

2019 年度

博士学位論文

風車ブレード内ダウンコンダクタの断線検出手法

Disconnection Detection Methods of a Down Conductor
in a Wind Turbine Blade

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ACKNOWLEDGEMENTS

I would like to express my deepest gratitude and sincere appreciation to my advisor, Prof. YAMAMOTO Kazuo, Prof. SUMI Shinichi and Prof. NAKAMURA Keiji for his continuous support throughout my study. They have provided me with guidance and excellent opportunities to learn new things. Also, I would like to give an exceptional thank you to Prof. AMETANI Akihiro, who gives me the knowledge on the topic of Surge impedances. And, I am tremendously grateful for all members of our laboratories for helping and teaching the Japanese language. Without them, my life in Japan would be tough.

My appreciation also goes to Prof. YUTTHAGOWITH Peerawut, including all members in the High-Voltage Laboratory of KMITL, from their encouragement, when things did not go as planned.

Finally, I owe my parents. They have always supported wholeheartedly and praise, for which I am grateful.

ABSTRACT

This study presents on the simplified techniques that consist of an electrostatic capacity, a half-wave dipole-antenna, and a propagation phenomena of a surge waveform for detecting disconnected locations of down conductors. The proposed techniques start with creating the Finite-Difference Time-Domain (FDTD) simulation models to calculate the transient current and resonance current while down conductors' length is varying and the coordination curves of length-capacitance and length-current are produced. The validities of the simulation results from the electrostatic capacity and the half-wave dipole-antenna have been verified by the experiments with a reduced scale model and a small wind turbine. From the comparison, the simulation and experimental results, good agreement has been observed.

From the achievement, the applications of the electrostatic capacity and the half-wave dipole-antenna were employed to estimate the disconnected locations of the Mitsubishi MWT-1000A, and the Gamesa G80-2.0 MW in the real practices. Using the preliminary data from manufacturers, the FDTD simulation models were created. In the same manner, the simulation results from the electrostatic capacity, and the half-wave dipole-antenna were used to produce the length-capacitance and length-current coordination curves. To estimate disconnected locations, the measured results that carried out on those wind turbines when applying the proposed techniques were compared with the length-capacitance and length-current coordination curves. Thus, disconnected locations have been obtained. To examine the validity of the disconnection, the

associated with the implementation of the traveling time of the propagation waveform in a conductor was employed to confirm the estimated results from the curves. The comparison results have found that there are some deviations of the estimated location obtained by the proposed techniques. However, it can be accepted because the proposed techniques can be combined to consider where the disconnected location of the down conductor has occurred. From this achievement, the proposed techniques are useful to be applied for the detection of disconnected locations of down conductors. Moreover, the proposed techniques are sufficiently economical for real practice and can be adapted to support maintenance engineers to observe disconnected locations without the trial-and-error.

Keywords: Down conductor, Electrostatic capacity, Half-wave dipole-antenna, Propagation phenomena, Wind turbines.

CONTENTS

	PAGE
ACKNOWLEDGEMENTS	i
ABSTRACT	ii
CONTENTS	iv
LIST OF TABLES	viii
LIST OF FIGURES	xii
 CHAPTER	
1 INTRODUCTION	1
1.1 RATIONALE	1
1.2 LITERATURE REVIEW.....	5
1.2.1 LIGHTNING PROTECTION OF WIND TURBINE BLADES	5
1.2.2 GUIDELINE FOR LIGHTNING PROTECTION OF WIND TURBINES IN JAPAN [9].....	6
1.2.3 NONCONTACT METHOD TO DIAGNOSE DOWN- CONDUCTOR DISCONNECTIONS IN A WIND TURBINE BLADE USING X-RAY APPARATUSES [7]	9

1.3 OBJECTIVE.....	10
2 THEORIES.....	12
2.1 TYPES OF LIGHTNING.....	12
2.2 LIGHTNING PROTECTION SYSTEM FOR WIND TURBINES.....	16
2.3 DETECTION TECHNIQUES OF THE DISCONNECTED LOCATION OF THE DOWN CONDUCTOR IN WIND TURBINE BLADES	19
2.3.1 DETECTION TECHNIQUE USING THE CHANGE IN THE ELECTROSTATIC CAPACITANCE.....	20
2.3.2 DETECTION TECHNIQUE USING THE HALF- WAVE DIPOLE-ANTENNA THEORY	22
2.3.2 DETECTION TECHNIQUE USING THE WAVE PROPAGATION METHOD	25
2.4 FINITE-DIFFERENCE TIME-DOMAIN (FDTD).....	26
3 THE PROPOSED CONCEPT.....	35
3.1 EFFECT OF THE CHARACTERISTIC IMPEDANCE	35
3.2 APPLICATION OF THE DETECTION TECHNIQUE USING THE CHANGE IN THE ELECTROSTATIC CAPACITANCE	39
3.2.1 REDUCED SCALE MODEL.....	41

3.2.2 SMALL WIND TURBINE	44
3.2.3 MITSUBISHI MWT-1000A.....	46
3.2.4 GAMESA G80-2.0 MW	48
3.3 APPLICATION OF THE DETECTION TECHNIQUE USING THE HALF-WAVE DIPOLE-ANTENNA THEORY	49
3.3.1 REDUCED SCALE MODEL.....	49
3.3.2 SMALL WIND TURBINE.....	50
3.3.3 MITSUBISHI MWT-1000A.....	51
3.3.4 GAMESA G80-2.0 MW	52
3.4 APPLICATION OF THE DETECTION TECHNIQUE USING THE PROPAGATION METHOD.....	53
4 SIMULATION AND EXPERIMENTAL RESULTS.....	56
4.1 REDUCED SCALE MODEL	56
4.2 SMALL WIND TURBINE	64
4.3 MITSUBISHI MWT-1000A	71
4.4 GAMESA G80-2.0 MW	92
5 CONCLUSIONS.....	101
REFERENCE	103

APPENDIX	107
A. M-FILES MATLAB SOURCE CODE	107
B. LIST OF PUBLISHED PAPERS.....	131

LIST OF TABLES

	PAGE
 TABLE	
Table 1.1 Degree of loss and probability of damage assumed in a wind power plant.....	8
Table 1.2 Evaluation of the effectiveness of lightning protection measures.....	9
Table 2.1 Classification of the blade damage due to lightning.....	18
Table 2.2 Classification of the damage to the other components due to lightning	19
Table 3.1 Comparison of the measured and theoretical surge impedances.....	38
Table 4.1 Comparison of the capacitance values obtained by the simulation and the experiment when applying the electrostatic capacitance between the two down conductors for the reduced scale model.....	58
Table 4.2 Comparison of the capacitance values obtained by the simulation and the experiment when applying the electrostatic capacitance between the tower body and the down conductor for the reduced scale model	61

