UNIVERSITI PUTRA MALAYSIA

LIGHTNING-INDUCED TRANSIENT EFFECTS IN HYBRID PV–WIND SYSTEM AND ITS MITIGATIONS

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By

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Lightning strikes cause current injection into the hybrid PV–wind system at the point of contact. Overvoltage generated due to lightning travels along the system where it can affect expensive equipment in the hybrid PV–wind system. The literature review examines related previous works and identifies the gaps created by earlier works that have focused only on the problems associated with the lightning effects on the PV and WT systems either theoretically or experimentally. Studies also have focused on a single type of RE source and not on hybrid systems. The current study fills the gap concerning the lightning-induced transient effect on a 4.1 MW grid-connected hybrid PV–wind system and the mitigation of the lightning effect using the Power Systems Computer Aided Design (PSCAD) software. The system consists of a 2 MW PV farm, a 2.1 MW wind farm, battery system and loads which are all connected to a 33 kV grid along with a 0.480 kV AC bus and a boost interfacing transformer. In addition, the Heidler function was modelled to generate different lightning currents using the software mentioned above.

In this research, transient effects simulation and analysis due to direct lightning strikes to the system were conducted, three points of the hybrid system were selected to observe the transient overvoltage when each point was subjected to lightning strokes separately. The simulation results were obtained for different lightning current waveforms such as 8/20 μs, 10/350 μs, negative first stroke, negative subsequent stroke and positive stroke with and without lightning protection system (LPS) in several simulation cases. In addition, surge protective devices (SPDs) have been developed based on the European Commission for Electrotechnical Standardization (CENELEC) standard with the most appropriate ratings for the threat level and the equipment/component specification of the hybrid system to investigate mitigation of the lightning transient to an acceptable level. The results showed that the connected

SPDs to the system can successfully clamp the generated transient overvoltages due to lightning for all simulation cases, except the SPDs connected at the DC side of PV system fail to clamp the generated overvoltage in the case with 5% of positive stroke lightning current. On the basis of the simulation results, the recommendations have been proposed to developers of lightning protection. The research objectives were achieved through simulation and analysis, findings of this research can be a useful guideline towards the application of a lightning protection standard for the hybrid PV–wind system.

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

KESAN FANA ARUHAN-KILAT DI DALAM SISTEM HIBRID PV-ANGIN DAN PENGURANGAN

Oleh

ZMNAKO MOHAMMED KHURSHID

Ogos 2018

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Sambaran kilat menyebabkan suntikan arus ke dalam sistem hibrid PV-angin di titik sentuhan. Voltan lampau yang dihasilkan oleh kilat berjalan di sepanjang sistem di mana ia boleh menjejas peralatan mahal di dalam sistem hibrid PV-angin. Kajian kepustakaan mengkaji kerja-kerja berkaitan yang lalu dan mengenal pasti jurang-jurang yang dihasilkan oleh karya-karya terdahulu yang hanya memberi tumpuan pada masalah-masalah yang berkaitan dengan kesan kilat ke atas sistem PV dan WT baik secara teori atau eksperimen. Kajian juga telah menumpukan pada satu jenis sumber RE dan bukan pada sistem-sistem hibrid. Kajian semasa ini mengisi jurang mengenai kesan sementara yang disebabkan oleh kilat pada sistem hibrid PV-angin yang terhubung-grid 4.1 MW dan pengurangan kesan kilat menggunakan perisian Reka Bentuk Bantuan Komputer Sistem Kuasa (PSCAD). Sistem ini terdiri dari ladang PV 2 MW, sebuah ladang angin 2.1 MW, sistem bateri dan beban yang semuanya disambungkan ke grid 33 kV bersama dengan bas AC 0.480 kV dan satu transformer penambah antara muka. Di samping itu, fungsi Heidler telah dimodelkan untuk menghasilkan arus kilat yang berbeza menggunakan perisian yang disebutkan di atas.

