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LIGHTNING PERFORMANCE ANALYSIS OF A GRID-CONNECTED SOLAR PHOTOVOLTAIC SYSTEM

NUR HAZIRAH BINTI ZAINI

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By

NUR HAZIRAH BINTI ZAINI

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

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DEDICATION

To rise after each fall

Correct after mistaking

Improve after each fail

This work is dedicated to my beloved parents and husband for their endless support

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree ofDoctor of Philosophy

LIGHTNING PERFORMANCE ANALYSIS OF A GRID-CONNECTED SOLAR PHOTOVOLTAIC SYSTEM

By

NUR HAZIRAH BINTI ZAINI

January 2019

Chairman : Mohd Zainal Abidin Ab. Kadir, Phd PEng CEng
Faculty : Engineering

The Malaysian government implemented the Feed-in-Tariff (FiT) and the Net Energy Metering (NEM) programme to accelerate the deployment of renewable energy, and encourage the production of clean green energy approaches like the solar PV system. Malaysia is a good fit for the deployment of solar PV system due its high daily radiation but unfortunately, the solar PV farm in Malaysia is highly susceptible to lightning strikes considering most solar PV farms are installed in wide-open areas that consequently attract lightning. This leads to very considerable repair costs, replacement of parts and the interruption of power supply to a large number of consumers. Therefore, the installation of a lightning protection system (LPS) in the solar PV farm is imperative to ensure the protection of all electronic equipment from damage due to lightning strikes. However, no specific standard or guideline is available for LPS, specifically for the solar PV system. Currently, installation of LPS for the solar PV system refers to Malaysian standard, which include MS 1837, MS IEC 62305, and technical document CLC/TS 50539-12 which provide just a brief overview. Hence, this study was conducted to determine a guideline and recommend suitable installation of LPS especially the surge protective device (SPD). This study provides a comprehensive model of a grid-connected solar PV farm system in PSCAD software consisting of a typical arrangement of solar PV modules, inverter, and transformer to observe the lightning effect and to coordinate an appropriate LPS. Depending on the location of the solar PV farm, engineers can obtain information on the peak current and median current of the site from the lightning location system (LLS). A statistical analysis of lightning peak current was performed and the findings revealed that the solar PV farm at Puchong Gateway have a total of 8788 strikes lightning strikes. In the simulation, the lightning strikes were applied without any LPS installed at the solar PV farm to show the consequences if the design engineers and developer neglect the installation of an LPS. In addition, the SPD rating was also established by comparing the SPD Type I and SPD Type II. Results obtained were utilised in this study to appropriately assign an SPD in the solar PV farm. One the DC side a single SPD installed near inverter was not enough to protect the solar PV even though the cable

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length is less than 10 m. Furthermore, a single SPD installed on the AC side positioned near the origin of installation for cable length less than 10 m was also not enough to protect the inverter from high transient voltage and current cause by lightning. Hence, a step of SPD installation and a recommendation of SPD installations for a solar PV farm were made in the form of guidelines to designers in order to decide on the placement, number and suitable rating of SPDs to be installed for full protection of all equipment. Findings of this study will help improve the existing standards and assist engineers to design an integral part of the installation of LPS for grid-connected solar PV farm system. Ultimately, it will significantly reduce the expensive cost of repairing damages caused by lightning strikes and enhance the efficiency of the power supply.

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Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazahDoktor Falsafah

