



Faculty of Electrical Engineering

**OPTIMAL SOLAR CABLE SELECTION FOR GRID-CONNECTED
PHOTOVOLTAIC SYSTEMS**

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**Master of Electrical Engineering
(Industrial Power)**

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**OPTIMAL SOLAR CABLE SELECTION FOR GRID-CONNECTED
PHOTOVOLTAIC SYSTEMS**

AHMED DAUD MOSHEER

**A dissertation submitted
in partial fulfillment of the requirements for the degree of Master of
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Faculty of Electrical Engineering

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2016

DECLARATION

I declare that this thesis entitled “Optimal Solar Cable Selection for Grid-Connected Photovoltaic Systems” is the result of my own research except as cited in the references. The dissertation has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

Name :

Date :

APPROVAL

I hereby declare that I have read this dissertation and in my opinion this dissertation is sufficient in terms of scope and quality for the award of Master of Electrical Engineering (Industrial Power).

Signature :.....

Supervisor Name :.....

Date :.....

DEDICATION

I dedicate my dissertation work to my beloved father and mother, thank you from the bottom of my heart for your support me along my life and patronage me. I ask Allah to give you health, wellness and longevity, and keep you stalwarts to me. I love you so much.

I also dedicate this dissertation to my brothers and sisters, a lot of thanks for you; you are wonderful brothers and sisters in this world.

ABSTRACT

As a solution for the depletion of fossil fuel and its influence on the environment (i.e. CO₂), photovoltaic (PV) systems have been considered as alternative renewable energy (RE) resources. The common practice in sizing the solar cables of photovoltaic systems follows the maximum voltage drop and thermal limit constraints (i.e. maximum allowed current and maximum allowed voltage drop). Little attention has been paid on the estimation of the annual energy losses for solar cables. According to Malaysian standards, for solar cable sizing, the maximum allowed voltage drop is five percent. Though seemingly insignificant, a five percent voltage drop losses, when calculated throughout the life span of a photovoltaic system, will have a huge impact on the profitability of the PV system. This dissertation presents investigation on the annual energy losses for standard solar cables. More importantly, instead of using conventional methods that follows the maximum allowed voltage drop and maximum allowed current calculations for sizing the solar cables, this dissertation presents a method for selecting optimal solar cable capacity for grid-connected solar Photovoltaic (PV) systems. The optimization method takes into consideration the cost of losses and solar cable investment cost throughout the technical lifespan of the cable. In addition, the effects of using actual field data of different time resolution irradiation data on the calculation of energy losses, and optimal solar cable selection are presented and discussed in this dissertation. Additionally, the sensitivity of different feed-in tariff rates on optimal solar cable selection had been considered in this work. The key findings of the dissertation suggest that oversizing the solar cable for PV system plays an important role in losses reduction, and at the same time yields monetary savings in the long run. Also, the results showed that the time resolution solar radiation data has important role on optimal solar cable selection and economic calculations of PV system.

ABSTRAK

Sebagai penyelesaian kepada penyusutan bahan api fosil dan kesannya kepada alam sekitar (CO^2), sistem photovoltaic (PV) telah dikenalpasti sebagai alternatif kepada sumber bahan api yang boleh diperbaharui (RE/renewable energy). Cara umum untuk penentuan saiz kabel solar sistem photovoltaic adalah berdasarkan kejatuhan voltan maksimum dan halangan had termal (arus maksimum yang dibenarkan dan kejatuhan voltan maksimum yang dibenarkan). Anggaran kehilangan tenaga dalam setahun untuk kabel solar jarang diberi perhatian sebelum ini. Berdasarkan piawaian Malaysia untuk penentuan saiz kabel solar, kejatuhan maksimum voltan yang dibenarkan adalah lima peratus sahaja. Walaupun nilai ini adalah kecil, kejatuhan sebanyak lima peratus voltan sepanjang tempoh hayat sistem photovoltaic mempunyai impak yang sangat besar ke atas faedah sistem PV. Kertas kajian ini membincangkan kaji selidik ke atas kehilangan tenaga dalam setahun untuk kabel solar yang standard. Lebih penting, selain daripada menggunakan kaedah konvensional untuk penentuan saiz kabel solar, kajian ini memperkenalkan kaedah baru untuk memilih muatan optimum kabel solar untuk sistem photovoltaic (PV) yang berhubung dengan grid. Kaedah ini mengambilkira kos kehilangan dan pelaburan kabel solar sepanjang hayat teknikal kabel. Kertas kajian ini juga membincangkan kesan-kesan penggunaan data lapangan sebenar berkaitan sinaran data resolusi masa ke atas pengiraan kehilangan tenaga, dan juga pemilihan kabel solar optimum. Di samping itu, tahap sensitiviti kadar tarif kemasukan yang berlainan menunjukkan bahawa pembesaran kabel solar untuk sistem PV memainkan peranan penting dalam pengurangan kehilangan tenaga; selain penjimatan wang dalam jangka panjang. Hasil kajian juga menunjukkan sinaran data resolusi masa mempunyai peranan penting ke atas pilihan optimum kabel solar dan pengiraan ekonomi sistem PV.