Table 4.3	Comparison of the resonant peak current values obtained by the simulation and the experiment when applying the half-wave dipole-antenna for the reduced scale model.....	63
Table 4.4	Comparison of the capacitance values obtained by the simulation and the experiment when applying the electrostatic capacitance between the two down conductors for the small wind turbine	66
Table 4.5	Comparison of the capacitance values obtained by the simulation and the experiment when applying the electrostatic capacitance between the tower body and the down conductor for the small wind turbine	68
Table 4.6	Comparison of the resonant peak current values obtained by the simulation and the experiment when applying the half-wave dipole-antenna for the small wind turbine	70
Table 4.7	Capacitance values obtained by the simulation when applying the electrostatic capacitance between the two down conductors for the Mitsubishi MWT-1000A	72
Table 4.8	Capacitance values obtained by the simulation when applying the electrostatic capacitance between the tower body and the down conductor for the Mitsubishi MWT-1000A.....	74
Table 4.9	Resonant peak current values obtained by the simulation when applying the half-wave dipole-antenna for the Mitsubishi MWT-1000A	75

Table 4.10	Capacitance values obtained by the experiment when applying the electrostatic capacitance between the two down conductors of the wind turbines during testing	78
Table 4.11	Capacitance values obtained by the experiment when applying the electrostatic capacitance between the tower body and the down conductor of the wind turbines during testing .	78
Table 4.12	Resonant peak current values obtained by the experiment when applying the half-wave dipole-antenna of the wind turbines during testing	79
Table 4.13	Disconnected locations from the estimations	91
Table 4.14	Capacitance values obtained by the simulation when applying the electrostatic capacitance between the two down conductors for the Gamesa G80-2.0 MW.....	93
Table 4.15	Capacitance values obtained by the simulation when applying the electrostatic capacitance between the tower body and the down conductor for the Gamesa G80-2.0 MW	94
Table 4.16	Resonant peak current values obtained by the simulation when applying the half-wave dipole-antenna for the Gamesa G80-2.0 MW	96
Table 4.17	Capacitance values obtained by the experiment when applying the electrostatic capacitance between the two down conductors of the wind turbine	98

Table 4.18	Capacitance values obtained by the experiment when applying the electrostatic capacitance between the tower body and the down conductor of the wind turbine	98
Table 4.19	Resonant peak current values obtained by the experiment when applying the half-wave dipole-antenna of the wind turbine	98
Table 4.20	Disconnected locations obtained by the estimation.....	100

LIST OF FIGURES

		PAGE
FIGURE		
Fig. 1.1.	Historical development of new installations of wind turbines [1]	2
Fig. 1.2.	Electricity production of Japan [2]	2
Fig. 1.3.	Causes of failure of domestic wind turbines [3]	3
Fig. 1.4.	Lightning hazard map of Japan [9]	7
Fig. 2.1.	The four types of lightning discharges	13
Fig. 2.2.	Schematic representation of the current versus height profiles for the three modes of charge transfer to the ground in negative lightning subsequent strokes	14
Fig. 2.3.	Map of Japan and the Tsushima warm current.....	16
Fig. 2.4.	Wind turbine components and the grounding.....	17
Fig. 2.5.	Basic configuration of a capacitor [12]	21
Fig. 2.6.	Electric field between the two down conductors, and the electric field between the tower body and the down conductor.....	22
Fig. 2.7.	Linear dipole-antenna [13].....	24

Fig. 2.8.	Current distributions along the length of a linear wire antenna [13]	24
Fig. 2.9.	Traveling waves initiated by energizing an open-circuited line [14].....	25
Fig. 2.10.	Position of the electric and magnetic field vector components about a cubic cell for Yee's space lattice.....	31
Fig. 3.1.	A vertical line.....	36
Fig. 3.2.	Equivalent circuit of the RC series circuit.....	40
Fig. 3.3.	Analytical space of the reduced scale model when applying the electrostatic capacitance between two down conductors..	42
Fig. 3.4.	Staircase approximation for the down conductor	43
Fig. 3.5.	Analytical space of the reduced-scale model when applying the electrostatic capacitance between the tower body and a down conductor.....	43
Fig. 3.6.	Analytical space of the small wind turbine when applying an electrostatic capacitance between the two down conductors..	45
Fig. 3.7.	Analytical space of a small wind turbine when applying an electrostatic capacitance between a tower body and a down conductor.....	45
Fig. 3.8.	Analytical space of the Mitsubishi MWT-1000A when applying the electrostatic capacitance between the two down conductors	46

Fig. 3.9.	Analytical space of the Mitsubishi MWT-1000A when applying the electrostatic capacitance between the tower body and the down conductor	47
Fig. 3.10.	Analytical space of the Gamesa G80-2.0 MW when applying the electrostatic capacitance between two down conductors..	48
Fig. 3.11.	Analytical space of the Gamesa G80-2.0 MW when applying the electrostatic capacitance between the tower body and the down conductor.....	49
Fig. 3.12.	Analytical space of the reduced-scale model when applying the half-wave dipole-antenna theory	50
Fig. 3.13.	Analytical space of the small wind turbine when applying the half-wave dipole-antenna.....	51
Fig. 3.14.	Analytical space of the Mitsubishi MWT-1000A when applying the half-wave dipole-antenna.....	51
Fig. 3.15.	Analytical space of the Gamesa G80-2.0 MW when applying the half-wave dipole-antenna.....	52
Fig. 3.16.	Analytical space for the injected step waveform for two conductors (open circuit of both conductors)	54
Fig. 3.17.	Analytical space for the injected step waveform in two conductors (conductor B is connected to the ground)	55
Fig. 3.18.	Analytical space for the step waveform in two conductors (conductor B is connected to the tower)	55