ANALISIS PRESTASI KILAT UNTUK SISTEM SOLAR FOTOVOLTA SAMBUNGAN KE GRID

Oleh

NUR HAZIRAH BINTI ZAINI

Januari 2019

Pengerusi : Mohd Zainal Abidin Ab. Kadir, Phd PEng CEng
Fakulti : Kejuruteraan

Kerajaan Malaysia melaksanakan program Feed-in-Tariff (FiT) dan program Net Energy Metering (NEM) untuk menggalakkan penggunaan tenaga boleh baharu, dan menggalakkan pengeluaran tenaga hijau bersih seperti sistem solar PV. Malaysia adalah sesuai untuk penggunaan sistem solar PV kerana radiasi harian yang tinggi tetapi walaubagaimanapun, ladang solar PV di Malaysia mudah terdedah kepada serangan kilat memandangkan kebanyakan pemasangan ladang solar PV adalah di kawasan yang terbuka luas yang menarik serangan kilat. Ini menjadi punca kepada kos yang tinggi dalam pembaikan, penggantian barang dan juga gangguan bekalan kuasa kepada sebahagian besar pengguna. Oleh itu, pemasangan sistem perlindungan kilat (LPS) di ladang solar PV adalah penting untuk memastikan semua peralatan elektronik dilindungi daripada kerosakan akibat serangan kilat. Walaubagaimanapun, tiada piawaian atau garis panduan boleh didapati untuk LPS khususya untuk sistem PV solar. Pada masa ini, pemasangan LPS untuk sistem solar PV adalah merujuk kepada piawaian Malaysia, iaitu MS 1837, MS IEC 62305, dan dokumen teknikal CLC / TS 50539-12 yang memberikan gambaran secara ringkas sahaja. Oleh itu, kajian ini dijalankan untuk memberi garis panduan dan cadangan yang sesuai dalam pemasangan LPS khususnya surge protective device (SPD). Kajian ini menyediakan sistem ladang solar PV sambungan ke grid dalam perisian PSCAD sebagai model yang komprehensif yang terdiri daripada susunan iaitu solar PV modul, penyongsang, dan pengubah untuk memerhatikan kesan kilat dan menyelaras LPS yang sesuai. Bergantung kepada lokasi ladang solar PV, jurutera boleh mendapatkan maklumat mengenai puncak arus dan median arus lokasi tapak daripada sistem lokasi petir (LLS). Analisis statistik puncak arus kilat telah dilakukan dan penemuan mendapati bahawa ladang solar PV di Puchong Gateway mempunyai bilangan serangan kilat yang banyak iaitu 8788. Di dalam simulasi, serangan kilat digunakan tanpa pemasangan LPS di ladang solar PV untuk menunjukkan kesan jika jurutera rekabentuk dan pemaju mengabaikan pemasangan LPS. Di samping itu kadaran SPD juga diperkukuhkan dengan membandingkan Jenis SPD I dan Jenis SPD II. Keputusan yang diperolehi dalam kajian ini digunakan dalam menentukan kedudukan SPD yang sesuai di ladang solar

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PV. Di bahagian DC satu SPD dipasang berhampiran penyongsang tidak mencukupi untuk melindungi solar PV walaupun panjang kabel adalah kurang dari 10 m.Tambahan pula, satu SPD dipasang di sebelah AC yang diletakkan berhampiran asal-usul pemasangan untuk panjang kabel kurang daripada 10 m juga tidak cukup untuk melindungi penyongsang dari voltan dan arus fana tinggi yang disebabkan oleh kilat. Oleh itu, satu langkah pemasangan SPD dan cadangan pemasangan SPD untuk ladang PV solar telah dibuat dalam membentuk garis panduan kepada pereka untuk menentukan kedudukan, bilangan dan kadaran SPD yang sesuai untuk dipasang bagi melindungi semua peralatan. Penemuan kajian ini akan membantu membaiki piawaian sedia ada dan membantu jurutera dalam merekabentuk pemasangan LPS untuk sistem ladang solar PV sambungan ke grid. Akhirnya, ini akan mengurangkan kos yang tinggi untuk memperbaiki kerosakan yang disebabkan oleh serangan kilat dan meningkatkan kecekapan bekalan kuasa.

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I certify that a Thesis Examination Committee has met on 14 January 2019 to conduct the final examination of Nur Hazirah Binti Zainion her thesis entitled "Lightning Performance Analysis of a Grid-Connected Solar Photovoltaic System"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.

