di atas. Penemuan ini memberikan inspirasi bagi perumusan kecekapan berwajaran baru untuk iklim khatulistiwa (η_{EQUA}). Tiga kaedah telah digunakan, iaitu Piawai IEC61683, Metodologi Permukaan Tindak-Balas (RSM) dan Keluk Sinaran Matahari-Tempoh Khatulistiwa. Hasilnya menunjukkan bahawa pendekatan terakhir memberikan penyelesaian yang paling praktikal untuk merumuskan η_{EQUA}. Rumus yang baru dibangunkan ini telah disahkan dengan data yang diambil dari lapangan. Ianya telah menunjukkan bahawa ramalan E_{sys} menggunakan η_{EQUA} memberikan jawapan yang hampir sama dengan E_{sys} bagi sebuah sistem PV 3 kW yang sebenar, dengan perbezaan hanya 0.16% di antara kedua-duanya. Adalah dijangkakan yang penggunaan η_{EQUA} dan bukannya η_{max} (atau η_{EURO}) akan menghasilkan pengiraan E_{sys} dan ramalan ROI yang lebih tepat untuk sistem PV yang dipasang di kawasan khatulistiwa.

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LIST OF ABBREVIATIONS

RE	-	Renewable Energy
PV	-	Photovoltaic
SEDA	-	Sustainable Energy Development Authority of Malaysia
FiT	-	Feed-in-Tariff
NEM	-	Net metering
LSS	-	Large Scale Solar
GCPV	-	Grid-Connected Solar PV
ROI	-	Return of Investment
STC	-	Standard Test Condition
RSM	-	Response Surface Methodology
UTeM	-	Universiti Teknikal Malaysia Melaka
MPPT	-	Maximum Power Point Tracking
PSH	-	Peak Sun Hour
NOCT	-	Nominal operating cell temperature
LF	-	Low frequency transformer
PWM	-	Pulse width modulation
HF	-	High frequency transformer
TL	-	Transformerless
RCD	-	Residual Current Protective Device
PID	-	Potential Induced Degradation
TCO	-	Transparent Conductive Oxides
P&O	-	Perturb and Observe
W	-	Watt
DC	-	Direct current
AC	-	Alternating current
KGCCS	-	Koppen-Geiger Climatic Classification System
AIT	-	Austrian Institute of Technology
IEC	-	International Electrotechnical Commission
MS	-	Malaysian Standard
PVAS	-	PV Array Simulator

DUT	-	Device under test
RAID	-	Redundant Array of Independent Disks
MOSFET	-	Metal–oxide–semiconductor field-effect transistor
MLR	-	Multiple Linear Regression
RMSE	-	Root Mean Square Error

LIST OF SYMBOLS

E_{sys}	-	System Energy Yield
η_{max}	-	Peak or Maximium Efficiency
η_{EURO}	-	European Weighted Efficiency
η_{CEC}	-	California Energy Commission Weighted Efficiency
η_{EQUA}	-	Equatorial Weighted Efficiency
P_{array}	-	Power from PV Array
f_{temp}	-	Temperature loss
f_{mm}	-	Mismatch loss due to manufacturer
f_{dirt}	-	Loss due to accumulation of dirt
η_{cable}	-	DC cable loss
η_{inv}	-	Inverter efficiency
V_{DC}	-	Direct current voltage
η_{MPPT}	-	MPPT efficiency
G	-	Irradiance
T	-	Temperature
Φ	-	Perturbation
P_O	-	Output power
P_L	-	Total power loss
P_S	-	Switching loss
P_D	-	Diode conduction loss
P_R	-	Inverter total ohmic losses
P_M	-	Total magnetic component losses
P_C	-	Electronics control power consumption
t_{on}	-	On-time delay
t_{off}	-	Off-time delay
f_s	-	PWM switching frequency
I_{Load}	-	Conducting current
V_F	-	Voltage drop
N	-	Transformer turns ratio
r	-	Transformer internal winding resistance

r_{mod}	-	Modulator internal ouput resistance
K_h, K_e	-	Constants depending on magnetic materials
B_{max}	-	Maximum value of flux density
z	-	Steinmetz constant
V_{IN}	-	Direct input voltage
I_C	-	Controller current
P_{dc}	-	Inverter input power
P_{dc_rated}	-	Rated inverter input power
τ_r	-	Sampling time
η_{IZM}	-	Izmir weighted efficiency
η_{CHE}	-	Chennai weighted efficiency
η_{KAN}	-	Kanpur weighted efficiency
G_h	-	Global or horizontal irradiance
G_i	-	Tilted or in-plane irradiance
T_a	-	Ambient temperature
T_m	-	Module temperature
V_{oc}	-	Open circuit voltage
I_{sc}	-	Short circuit current
V_{mpp}	-	Maximum power point voltage
I_{mpp}	-	Maximum power point current
I_{DC}	-	DC current
V_{ac}	-	AC voltage
I_{ac}	-	AC current
P_{ac}	-	Inverter output power
η_{WT}	-	Weighted efficiency
G_n	-	Irradiance level
T_n	-	Amount of time
G_T	-	Total Irradiance level
LO	-	Level of operation
WT	-	Weightage
η_{EURO_recal}	-	Recalculated η_{EURO}
E_{sys_meas}	-	Measured energy system yield
E_{sys_calc}	-	Calculated Energy System Yield