Fig. 4.1.	Transient current waveforms: the length of down conductor B, the charging voltage, and the series resistance varied from 0.0 m to 0.9 m, 100 V, and 10 k Ω , respectively	57
Fig. 4.2.	Simulation and experimental results: comparison of the capacitance between the two down conductors	59
Fig. 4.3.	Transient current waveforms: the down conductor's length, the charging voltage, and the series resistance varied from 0.0 m to 0.9 m, 100 V, and 10 k Ω , respectively	60
Fig. 4.4.	Simulation and experimental results: comparison of the capacitance between the tower body and the down conductor	61
Fig. 4.5.	Resonant current waveforms: the length of down conductor B, the peak alternating voltage, and the resonance frequency varied from 0.0 m to 0.9 m, 1.4 V, and 70.8 MHz, respectively	62
Fig. 4.6.	Simulation and experimental results: comparison of the peak current for each down conductor length when applying the half-wave dipole-antenna.....	64
Fig. 4.7.	Transient current waveforms: the length of down conductor B, the charging voltage, and the series resistance varied from 0 m to 14 m, 100 V, and 5 k Ω , respectively	65

Fig. 4.8.	Simulation and experimental results: comparison of the capacitance between the two down conductors for each length.....	66
Fig. 4.9.	Transient current waveforms: the down conductor's length, the charging voltage, and the series resistance varied from 0 m to 14 m, 100 V, and 5 k Ω , respectively	67
Fig. 4.10.	Simulation and experimental results: comparison of the capacitance between the tower body and the down conductor at each length	68
Fig. 4.11.	Simulation and experimental results: comparison of the capacitance between the tower body and the down conductor at each length	69
Fig. 4.12.	Half-wave dipole-antenna: comparison of the simulation and the experimental values of the peak current for each down conductor length.....	70
Fig. 4.13.	Transient current waveforms: the length of down conductor B, the charging voltage, and the series resistance varied from 0 m to 29.5 m, 100 V, and 5 k Ω , respectively	72
Fig. 4.14.	Simulation results: trend curve of the capacitance between the two down conductors at each length.....	73
Fig. 4.15.	Transient current waveforms: the length of the down conductor, the charging voltage, and the series resistance varied from 0 m to 29.5 m, 100 V, and 5 k Ω , respectively	73

Fig. 4.16.	Simulation results: trend curve of the capacitance between the tower body and the down conductor at each length	74
Fig. 4.17.	Resonant current waveforms: the length of down conductor B, the peak alternating voltage, and the resonance frequency varied from 0 m to 29.5 m, 14 V, and 1.89 MHz, respectively	75
Fig. 4.18.	Simulation results: trend curve of the peak resonant current at each length of the down conductor	76
Fig. 4.19.	Positioning of the blades during the test.....	76
Fig. 4.20.	Process of the proposed techniques	80
Fig. 4.21.	Estimated locations when comparing the simulation results of wind turbine No. 1	81
Fig. 4.22.	Estimated locations when comparing the simulation results of wind turbine No. 2	82
Fig. 4.23.	Estimated locations when comparing the simulation results of wind turbine No. 3	83
Fig. 4.24.	Estimated locations when comparing the simulation results of wind turbine No. 4	84
Fig. 4.25.	Estimated locations when comparing the simulation results of wind turbine No. 5	85
Fig. 4.26.	Simulation results for the injected step waveform for the two conductors (open circuit of both conductors)	86

Fig. 4.27.	Simulation results for the injected step waveform for two conductors (conductor B was connected to the ground).....	87
Fig. 4.28.	Simulation results for the injected step waveform for two conductors (conductor B was connected to the tower).....	87
Fig. 4.29.	Measured results of the traveling time of the reflected waveform for wind turbine No. 1	89
Fig. 4.30.	Measured results of the traveling time of the reflected waveform for wind turbine No. 2	89
Fig. 4.31.	Measured results of the traveling time of the reflected waveform for wind turbine No. 3	90
Fig. 4.32.	Measured results of the traveling time of the reflected waveform for wind turbine No. 4	90
Fig. 4.33.	Measured results of the traveling time of the reflected waveform for wind turbine No. 5	91
Fig. 4.34.	Transient current waveforms: the length of down conductor B, the charging voltage, and the series resistance varied from 0 m to 39 m, 100 V, and 5 k Ω , respectively	92
Fig. 4.35.	Simulation results: best-fit curve of the capacitance between two down conductors for each length.....	93
Fig. 4.36.	Transient current waveforms: the down conductor length, the charging voltage, and the series resistance varied from 0 m to 39 m, 100 V, and 5 k Ω , respectively	94

Fig. 4.37.	Simulation results: best-fit curve of the capacitance between the tower body and the down conductor for each length.....	95
Fig. 4.38.	Transient current waveforms: the down conductor length, the charging voltage, and the series resistance varied from 0 m to 39 m, 100 V, and 5 k Ω , respectively	95
Fig. 4.39.	Simulation results: best-fit curve of the peak resonant current at each length of the down conductor	96
Fig. 4.40.	Positioning of the wind turbine blades during testing	97
Fig. 4.41.	Estimated locations when compared to the simulation results	99
Fig. 4.42.	Measured results of the reflected waveform's time for a wind turbine during testing	100
Fig. A.1	MATLAB GUI for the estimated locations of the disconnection	107

CHAPTER 1

INTRODUCTION

1.1 Rationale

Recently, renewable forms of energy such as wind power, hydropower, and solar power, have gained popularity. The most common goals that the use of such renewable forms aims to achieve include the decrease in greenhouse gases in electricity generation for supporting the world economy as well as addressing the scarcity of energy resources due to the depletion of fossil fuels (e.g., coal, oil, gas). Among the renewable energy resources, wind power is rapidly spreading internationally because of its high efficiency as an energy source, and the ease of commercialization on a large scale as illustrated in Fig. 1.1. The 51.3 GW of new installations for the onshore and offshore market in 2018 brings the total cumulative installations up to 591 GW [1].

Japan is one of the key countries that use renewable forms of energy in Asia. To meet the electricity demand, new installations of 262 MW for onshore wind turbines were installed in 2018. Moreover, the Japanese government passed a new Offshore Wind Law to give the mandate to define several areas for offshore wind development. The intention is to have a competitive process for awarding 30-year projects by mid-2020. As Fig. 1.2 indicates [2], the share of electricity production from renewable sources has been continuously growing in the past decade. This also shows that the installation of wind turbines in Japan has been increasing. However, with the installation of more wind

turbines, the number of failure reports of wind turbines is simultaneously increasing, thereby resulting in problems for energy security. In terms of the causes of wind turbine failures in Japan, the most frequent are lightning strikes, as illustrated in Fig. 1.3 [3].