Members of the Thesis Examination Committee were as follows:

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Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Jasronita Bt. Jasni, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Suhaidi B. Shafie, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Francisco Jose Roman Campos, PhD
Professor
Faculty of Engineering
National University of Colombia
Colombia
(External Examiner)

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

Date:

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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 Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Mohd Zainal Abidin bin Ab. Kadir, PhD
Professor/Ir
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mahdi Izadi, PhD
Fellow Research
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohd Amran Mohd Radzi, PhD
Associate Professor/Ir; if applicable)
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Norhafiz Azis, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

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ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

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LIST OF SYMBOL

A_c	Cross section of the conductor
D	Diode
I_d	Diode current
I_{imp}	Impulse discharge current
I_m	Peak current
I_n	Nominal discharge current
I_{ph}	Photocurrent source
I_{pv}	Solar PV current
I_s	Diode reverse saturation current
I_{sc}	Cells short circuit current at 25 °C
$I_{sc\ STC\ MOD}$	Short circuit current of a PV module or PV string at standard test
$I_{sc\ STC\ String}$	Short circuit current of a solar PV string at standard test condition
k	Boltzmann's constant
l	length
K_i	Cell's short circuit temperature coefficient
N	Ideality factor of the diode
N_p	Number of cell connected in parallel
N_s	Number of cell connected in series
q	Electron charge
R_{DC}	Resistance for the core
R_s	Series resistance
R_{sh}	Shunt resistance
t_t	Tail time
t_f	Front time
T_j	Junction temperature
T_c	Cell operating temperature
T_{ref}	Cell reference temperature
U_{10}	Discharge voltage at 10 kA
U_c	Maximum continuous operating voltage
$U_{OC\ MAX}$	Maximum voltage across an unloaded (open) PV Array
$U_{OC\ STC}$	Voltage under standard test conditions across an unloaded (open) PV array
U_p	Voltage protection level
U_w	Impulse withstand voltage
V_d	Voltage across the diode
$V_{OC\ STC\ ARRAY}$	Open circuit voltage at standard test condition of a PV array
$V_{OC\ STC\ MOD\ NS}$	Open circuit voltage of a PV at standard test condition
ρ_c	Resistivity of the core material
$\rho_c{}'$	Corrected resistivity
x	Random variable
μ	Mean value
σ	Standard deviation

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LIST OF ABBREVIATIONS

AC	Alternating Current
BoS	Balance-of-System
CDF	Cumulative Distribution Function
DC	Direct Current
DL	Distribution Licences
EC	Energy Commission
EMT	Electromagnetic Transient
FiT	Feed-in-Tariffs
GDT	Gas Discharge Tube
GEV	General Extreme Value
GTO	Gate Turn off
IGBT	Insulated Gate Bipolar Transistor
KCL	Kirchhoff's Current Law
LDN	Lightning Detection Network
LLS	Lightning Location System
LPS	Lightning Protection System
LPZ	Lightning Protection Zones
KeTTHA	Ministry of Energy, Technology, Science, Climate Change and Environments
MOSFET	Metal Oxide Semi-conductor Field Effect Transistor
MOV	Metal Oxide Varistor
NEM	Net Energy Metering
PDF	Probability Density Function
PLL	Phase-Locked Loop
PV	Photovoltaic
RE	Renewable Energy
SEDA	Sustainable Energy Development Authority
SESB	Sabah Electricity Sdn. Bhd.
SPD	Surge Protective Device
SPWM	Sinusoidal Pulse Width Modulation
SREP	Small Renewable Energy Power
STC	Standard Test Conditions
TNB	Tenaga Nasional Berhad
TNBR	Tenaga Nasional Berhad Research
VSI	Voltage Source Inverters

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CHAPTER 1

INTRODUCTION

1.1 Overview

Over the past few years, there has been very significant increase of interest in renewable energy due to some very crucial factors: the inevitable concern about diminishing fossil fuels, and serious wide-ranging environmental challenges such as acid rain, greenhouse effects, and ozone layer depletion [1]. Like so many other countries, Malaysia also is exploring and implementing renewable energy options including biomass, hydro and solar photovoltaic (PV) as possible long-term and viable green technology alternatives.

The Malaysian government is providing various incentives likes Feed-in-Tariffs (FiT) and Net Energy Metering (NEM) programmes to encourage the development of renewable energy [2]. Additional support with these incentives offer advantages and create great interest in developing various renewable energy models to meet the far, energy demands in Malaysia. So far, the solar PV system has surpassed all other renewable energy sources due to high daily radiation and high number of sunny days in most parts of Malaysia [3].