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CHAPTER 1

INTRODUCTION

1.1 Overview

Since the first electric power plant was built by Thomas Edison in 1882, fossil fuels such as coal, natural gas and oil has become the preferred choice to drive the prime movers [1, 2]. This is due to the fact that fossil fuels are the most cost effective, easy to transport and most importantly is its ability to generate huge amount of electricity at just one particular location. However, their use contaminates the environment and it is now identified to be the main culprits for greenhouse effect—as a result of the large amount of carbon dioxide that they release [3]. As suggested by Figure 1.1, the conventional electricity generation by fossil fuels is the main contributory factor for global warming experienced throughout the world [4].

With regard to these concerns, the renewable energy (RE) sources are envisaged to be important players in the future energy mix. RE is defined as the energy that will not be depleted when used, can be replenished and effectively, does lesser harm to the environment. They are harnessed naturally from the environment such as solar, wind, tides, waves, biomass and geothermal heat [5]. Among these RE sources, the solar photovoltaic (PV) can be considered as the most viable option. It is easier to install and does not have moving mechanical parts. In comparison to wind, the sunlight is most likely to be available more often. As long as there is sunlight, the PV energy will always be available for harvesting.

This PV energy is especially attractive for countries located near the equator where the longer and consistent sunlight is available. For example, it is normal for Malaysia—a country which is located 3^{o} from the equator, to receive eight to twelve hours of sunlight for every single day of the year [6]. In comparison, the temperate regions, such as the Scandinavia countries receives less than 3 hours of sunlight in the winter season. Realising the enormous potential that the country possesses, the government of Malaysia proactively emulate the RE techno-business model of advanced countries such as Germany and Spain in trying to develop its own solar PV industry. Figure 1.2 presents the RE development plan (which includes PV) by the Sustainable Energy Development Authority of Malaysia (SEDA)—a regulatory body that oversees the development of RE in the country. Thus far, several attractive schemes to jump start the industry are introduced: the feed-in-tariff (FiT), Net Metering (NEM) and large scale solar (LSS) generation in order to meet the national renewable energy policy of achieving 20% RE capacity mix by 2025 [7]. The FiT program for instance, provides opportunities for consumers to install grid-connected solar PV (GCPV) of various capacities on their own rooftops. By law, the generated power is contracted for 21 years to be sold to the local electricity distribution company at an attractive price [8].

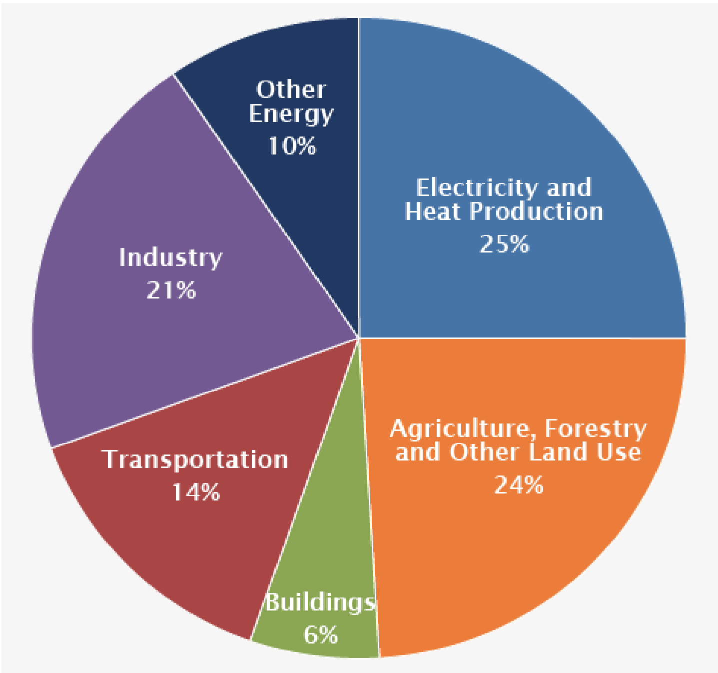

Figure 1.1 Global greenhouse gas emissions by economic sectors [4]