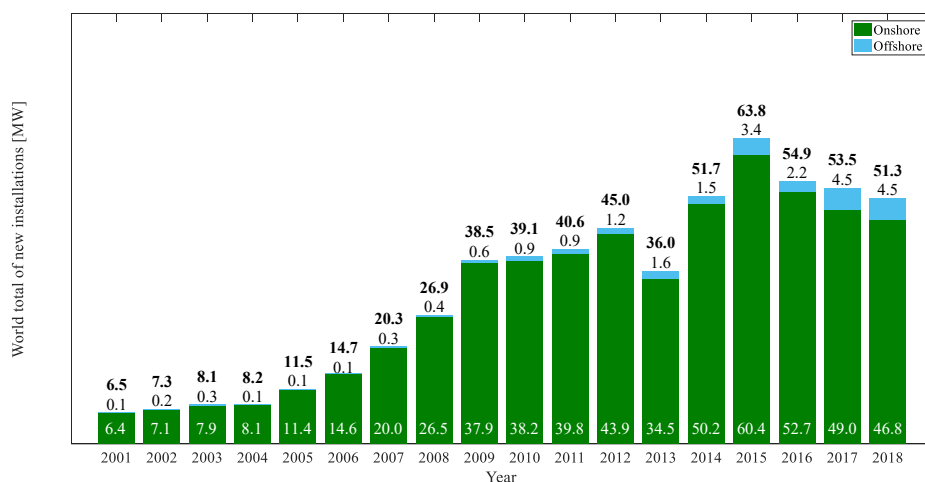


Fig. 1.1. Historical development of new installations of wind turbines [1].

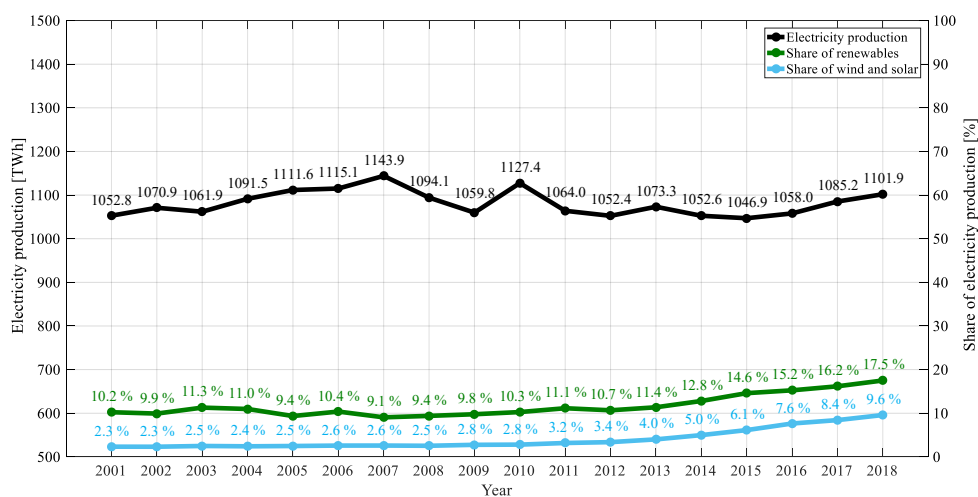


Fig. 1.2. Electricity production of Japan [2].

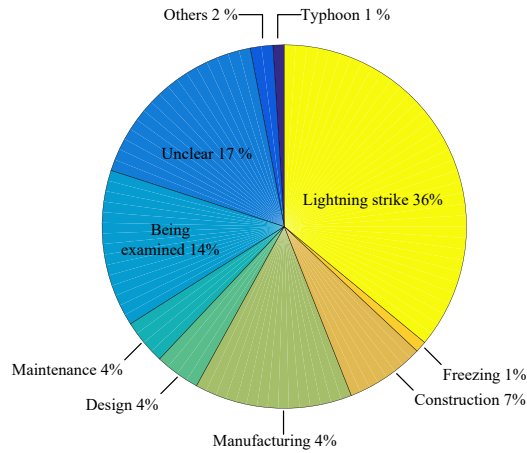


Fig. 1.3. Causes of failure of domestic wind turbines [3].

Japan's wind turbines are usually installed in the coastal areas where there are good wind conditions. However, these areas are frequently affected by lightning, especially in the west coast areas where winter lightning is frequent [4]. Since the height of the thundercloud in case of winter lightning is lower than that of summer lightning, the initial electric field occurs around the protruded structures on the ground. Thus, the discharge of winter lightning is likely to occur due to high-rise wind turbine structures that reaches towards the thundercloud [5]. Furthermore, the duration of the winter lightning current wave shape is longer than 10 ms and its electric charge is more than 300 C in some cases. Thus, the characteristics of winter lightning is significantly different from those of summer lightning. In addition, the structural damage due to lightning is most likely to be more severe for winter lightning.

As aforementioned, wind turbines that are located in coastal areas have a high risk of being struck by lightning. Therefore, Japan's wind turbines are

strictly designed with the requirement of lightning protection equipment, such as air terminal receptors, down conductors, and grounding systems, that follows IEC 61400-24 [6] to avoid the risks of structural damage. When lightning strikes any of the receptors located at the tip or in the middle of a wind turbine blade, the lightning current flows to the ground via the down conductors. Although lightning protection equipment has been designed to withstand damage due to lightning through lightning protection systems, the down conductor in wind turbine blades still involves risks. This includes laceration or being separated from the rest of the structure due to aged deterioration or electrodynamic forces. Thus, if there is a large amount of lightning current that passes through it, the blades will be ruptured, and can cause harm to the buildings and/or living things around the wind turbine. Therefore, wind turbine companies in Japan usually stop running their wind turbines every two or three years to perform checks and to maintain the lightning protection systems. However, down conductors are often installed in wind turbine blades to preserve their aerodynamic characteristics, thereby making it laborious for maintenance engineers to observe the damage and to properly fix them.