Dalam kajian ini, simulasi dan analisis kesan-kesan fana disebabkan oleh kilat terus kepada sistem telah dijalankan, tiga titik sistem hibrid tersebut telah dipilih untuk memerhatikan voltan lampau fana apabila setiap titik tertakluk kepada kilat secara berasingan. Hasil simulasi diperoleh untuk bentuk gelombang arus kilat yang berbeza seperti 8/20 μs, 10/350 μs, sambaran pertama negatif , sambaran seterusnya negatif dan sambaran positif dengan dan tanpa sistem perlindungan kilat (LPS) di dalam beberapa kes simulasi. Di samping itu, peranti pelindung pusuan (SPD) telah dibangunkan berdasarkan piawaian Suruhanjaya Eropah bagi Pemiawaian Elektroteknik (CENELEC) dengan penilaian yang paling sesuai untuk tahap ancaman dan spesifikasi peralatan/komponen sistem hibrid untuk menyiasat pengurangan kesan

sementara kilat ke suatu tahap yang boleh diterima. Hasilnya menunjukkan bahawa SPD yang bersambung ke sistem itu dapat berjaya mengatasi voltan sementara yang dijana disebabkan oleh kilat bagi semua kes simulasi, kecuali SPD yang disambungkan di sebelah DC sistem PV gagal untuk mengatasi voltan lampau yang dijanakan dalam kes 5% arus sambaran kilat positif. Berdasarkan keputusan simulasi, saranan telah dicadangkan kepada pemaju perlindungan kilat. Objektif penyelidikan telah dicapai melalui simulasi dan analisis, penemuan penyelidikan ini boleh menjadi garis panduan yang berguna ke arah penggunaan piawaian perlindungan kilat untuk sistem hibrid PV-angin.

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I certify that a Thesis Examination Committee has met on 28 August 2018 to conduct the final examination of Zmnako Mohammed Khurshid Abda on his thesis entitled "Lightning-Induced Transient Effects in Hybrid PV-Wind System and its Mitigation" 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.

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This is to confirm that:

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LIST OF ABBREVIATIONS

AC	Alternating Current
ANSI	American National Standards Association
ATP	Alternative Transient Program
CENELEC	European Commission for Electrotechnical Standardization
CIGRE	International Council on Large Electric Systems
DC	Direct Current
DFIG	Doubly-Fed Induction Generator
DLP	Dynamic Lightning Protection
EMTDC	Electromagnetic Transient Direct Current
EMTP	Electro-Magnetic Transients Program
EPRI	Electric Power Research Institute
ESE	Early Streamer Emitter
FDTD	Finite Difference Time Domain
FEM	Finite Element Method
GB	GigaByte
GDT	Gas Discharge Tubes
GHz	GigaHertz
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IGBT	Insulate Gate Bipolar Transistor
ILPA	International Lightning Protection Association
ISO	International Organization for Standards
ITU	International Telecommunications Union
JISC	Japan Industrial Standards Commission

LPS	Lightning Protection System
MCOV	Maximum Continuous Operating Voltage
MOV	Metal Oxide Varistor
MPPT	Maximum Power Point Tracking
NFPA	National Fire Protection Association
P & O	Perturb and Observe
PLL	Phase Locked Loop
PSCAD	Power System Computer Aided Design
PV	Photovoltaic
PWM	Pulse Width Modulation
RAM	Random-Access Memory
RE	Renewable Energy
SAD	Silicon Avalanche Diode
SPD	Surge Protective Device
STC	Standard Test Condition
TV	Television
US	United State
UPS	Uninterruptible Power Supply
VSI	Voltage Source Inverter
WT	Wind Turbine

LIST OF NOTATIONS

°C	Celsius
µF	Microfarad
µs	Microsecond
A	Ampere; Turbine Swept Area
C	Capacitor
CO_2	Carbon Dioxide
C_p	Coefficient Performance of the Turbine
d	Length of Arrester Column
E	Energy
EN	European Standard
exp	Exponential
F	Frequency
Hz	Hertz
I	Current
i	Peak Value of Lightning Current
I_0	Maximum Peak Current
I-V	Current-Voltage
J	Joule
kA	Kilo Ampere
kg	Kilogram
K_i	Integral Gain
K_p	Proportional Gain
kV	Kilo Volt
kW	Kilo Watt