In a grid-connected solar PV farm system, very high costs are involved for the installation as it involves various highly expensive equipment likes solar PV modules and inverters[4]. Therefore, it is very important to sustain performance and efficiency of the solar PV farm and avoid downtime for the investors to be able to enjoy a return on their investment over a reasonable period[5]. Any interruption or damage of equipment can contribute to losses and affect the solar PV performance[6]. As such, some researchers have conducted studies in efforts to enhance the solar PV performance and offer greater reliability and security for the solar-based model.

The solar PV farm installed in Malaysia has been exposed to a direct strikes as well as indirect lightning strikes because of the nature of its installation in the open area. The Puchong Gateway solar PV farm has also experienced the damage caused by lightning, although there is no officially damage data recorded. A lightning strike can result in interruption and damage equipment of the solar PV system. [7]. The United States National Lightning Safety Institution has reported that Malaysia has an average thunder level of 180-260 days per year [8].

The extent of damage to the solar PV system depends on the characteristics of the lightning current waveshape, magnitude of the lightning current, the point of the lightning strike and the selection of lightning protection system installed [9]. The lightning striking point is inversely proportional to the distance of the of impact of the

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lightning strike [10]. The solar PV farm in Tucson Electric Power has experienced lightning strikes during its operations which have incurred substantial equipment replacement costs due to lightning strike [11, 12]. Consequences of the direct and indirect lightning strikes also have been revealed where both lightning strikes can cause significant damage and incur costs for repairs [13, 14].

Despite the fact that the solar PV farms face the risk of lightning strikes, many solar PV farms are still not protected against such events, either because the designers ignored the requirement of LPS or underestimated the crucial importance of having an LPS [15]. The lack of an LPS exposes solar PV farms to possible extensive damages of equipment and destructions in the main system. Some designers do not realise that the cost of replacing or repairing equipment damaged by a strike could far exceed the cost of installing an LPS [16]. In light of this, the design and installation of an LPS for a solar PV farm is an urgent necessary [17].

Investors usually try to minimise the cost of installing the solar PV farm and some neglect the inclusion of a lightning protection system (LPS). Additionally, some of them install the LPS to meets requirement without fully understanding the implications. Furthermore, there are often no proper references or guidelines with regard to the installation of the LPS for the solar PV system and this pose problems in sustaining uninterrupted performance for the plant. Currently, the performance of solar PV system with LPS in Malaysia with its tropical climate that has high lightning activities has been scarcely reported and studied.

1.2 Problem Statement

Lightning strikes are a major threat to solar PV farms as the damage they cause can mean high replacement and repair costs as well as convenience to the power users. The solar PV farm is installed in an open area without the presence of tall buildings or trees in the vicinity which contributes to a high solar radiation and air humidity thus rendering the farm area susceptible to lightning strikes. A lightning strike occurs because there is a connection between the solar radiation, air humidity and frequency of the lightning discharges [18].

Many designers are unable to identify a suitable LPS that could minimise damage to the solar PV system. Currently, there is no proper standard and there are also no guidelines on the LPS design and installation proposed. As such, current LPS designs and installation for solar PV systems have to refer to the local standard MS 1837, MS IEC 62305 Part 1 until Part 4 and also the technical document CLC/TS 50539-12 as they are the only available guidelines. Apart from these standards, and to the best knowledge of this researcher, there are no other available standards.

In general, these standards give only an overview of the LPS of the solar PV systems which cover the installation of surge protective devices (SPDs). The number of installation SPDs depends on the distance of the inverters which are less or more than 10 m distance and this was proven to be ineffective as reported in for low distribution

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systems [19-21]. Furthermore, a minimum rating of 5 kA 8/20 µs for SPDs Type II and 12.5 kA 10/350 µs for SPD Type I state in the standard also needs to be investigated. Therefore, whatever LPS that has been installed in any solar PV system would need to be scrutinised, revised and improved.