There are only a few studies that specifically focus on the detection of disconnection of down conductors in wind turbine blades. Nevertheless, the recent application of X-rays to identify the disconnected location of down conductors has been performed. Although this application afforded high efficiency, and such investigation systems were essential, significant expenses were incurred [7]. Therefore, this research will focus on simplified testing techniques that can provide a high efficiency using the applications of electrostatic capacity, half-wave dipole resonance, and the propagation

phenomena of a surge waveform. Finite-difference time-domain (FDTD) simulation models were used to guide the maintenance engineers. Thus, maintenance engineers are able to detect a disconnected location of the down conductors in wind turbine blades without performing a trial and error experiment.

1.2 Literature Review

1.2.1 Lightning Protection of Wind Turbine Blades [8]

Yokoyama clarified the lightning damage of wind turbine blades by observing lightning and performing experiments in a high-voltage laboratory [8]. The author investigated the characteristics of lightning attachment and lightning current, especially for winter lightning that frequently occurs along the Sea of Japan coastline. In 2002–2006, the average annual disruptions to wind turbines caused by lightning in Japan ranged from 10 to 20%, and this occurred for approximately 30% of wind turbines installed near the coastline [8]. Among the damages caused by lightning for wind turbine generators over 1000 kW, 75% of the total losses are blade damages. This resulted in significant expenses for the transportation of large blades and their replacement. Thus, large-scale wind turbine generators must be more concerned with lightning protection systems compared with small-scale wind turbines.

Specifically, Yokoyama conducted a series of experiments that featured a 12 MV high-voltage impulse generator that delivered wave shape lightning impulses [8]. These impulses were carried out to investigate the wind turbines

blades with various blade conditions. The first experiment was carried out on a non-conductive blade in which water was mixed with salt and powdered clay and this was sprayed onto the blade. The equivalent salt deposit density of 0.1 mg/cm³ was considered to simulate the wind turbines that are located near the seacoast. A second experiment was carried out on a blade with a metal receptor's diameter of 25 mm. The receptor was installed 250 mm from the blade tip and was connected to the down conductor inside the cavity of the blade. The second experiment was performed for four typical arrangements of the blade, which include a horizontal arrangement with a leading-edge facing electrode; a horizontal arrangement with a trailing-edge facing electrode; an oblique 45-degree arrangement; and a vertical arrangement.

Based on the experimental results, it can be concluded that the creeping discharge occurred more frequently under the polluted conditions for the non-conductive blades. In addition, a penetrative discharge into the cavity of the blade sometimes occurred. For the blade with the metal receptor, the discharge entered the edge of the middle part of the blade during testing for the horizontal arrangement cases. However, the blade under testing for the vertical arrangement case was damaged at the tip. Thus, it is essential to develop protection for the wind turbine blades with high-performance materials such as carbon fiber reinforced plastics.

1.2.2 Guideline for Lightning Protection of Wind Turbines in Japan [9]

Natsuno et al. described the damage to wind turbines from lightning strikes as well as the features of lightning in Japan [9]. They observed lightning

strikes from April to October for summer lightning and the period of November to March for winter lightning. They discovered that the bottom height of the thunderclouds during summer lightning is higher in comparison to winter lightning. It can be pointed out that approximately 90% of summer lightning has negative polarity; however, for winter lightning, the negative polarity ranges from 50 to 70%. In addition, the wave shape of winter lightning has a long duration current and a lower frequency in comparison with summer lightning. In some cases, the electric charge is higher than 300 C. Fig 1.4 illustrates the lightning hazard map in Japan.

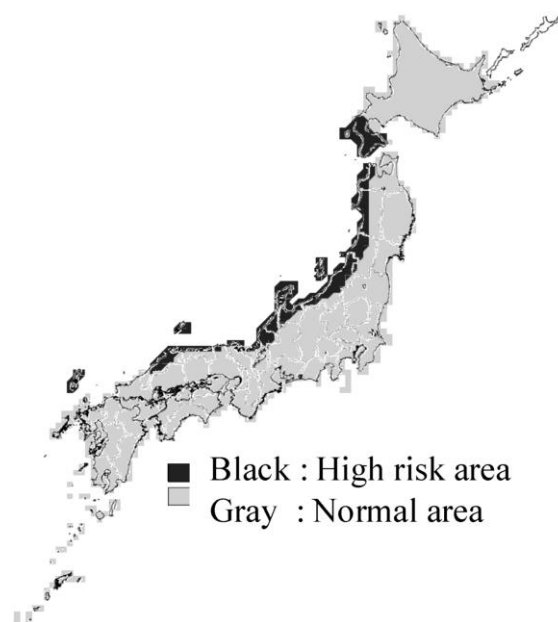


Fig. 1.4. Lightning hazard map of Japan [9].

Furthermore, the lightning voltage tests and lightning current tests that were carried out in the laboratory were employed to investigate the mechanism and to evaluate the effectiveness of various types of lightning protection for

wind turbines. From this experiment, receptors were determined to be one of the most useful methods for protecting wind turbine blades from lightning strikes.

Natsuno et al. also provided guidelines for the risk management of lightning strikes for wind turbine blades. This has been described in terms of the degree of loss and the frequency of the occurrence damage; this is listed in Table 1.1. Furthermore, Natsuno et al. summarized the evaluated qualitative effectiveness of lightning protection measures, which is presented in Table 1.2.

The authors recommended placing a receptor on the tip of a blade or using a metal to cover the tip of a blade for the high-risk areas. In addition, the diameter of the down conductors, which indicates the current withstanding, needed to be considered. They also specified that the lightning tower needed to be installed along the upwind side to deal with winter lightning.

Table 1.1 Degree of loss and probability of damage assumed in a wind power plant

No.	Part	Damage contents	Degree of damage (Repair costs, time)	Frequency if occurrence
1	Blade	Fusion of the receptor	Small	- (Medium)
2		Burn around the receptor	Small	- (High)
3		Scattering of the receptor	Medium	- (Low)
4		Through-bore in the blade	Medium	Medium (Medium)
5		Laceration of the blade	Extremely large	Medium (Low)
6		Falling off of the blade	Extremely large	Medium (Low)
7		Burn of the blade surface	Small	High (High)
8		Blowout of the conductor	Large	- (Low)
9	Nacelle	Burn of the anemometer and the wind vane	Small	Low
10		The electrolytic corrosion of the generator, the bearing	Large	Low
11		Breakdown of the winding of the generator	Large	Low
12	Electric apparatus Control Electronic	Breakdown of the electric apparatus	Large	Low
13		Breakdown of the low voltage circuit	Medium	Low
14		The malfunction, the damage of electronics	Small	High