L	Inductance
m	Meter
mH	Millihenry
ms	Millisecond
MW	Mega Watt
n	Steepness Factor; Number of Parallel Columns of Metal Oxide Disks
ns	Nanosecond
N-type	Negative Charge of the Electron
ϴ	Phase Angle
P	Active Power
PI	Proportional-Integral Controller
P-type	Positive Charge of the Hole
pu	Per Unit
Q	Reactive Power
R	Resistance
r	Wind Turbine Rotor Blade Radius
RLC	Resistor, Inductor, And Capacitor
s	Second
T	Mechanical Torque from Wind Turbine
t	Time
Uc	Maximum Continuous Operating Voltage
U_p	Protection Level
V	Voltage
Vmax	Threat Level
Vn	Arrester Rated Voltage

Vr	Residual Voltage
W	Watt
W/R	Energy Dissipation
η	Peak Current Correction Factor
ν	Wind Speed
π	Pi
ρ	Air Density
τ_1	Rise Time Constant
τ_2	Decay Time Constant
Ω	Ohm
ω	Rotor Angular Speed in Rad/Sec
β	Blade Pitch Angle

CHAPTER 1

INTRODUCTION

1.1 Background

Grid-connected hybrid systems which are based on renewable energy (RE), such as combined generations of wind turbine (WT) and photovoltaic (PV) power, have become increasingly popular. This popularity is due to the need to address environmental issues, the outlook of depletion of fossil fuel reserves and the world's energy demands (Ghoddami, 2013). The significance of hybrid systems arises from several factors, such as the security of electricity supply to customers, reduced CO_2 emissions by introducing RE sources, liberalisation of the electricity market, increased power availability and reliability, improved power quality, grid support and great long-term potential for the development of sustainable energy (Massoud et al., 2009; Renewables, 2012). They can also overcome the disadvantage of intermittent power output in stand-alone RE source and provide constant power supply. These systems, however, have disadvantages, such as high installation costs compared with those of traditional technologies for power generation (Nehrir et al., 2011). Moreover, they are vulnerable to direct or indirect lightning strokes due to their installation location and their expanded surface in wide-open areas (Christodoulou et al., 2016). Lightning stroke is an impulsive transient variation which is unidirectional in polarity (either negative or positive) generated during a thunderstorm (Berger, 1975). This transient variation is occasionally related to thunder due to electric charges that pass through the lightning channel. The main lightning source is rainstorms which infrequently occur during snowstorms (Sabiha, 2010).

1.2 Problem Statement

Hybrid PV–wind systems are exposed to direct and indirect lightning discharge. The probability of the hybrid systems to be struck by lightning is higher than that of conventional power systems due to the larger layout of PV and wind farm installations contained in the systems. WTs are also tall structures of more than 150 m in height and frequently placed at locations highly exposed to lightning. The International Electrotechnical Commission (IEC) standard for lightning protection recognises four sources of damage due to direct and indirect lightning flashes (Rodrigues et al., 2011; Pons & Tommasini, 2013). The travelling waves resulted from lightning flashes cause a temporary increase in voltage (overvoltage) within the systems. This overvoltage is a transitory phenomenon that plays a harasser roll over insulation of electrical systems and can affect other equipment connected to the hybrid systems, such as PV modules, inverters, batteries, control systems, distribution boards, induction generators, transformers and circuit breakers (Bak et al., 2008; Quintana, 2017).

Such frequent problems may cause a deterioration in the utilisation rate and interruption of power supply and thus increase power generation costs (Rodrigues et al., 2012). Various studies have been conducted on the lightning effects on PV and WT systems either theoretically or experimentally. However, the most of studies have focused on a single type of RE source, and researches on hybrid systems remain few, which more studies need to be conducted on such systems. Therefore, this study aims to fill the gap by analysing lightning-induced transient effects on a grid-connected hybrid PV–wind system, and mitigation of lightning effects is investigated by using PSCAD/EMTDC software. The primary step to reduce the harmful impacts of overvoltage is by determining the background of this phenomenon. The point where lightning current may possibly flow from a system without lightning-protective devices is then identified.