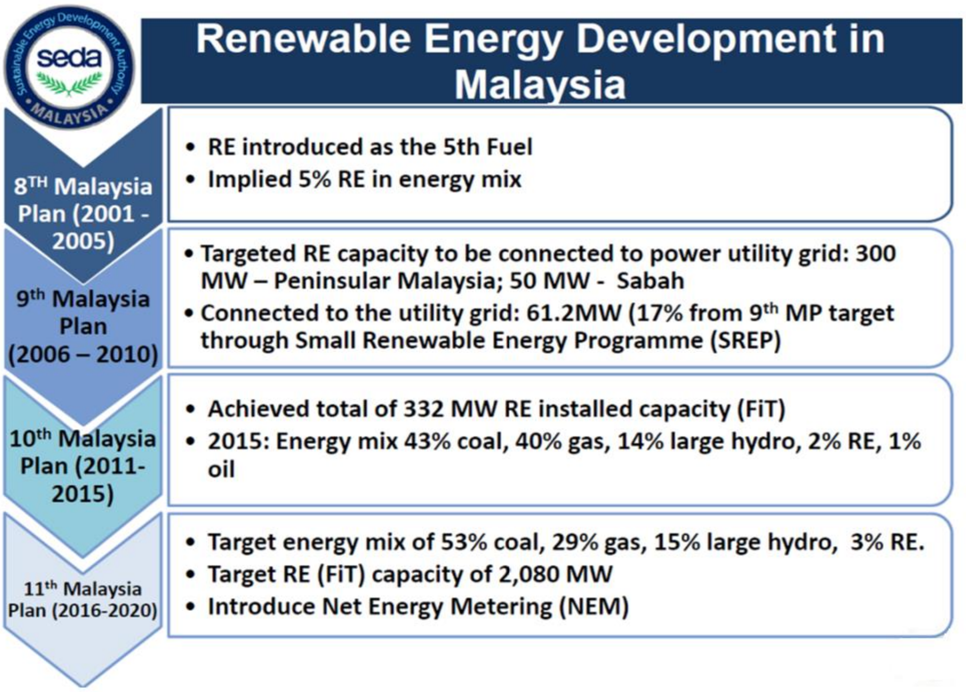

Figure 1.2 Renewable energy development plan in Malaysia [7]

The main concern for PV system owners is to recoup their investment in the shortest time possible. Currently, the projected payback period of GCPV system in Malaysia (with FiT) is typically to be between five to seven years. This is an attractive return of investment (ROI) for a system with a contractual obligation of 21 years [9]. One of the most important elements to predict the ROI is the system energy yield (E_{sys}) [10-12]. The computation of E_{sys} involves a number of variables, including the PV inverter efficiency value. Typically, the system designer (or installer) uses the peak efficiency (η_{max}) number stamped on the nameplate of the inverter as the input value to the E_{sys} equation. The η_{max} refers to highest efficiency that can achieved by the inverter—normally it is obtained when the inverter operates at the nominal (or rated) power. However, in most cases, inverter does not operate at this level because the environmental condition, particularly the irradiance is normally well below the standard test condition (STC). As a result, the input power fed into the inverter is lower than its rated power, which means that the power electronics components inside the inverter are forced to operate inefficiently. Thus, if η_{max} is used to compute the E_{sys}, the energy yield will be overrated. This will lead to incorrect ROI estimation.

A more acceptable value to be used is the weighted efficiency. The weighted efficiency of a PV inverter refers to the efficiency that takes into account the performance of the inverter when subjected to the variations in the irradiance. Currently there are two weighted inverter efficiency which are widely used throughout the PV industry: the European weighted (η_{EURO}) and the California Energy Commission (CEC) (η_{CEC}) efficiencies. According to [13], η_{EURO} efficiency is the benchmark value for countries with medium irradiance profile whereas η_{CEC} is the standard to be used for countries with high irradiance profile. This is partly due the fact that the derivation of the former originates from the middle region of Germany, while the latter is based on the irradiance profile of Sacramento, a city located in the west coast of USA.

Besides the two aforementioned weighted efficiencies, there are several attempts to formulate weighted efficiency based on local climate conditions. Examples of such efforts are the Izmir weighted efficiency for Turkish weather; the Kanpur and Chennai weighted efficiencies for Indian climate. However, these three newly developed indices are not well accepted by the PV community. Based on the literature review performed, the main reasons are: 1) they do not comply with the international standards during the metrological data collection; 2) the formulation of the weighted efficiency indices does not follow the standardized procedures. Moreover, the Izmir weighted efficiency is redundant because the climate condition at which the measurements are made are similar to the η_{CEC}.