The ideal LPS for the solar PV system is still under research as efforts are being made to improve the LPS to avoid any interruption during operations and reduce downtime as well as minimise repair and replacement cost of the damage equipment. Much research regarding lightning protection of the solar PV system either theoretically [16, 22-29] (using appropriate simulation tools) or experimentally [30-34] (laboratory or field tests) have been conducted to improve the LPS for the solar PV system but more studies still need be conducted in terms of:

1. The effect of characteristics of the lightning current strike on the grid-connected solar PV farm system
2. The coordination of the protection scheme of SPD in the grid-connected solar PV farm system since the SPD is critical to an effective LPS
3. Currently there is no specific guideline or standard for the installation of LPS for the solar PV system and so all installations of LPS for the solar PV system now refer to standard MS 1837, MS IEC 62305, and technical document CLC/TS 50539-12

1.3 Objectives of the Study

The main aim of this study is to establish a LPS for a grid-connected solar PV farm system model by providing a comprehensive guideline taking into consideration all the available standards. Other specific objectives are as follows:

1. To develop a model of grid-connected solar PV farm system using the Electromagnetic Transient (EMT) software
2. To evaluate the electrical performance of solar PV farm system under various conditions of lightning current wave shapes and lightning magnitude current
3. To coordinate an appropriate protection scheme which includes the rating, suitable position and number of SPDs to be installed between the solar PV, inverter and origin of installation

1.4 Scope and Limitations of the Study

The scope and limitations of this study are as follows:

1. In this study, the grid-connected solar PV farm system is based on the 1MW system that was modelled using the Electromagnetic Transient (PSCAD) software
2. The details of the grid-connected solar PV farm system will be modelled based on the Puchong Gateway solar PV farm
3. The irradiation and temperature of the solar PV were set according to the standard test conditions (STC)

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4. The lightning strike that was used to hit the solar PV system in the simulation was assumed to be a direct lightning strike
5. The SPDs installation was considered for PV installation without external LPS and the SPDs would be designed based on the manufacturer's data to ensure its performance

1.5 Contribution of the Study

This study will help to investigate the implications of installing the solar PV farm at a risky site and examine the effectiveness of the installed lightning protection system. The protection will cover the SPD regarding the selection of rating, suitable position and number of units of SPD to be installled will be analysed based on the standard to observe the optimum protection required for the grid-connected solar PV farm system. This will help to improve the existing standards and installation requirements and thus help the engineers to seriously consider a proper installation of SPD in their design. The high cost of repairing and replacement of the damaged equipment caused by a lightning strike can be reduced or avoided. The outcomes will not just be saving the cost of the investment but more importantly to save the lives of the people nearby.

1.6 Thesis Outline

The thesis comprises five chapters. Chapter One provides the background of the study and its purpose. The problem statement is identified and the objectives of this study as well as its scope and limitations and contribution are also stated in this chapter.

Chapter Two presents the review of tie literature and discusses various findings of previous studies related to the research topic. This chapter starts with an explanation on renewable energy in Malaysia in terms of policy and standards as well as problems and various other challenges related to the solar PV system. Further explanations are given on various related topics like lightning risk to the solar PV system and need to install the LPS for the solar PV system. Various lightning protection systems can be used to protect the grid-connected solar PV farm system and this chapter reviews the SPD among other LPSs.

Chapter Threefocuses on the modelling description of the grid-connected solar PV farm system and the lightning current model in PSCAD software. The components including PV Array, inverter, cables, transformer and grid are explained in detail including the selection methods used for each component. The validation of the grid-connected solar PV farm system and the lightning current model also is explained at the end of this chapter.

Chapter Fourhighlights and discusses the results obtained from the simulation after applying the lightning current to the grid-connected solar PV farm system. The results of simulation are based on the objectives and methodology stipulated in this study.
Chapter Five presents the conclusion of the overall research and makes some recommendations for future related work.

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BIODATA OF STUDENT

Nur Hazirah Binti Zaini was born in Penang, Malaysia on 23 April 1985. She received her Bachelor Degree in Electrical & Electronics Engineering from Universiti Putra Malaysia in 2008. After that she was appointed as PCB Design Engineer at SATO Malaysia Electronics Manufacturing Sdn. Bhd. for almost three years. Then she became a trainee at Tenaga NasionalBerhad (TNB) for one year. She got MSc in Engineering Management at Universiti Putra Malaysia in October 2014. She started to pursue her PhD degree in Electrical Power Engineering with Universiti Putra Malaysia since September 2014.

Email: nurhasz7@gmail.com

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