(); with receptor

Table 1.2 Evaluation of the effectiveness of lightning protection measures

Measures	Damage aspect number (refer to the Table 1.1)	Measures Effect size	Lightning Protection measure (*)	
			Risk area	High risk area
Upsizing of the receptor	1, 2, 3	Low	Medium or Low	Medium or Low
Multiple receptor	1, 2, 3, 4, 5, 6	Medium	Medium or Low	High
Install a receptor in the top of blade	1, 2, 3, 4, 5, 6, 7	High	High	Very High
Use metallic material for the tip part of blade	1, 2, 3, 4, 5, 6, 7	High	High	Very High
Reinforcement of the conductor	8	Low	Medium or Low	Very High
Install lightning rod on a nacelle	9	Medium	High	High
Use an insulation bearing and a ground brush for a generator and a gearbox	10	Low	Medium or Low	Medium or Low
Insulate a gearbox and generator	10	Low	Medium or Low	Medium or Low
Use of lightning-resistant transformer	12, 13, 14	Medium	High	High
Install arresters to the apparatus	12, 13, 14	Medium	High	High
Use optical fiber for signal lines	13, 14	Medium	High	High
Reinforcement of the grounding	11, 12, 13, 14	Medium	High	High

* This table shows the priority of lightning protection

1.2.3 Noncontact method to diagnose down-conductor disconnections in a wind turbine blade using X-ray apparatuses [7]

Disconnections of wind turbine down conductors from lightning strikes is one of the main failures of wind turbines from natural phenomena. These disconnections may affect the blade damage. This is detrimental in terms of electricity generation and profits. Thus, there is a demand for high-performance techniques that can be easily performed at a low cost for diagnosis down conductors. Yamamoto et al. proposed the idea of X-ray apparatuses for detecting disconnected locations of down conductors in wind turbine blades [7].

They uninstalled wind turbine blades and tested the four types of X-ray apparatuses for detecting a disconnected point of the down conductor, as follows:

1. microfocus X-ray tube transmission method;

2. vehicle's backscattering X-ray apparatus;
3. backscatter X-ray equipment for baggage inspection; and
4. portable backscatter X-ray apparatus.

From their results, Yamamoto et al. concluded that these techniques that used the X-ray apparatuses can be used for detecting the disconnected point. However, in order to inspect the wind without uninstalling the blade to the ground, it is essential to construct a detection system using a robot. It is likely that this will take time and may be costly in terms of putting it into practical use. From the measurements using the backscattered X-ray apparatus, it was possible to detect cases where the down conductor was completely disconnected. Measurements were performed with a portable backscatter X-ray device that has the best operability. By increasing the distance between the device and the down conductor, the image may become unclear. As a result, this might not be possible to determine whether there was a break.

1.3 Objective

This study focuses on the development of the FDTD method based on the Virtual Surge Test Lab (VSTL) software. This was done to simulate the disconnections of the down conductors along the wind turbine blades using the proposed methods. This consists of the electrostatic capacitance technique and the frequency resonance method based on the half-wave dipole-antenna theorem. The dimensions of the wind turbine generators, such as the rotor diameter and the tower height, were selected from the manufacturer's data to create the simulation model. The simulation results were used to obtain the trend

curves. These were obtained through the best-fit curves of the results to evaluate the performance of the proposed techniques. The experiments were conducted using real wind turbines in Japan.

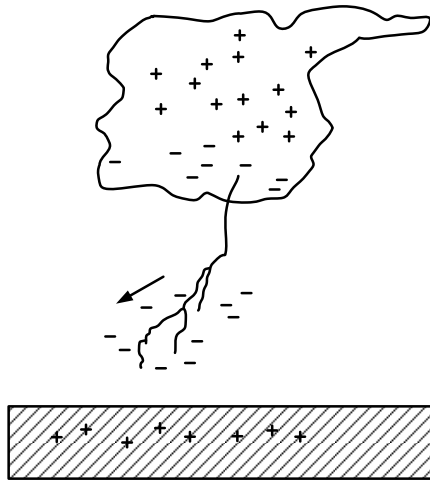
CHAPTER 2

THEORIES

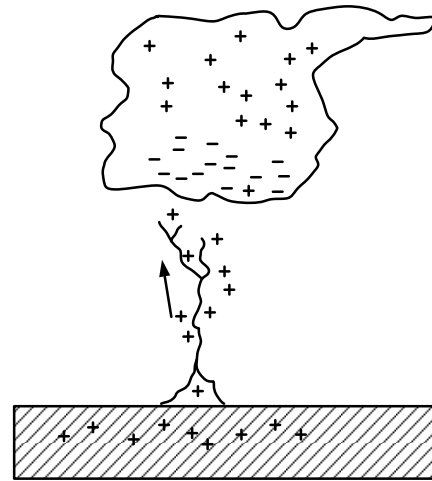
2.1 Types of Lightning

In 1752, Benjamin Franklin performed an experiment to prove that lightning strikes contain electricity, by flying a kite during a lightning storm. This experiment served as the foundation for research into lightning. By observing the polarity of the charge, the thundercloud was effectively lowered towards the ground. There are four types of lightning discharges that can occur between the thunderclouds and the ground. As shown in Fig. 2.1 [10], the four types of lightning discharges can be seen that are transported from the cloud to the ground. The four types of lightning discharges include downward negative lightning, upward negative lightning, downward positive lightning, and upward positive, respectively. The downward negative lightning discharges are initiated in the thunderclouds and negative charges are transported to the ground in the downward direction. This type of lightning discharge accounts for more than 90 % of the global cloud to ground discharges. The downward positive lightning discharges are positive charges that are transported from the cloud to the ground. It is thought that this accounts for 10% or less of the global cloud to the ground discharges. With regard to the other types, upward lightning discharges that originate from the stationary grounded objects typically occurs for tall structures. The direction of the propagation of the lightning discharges occurs upward for the charged clouds overhead. These types only occur from the high structures (higher than 100 m to 500 m or structures located on mountain tops).