Many lightning protection standards are available for PV and wind systems. However, standards for hybrid systems remain unavailable. In this study, the European Commission for Electrotechnical Standardization (CENELEC) standard, which is available for PV systems, is applied to the hybrid system. The selection of SPDs is according to the said standard. Whether the selected SPDs are appropriate is investigated. In any case, the compliance with national and international standards is significant to ensure the effectiveness of protection measures and thus guarantee the safe operation of the installation and the quality of supplied energy (Pons & Tommasini, 2013). The overvoltage waveforms that appear in various parts of a hybrid electrical system are computed. The possibility of damage depends on the impulse-withstanding voltage of each component. Thus, vital information is provided to enable relevant engineers to select surge protective devices (SPDs) with the most appropriate ratings for a given point according to threat level, and the equipment/component specifications can determine the vulnerability level. The selection of SPDs for a given purpose depends on threat level (Vmax), component vulnerability, impulse-withstanding voltage, lightning magnitude, rise time, decay time, maximum energy and total released lightning discharge.

1.3 Objectives of the Research

The objectives of this study are as follows:

1) To simulate a hybrid PV–wind system for lightning effects analysis performance,
2) to investigate the distribution of current and voltage in a hybrid PV–wind system due to direct lightning strikes,
3) to examine the levels of mitigation of lightning-related effects on the hybrid PV–wind system with the application of the recommendations given by the standard and determine whether they are appropriate, and
4) to propose recommendations for extending the existing lightning protection standards on PV energy source to hybrid systems.

1.4 Scope of the Work

The scope and limitation of this study are as follows:

1) The lightning-induced transient effects on a grid-connected hybrid PV–wind system and its mitigation are implemented using PSCAD/EMTDC software. The system consists of a 2 MW PV farm, a 2.1 MW wind farm, a $back_{up}$ battery system and a 300 kW three-phase resistor–inductor–capacitor (RLC) load bank. The temperature and solar irradiation of PV models are fixed at 25 °C and 1000 W/m^2, respectively. A fixed-speed WT generator is used in the wind farm to convert mechanical power into electrical power at a constant wind speed of 12 m/s.
2) The study is conducted for several simulation cases by using standard lightning impulses such as 8/20 µs and 10/350 µs, and also actual direct lightning current waveforms, such as negative first stroke, negative subsequent stroke and positive stroke. The lightning current waveforms are generated using Heidler function, and the transient overvoltage is evaluated at various parts of the system for each of those simulation cases.
3) The hybrid system does not include transmission lines; therefore, the corona effect on the lightning channel is not considered.

1.5 Significance of the Research

Lightning and its characteristic is significant to understand because it can only be diverted or intercepted to the path, if well-constructed and designed, which will reduce damage to hybrid PV–wind systems. Every year, lightning flashes cause damage to utility grids, including hybrid systems. Hybrid PV–wind systems comprise expensive components that cost a large amount of money in case of any damage due to lightning, especially in the large-scale power generation. Therefore, lightning protection for hybrid PV–wind systems based on the available standards for PV systems must be studied to design appropriate lightning protection measures for mitigating the transient effects of lightning strikes, considering that no standards are available for hybrid systems. This study helps to secure the operation of hybrid systems and ensure electrical power supply with reduced costs for customers.

1.6 Thesis Layout

This thesis is organised into the following five chapters: Introduction, Literature Review, Methodology, Results and Discussions, and Conclusions and Future Works.

Chapter 1 presents the research background, problem statements, research objectives, scope of work, significance of the research and thesis layout.

Chapter 2 provides the literature review. This chapter contains overviews on lightning, PV system and its different parts and configurations and wind energy. Overviews on global lightning protection codes and standards, previous studies on the lightning effects on PV and WT systems and different SPD types are also discussed.

Chapter 3 explains the research methodology. The model design of a hybrid PV–wind system is implemented using PSCAD/EMTDC software. This chapter includes the modelling of PV farm, battery system, wind farm, load, lightning current and surge arrester. Case studies for simulation are also described.

Chapter 4 discusses the simulation results. Results are generated from the hybrid system at normal steady-state operation condition without lightning current injection. The simulation results of the transient effect across the system without LPS and the system with LPS are given. In addition, this chapter includes the proposed recommendation guidelines to lightning protection developers.

Chapter 5 concludes the study, and future research is suggested to investigate and mitigate the transient effects on the hybrid PV–wind system due to indirect lightning strikes.

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