It is interesting to note that thus far, there is no work undertaken to study the performance of PV inverter when subjected to equatorial climate. There are many countries that can be included under this profile: Southeast Asia, Central Africa, South America and parts of Oceania. The equatorial region is unique because it is characterised by hot and humid condition all year round. It is expected the inverter will perform differently compared to its installation in other climatic regions. Therefore, it is necessary to revisit the weighted efficiency to ensure that the system yield can be correctly estimated.

1.2 Problem Statement

From literature, it is confirmed that there is no research have been carried out to formulate the weighted efficiency of PV inverter for the equatorial region. Clearly, there is a research gap here and an opportunity to address this specific issue. Since the installation of the inverter is typically based on the maximum efficiency, the estimated system yield is higher than the actual. This overrated performance is misleading as it will results in inaccurate estimation of ROI. Thus, there is a need to reformulate the weighted efficiency in order to match the equatorial climate conditions.

1.3 Research Objectives

Based on the problem statements mentioned, the specific research objectives of this work are stated below:

(a) To ascertain whether the European weighted efficiency (η_{EURO}) is suitable when PV inverter is installed in equatorial climate. This is done by using the equatorial irradiance data with the η_{EURO} formula.

(b) To formulate the Equatorial weighted efficiency (η_{EQUA}) equation based on IEC 61683 Standard, Response Surface Methodology (RSM) and Equatorial Irradiance-Duration Curve approach.

(c) To validate η_{EQUA} based on real data from a PV system in equatorial climate.

1.4 Research Scopes

To ensure completeness of the work within the given time frame and resources, the scopes of the research are defined as follows:

(a) The one-year equatorial irradiance data are gathered from a single PV monitoring station, i.e., the weather station at Universiti Teknikal Malaysia Melaka (UTeM).

(b) The proposed efficiency formula only involves with weighted conversion efficiency equation. It does not include Maximum Power Point Tracking (MPPT) efficiency equation.

(c) The measurement data is based on IEC 61724 (1998) Standard which is an international standard and guidelines, data exchange and analysis of PV system performance monitoring.

(d) The outcome of the research is based on the experimental work and analysis performed on four different inverters of different sizes and topologies.

1.5 Importance of the Work

Inaccurate usage of inverter efficiency will lead to inaccurate energy yield (E_{sys}) reading and inaccurate E_{sys} reading leads to inaccurate return of investment (ROI) projection. Hence this will cause for less real profit for the PV system installer. Thus, confidence level towards the PV system provider among the related parties such as bank which provide loans for the PV installation as well as the customers whom are investing their savings will be affected. Besides, it is a normal practice in Europe that when comparing two different brands of inverters with similar specifications, the one with one percent less in its efficiency value should be ten percent cheaper in price [14].

This actually shows the staggering impact that can be influenced by the incorrect interpretation of a PV inverter efficiency value. Therefore, it is an utmost importance and relevance for this research to be carried out in order to amend the incorrect implementation of PV inverter efficiency value.

1.6 Organization of Thesis

This thesis comprises of 5 chapters, chapter 1 is covered and the remaining chapters are organized as follows:

Chapter 2: This chapter starts with relevant background on system energy yield (E_{sys}) equation and its related element especially PV inverter efficiency. It then overviews the different types of PV inverter efficiencies which relates to different types of PV inverter topologies available and stress on the need for weighted efficiency to be associated with PV inverter instead of the use of the maximum efficiency that is normally applicable for normal inverter. This chapter also looks on the related international standards and guidelines to produce weighted efficiency and reviews the previous works for localization of weighted efficiency to draws out the gap for this research work to be carried out.

Chapter 3: This chapter focuses on the step by step research methodology performed and description on the tools and equipment involved. It starts with the profiling of one-year equatorial irradiance from a dedicated weather station. The gathered profile is to be used as input for PV array simulator to test four PV inverters with different topologies. This chapter then explain on the procedures taken to recalculate weighted European efficiency in equatorial climate. The results are then used to expose the mismatch of weighted European efficiency formula when applied in equatorial climatic region.

Chapter 4: This chapter continues by describing the process taken to produce weighted equatorial efficiency once it is proven that weighted European efficiency is incompatible to be applied in the equatorial region. Three methods are proposed i.e., as suggested by IEC 61683 Standard, Response Surface Methodology (RSM) and Equatorial Irradiance-Duration Curve approach. This chapter then compares the viability of three approaches to produce weighted equatorial efficiency equation. The equation from the selected method is then used to be validated with the performance of a real working PV system.

Chapter 5: This chapter summarizes the work that has been carried out in this thesis. It also draws the general conclusion and highlights the main contributions. Finally, it recommends the possible action that can be implemented to increase the accuracy of the findings.

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