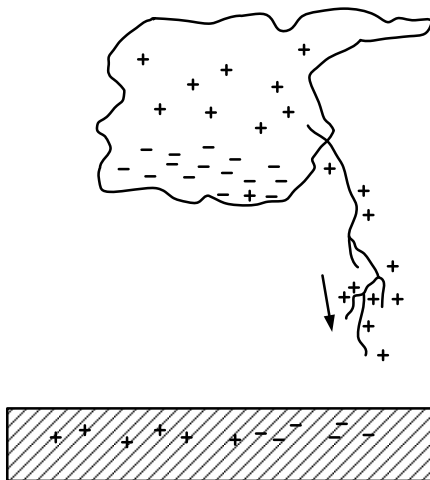
It has been observed that structures that are less than 100 m can be assumed to be struck by downward lightning discharges. In contrast, structures with a height greater than 500 m are struck by upward lightning discharges.



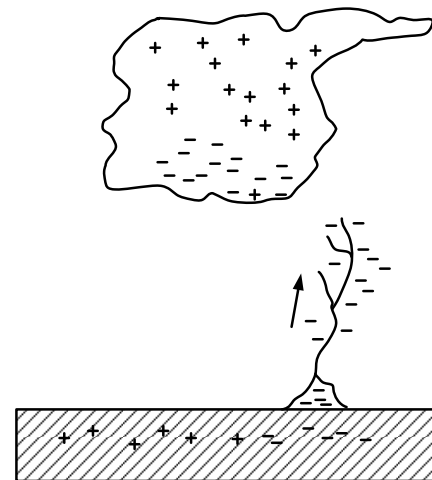
(a) Downward negative lightning.



(b) Upward negative lightning.



(c) Downward positive lightning.



(d) Upward positive lightning.

Fig. 2.1. The four types of lightning discharges.

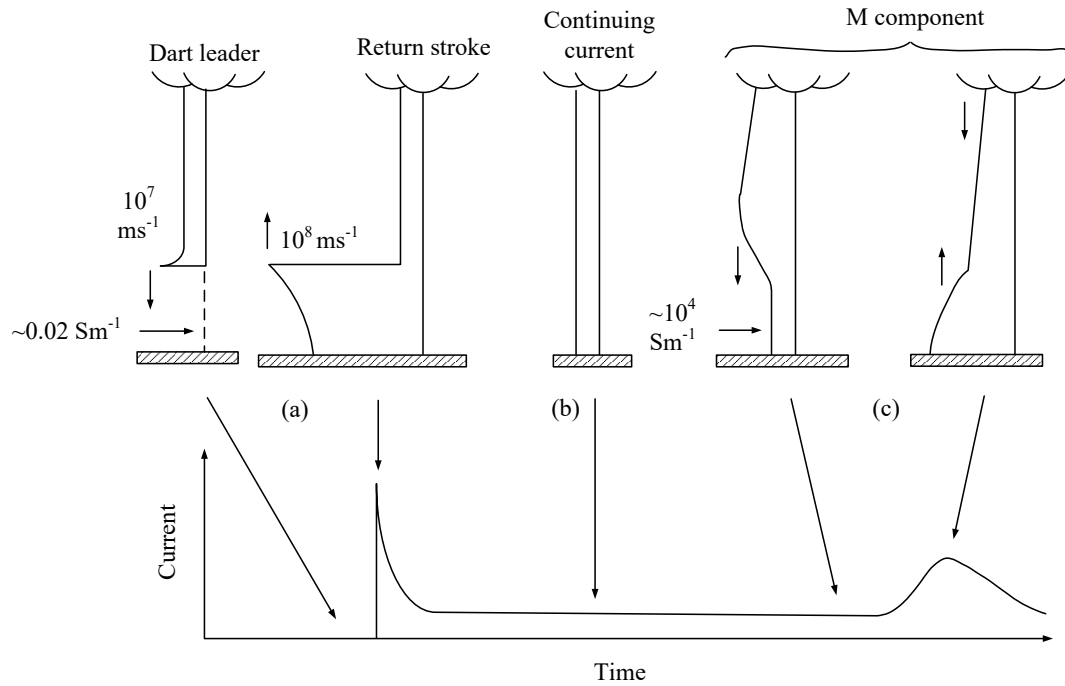


Fig. 2.2. Schematic representation of the current versus height profiles for the three modes of charge transfer to the ground in negative lightning subsequent strokes.

In addition, when studying lightning discharges, there are three types of charge transfers to the ground that occur during lightning discharges. Fig. 2.2 shows the negative subsequent strokes that consists of the dart-leader-return-stroke sequences, the continuing currents, and the M-components. In a leader-return-stroke sequence, as depicted in Fig. 2.2 (a), the descending leader produces a conductive path between the thundercloud and the ground; this path contains the negative charges. The following return stroke crosses that path by moving from the ground to the cloud charge source. Hence, the processes of the leader and the return-stroke serve to transport the negative charge from the

cloud to the ground. The continuing current, as illustrated in Fig. 2.2 (b), can be observed as a quasi-stationary arc between the cloud charge source and the ground. The typical arc current and the duration ranges from tens to hundreds of amperes and up to hundreds of milliseconds, respectively. Fig. 2.2 (c) can be observed as perturbations, or a surge, in the continuous current and the associated channel luminosity. The M-components involve the superposition of two propagated waves in the opposite directions. The spatial front length for the M-component waves is on the order of kilometers. Meanwhile for the dart-leader and return-stroke waves, the spatial front lengths are on the order of 10 m and 100 m, respectively. The M-component mode of the charge transfer to the ground needs the existence of a grounded channel that carries a continuous current that performs as a wave-guiding structure. In contrast, the leader-return stroke mode of the charge transfer to the ground occurs only in the absence of such a conducting path to the ground. In Fig. 2.2, the channel conductivity is 10^4 S.m^{-1} and this is accepted for all cases; however, the channel section between the dart-leader tip and the ground is shown by the dashed-line.

In Japan, there are two types of lightning discharges that have been observed. There is also published data over the last two to three decades for lightning depending on the season [11]. First, the summer season occurs when the air closer to the earth's surface is heated by strong sunlight that becomes a source of cumulonimbus clouds. Then, the clouds grow into thunderclouds that may reach up to 12-16 km above the earth's surface and they perform lightning discharges from the cloud to the ground. Second, during the winter season, winter lightning occurs when the cold air mass from Siberia moves over the Sea of Japan. When this occurs, the warm Tsushima Current flows up to the north

as illustrated in Fig 2.3. Due to the temperature level, cold air is closer to the earth's surface than in the summer, and the velocity of the updrafts at this level is very low. Therefore, upward lightning discharges that have a large amount of charge are initiated from the grounded structures.