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LIST OF SYMBOLS

W	-	Watt.
KW	-	Kilo watt
MW	-	Mega Watt.
GW	-	Giga Watt.
FiT	-	Feed in Tariff.
WP	-	Watt at Peak output.
\$	-	US Dollar.
KWh/m ²	-	Kilo Watt hour per meter square
I	-	electric current
I _{ph}	-	photon current.
I _s	-	reverse saturation current of the diode
q	-	electron charge
V	-	voltage
K	-	Boltzmann's constant
T _e .	-	temperature
N	-	ideality factor of the diode
R	-	resistance
R _s	-	series resistance
I _{sh}	-	shunt current
I _{s,c}	-	short circuit current

$V_{o.c}$	-	open circuit voltage
$^{\circ}\text{C}$	-	Celsius degree
%	-	percentage
Hz	-	Hertz
mm^2	-	millimeter square
p	-	power
kcmil	-	kilo circular mils
W/m^2	-	Watt per meter square
NPV	-	net present value
Pb	-	payback period
C	-	capital cost
S	-	annual savings
C_0	-	initial cost
C_t	-	net cash flow
n	-	lifespan
r	-	discount rate
t	-	time
V_{MPP}	-	voltage at maximum power point
N_{modules}	-	number of modules
I_{MPP}	-	current at maximum power point
N_{strings}	-	number of strings
A	-	cable cross section area
L	-	length
γ	-	conductivity

e	-	voltage drop
E_{lost}	-	energy lost
d	-	number of daylight hours
i	-	specific hour
I_i	-	current at hour i
I_{string}	-	string current
G_i	-	solar radiation
RM	-	Malaysian Ringgit
C_{losses}	-	losses cost
$C_{\text{standards}}$	-	standards cost
$C_{\text{investment}}$	-	investment cost
$A_{\text{standards}}$	-	standards cable cross section area
A_{new}	-	new cable section cross section area
j	-	specific year
RM/kWh	-	Ringgit Malaysian per kilo Watt hour
P	-	cable price
RM/m	-	Ringgit Malaysian per meter
RM/year	-	Ringgit Malaysian per year
P_{max}	-	maximum power
m	-	meter

LIST OF ABBREVIATION

PV	Photovoltaic
RE	Renewable Energy
MPPT	Maximum Power Point Tracking
STC	Standard Test Condition
SEDA	Sustainable Energy Development Authority
LCOE	Levelized Cost of Energy
MBIPV	Malaysia Building Integrated Photovoltaic
Si	Silicon
C-Si	Crystalline Silicon
Sc-Si	Single Crystalline Silicon
Mc-Si	Multi crystalline Silicon
Ga As	Gallium-Arsenide
CI-GS	Copper Indium Gallium Selenide
Cd-Te	Cadmium Telluride
PCU	Power Conditioning Unit
CCC	Current Carrying Capacity
PR	Performance Ratio
TLDC	Technique of Load Distribution Centre
TCT	Total-Crossed Tied

BL	Bridge-Link
DCF	Discount Cash Flow
CB	Combiner Box
CI	Central Inverter
CCR	Common Control Room

LIST OF PUBLICATION

Journal

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CHAPTER 1

INTRODUCTION

1.1 Research Background

As the fossil fuel is on the brink of depletion and its influence on the environment (i.e. CO₂ emission), and as the electrical energy becomes increasingly on demand, the world attention shifts towards finding resources of alternative renewable and environmentally friendly energy. Photovoltaic (PV) has been recognized as a promising renewable energy (RE) resource, based on the fact that the solar energy received by Mother Earth is abundant (Ogimoto et al., 2013) (Denholm et al., 2013). The direct conversion technology that leans on solar photovoltaics (PVs) boasts off some positive attributes and it appears to be the most promising. People have become more optimistic that solar PV systems will stand out as a primary means in coming decades (Kaushika and Rai, 2006). In this regard, there are more grid-connected PV system installations set up all over the world, from kW scale residential PV systems to MW scale utility solar PV farms. The main drive comes from the strong regulatory support in the respective countries (Gan et al., 2014). In Europe, for instance the combined target yielding a total expected PV power generation capacity is 15 GW by 2020, and 30 GW by 2030 (Hdr.undp.org, 2015). At the end of 2009, France kept its intention to multiply its solar power use by 400 in the coming 12 years. This is a smaller fraction of the whole plan to double the share of energy from renewable to 23% by 2020 to adhere with the European Union obligations as well as to stay in rivalry with Germany which is regarded as the giant in European Union countries (Solangi et al., 2011). Table 1 shows the anticipated development and installation of solar

photovoltaic electricity in the USA, Europe, and Japan as well as for the rest of the world countries until 2030.

Table 1.1: Development and Installation of Solar Photovoltaic Electricity in Various Countries (Hdr.undp.org, 2015).

Year	USA (MW)	Europe (MW)	Japan (MW)	Worldwide (MW)
2000	140	150	250	1000
2010	3000	3000	5000	14,000
2020	15,000	15,000	30,000	70,000
2030	25,000	30,000	72,000	140,000

The Malaysian government has established various energy-related policies in the attempt to address the climate change and ensure energy security. Pragmatic energy policies that have come into effect for the past thirty years have facilitated a clean energy development path. The five-fuel policy was embedded in the 8th Malaysian Plan as the extension of four fuel diversification policy, in which renewables as a fifth fuel have been included. The 5% contribution of the country energy, coupled with RE by year 2005 was targeted to reduce 70 million tons of CO₂ over a span of 20 years. Not only that, in the 9th Malaysian plan the utilization of RE resources and efficient use of energy were highlighted (Fayaz et al., 2011). Next, in the 10th Malaysian Plan, RE share is aimed to achieve 5.5% of Malaysia's total electricity generation mix, and can well escalate to 5.9% by 2030 (Epu.gov.my, 2015). Thus, the 2011 Renewable Energy Act has been enacted (Seda.gov.my, 2015) and the Feed-in Tariff (FiT) scheme has been properly introduced in 2011 (Handbook on the Malaysian Feed-in Tariff for the Promotion of Renewable Energy, 2011). Those were the beginning of the years where Malaysia demonstrated strong growth in the solar PV installation for both residential and commercial sectors (Muhammad-Sukki et al., 2014). Table 1.2 illustrates the rough estimation of the RE potential in Malaysia by