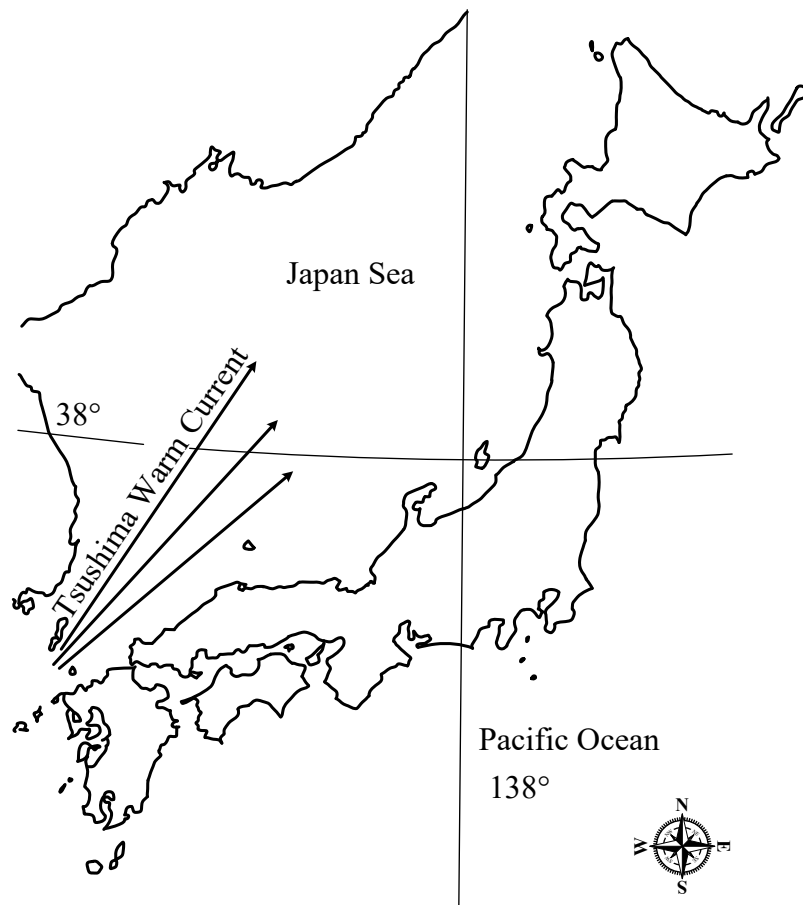


Fig. 2.3. Map of Japan and the Tsushima warm current.

2.2 Lightning Protection System for Wind Turbines

Lightning is one of the most significant problems for the stability of power system stabilities in wind farms and it remains as one of the main causes of structural damage of wind turbines. According to IEC 61400-24 [6], wind

turbines are strictly designed with lightning protection systems. These lightning protection systems consist of an air-terminal system, a down conductor system, and an earth-termination system to avoid structural damage from the electromagnetic interference (EMI) of lightning currents as demonstrated in Fig. 2.4. Usually, the air-terminal, also known as the receptor, contains metal studs along the blade surface. These metal studs are connected to the down conductor system. This is a part of the lightning current from the receptor to the earth-termination system and it can disperse current to the earth.

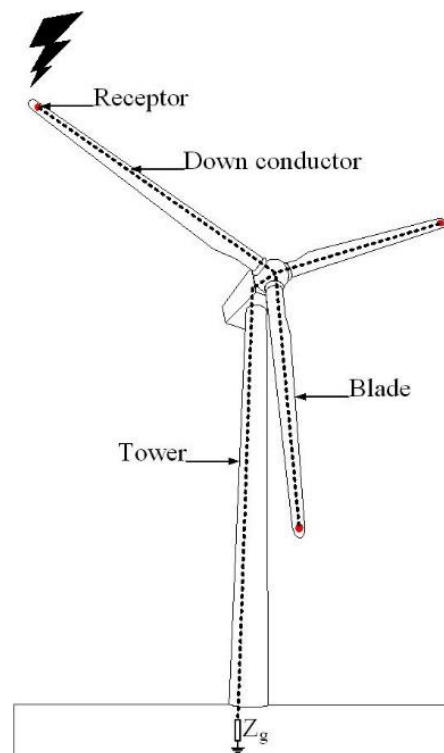


Fig. 2.4. Wind turbine components and the grounding.

N. Triruttanapiruk, et al., (2019). A simplified technique for detecting disconnections along down conductors in wind turbine blades, *ELECTR. POW. SYST. RES.*, 172, 177-182. DOI: 10.1016/j.epsr.2019.03.011

Although wind turbines have been designed to reduce the damage due to lightning through lightning protection systems, damage from lightning can occur from the structure due to aged deterioration or lightning currents.

Table 2.1 Classification of the blade damage due to lightning

Level	Incident
IV	Catastrophic: causes possible injury and/or death. (IV-a) Blade rupturing and falling (IV-b) Blade burnout and falling (IV-c) Melting and/or breaking of the control wire (IV-d) Falling of air terminal or other blade component(s)*
III	Serious: requires immediate repair (III-a) Cracking along bond weld (III-b) Tearing at blade edge (III-c) Melting and/or breaking of down conductor
II	Moderate: requires repair as soon as possible (II-a) Surface stripping (II-b) Loss of a small part of the air terminal
I	Minor: does not require immediate repair (I-a) Air terminal melting (I-b) Surface scorching (I-c) Other minor damages
* This event can be considered as (II-b) in case neither residents nor the passers-by are likely to be around the wind turbine.	

Following the IEC standard [3], the classification of lightning damage based on risk management has been published. The most structural damage is observed on the blades. This is because the blades are installed at the highest point of the wind turbine and they are designed with a fragile material. Thus, the blade damage due to lightning can be categorized into four levels based on the extent of damage as stated in Table 2.1. For the offshore wind turbines and the wind turbines that are installed in uninhabited areas, category (IV-d) can be

demoted to category (II-b). The reason for this demotion is that it may not create a public safety risk. For lightning damage to the other components, the damage classification of the wind turbine components, excluding the blades, is also categorized as the same as the blades. The damage is classified into four levels. Table 2.2 provides examples to classify the damage.

Table 2.2 Classification of the damage to the other components due to lightning

Level	Incident
IV	Catastrophic: - Injury and/or death of people inside/near the turbine - Burnout of nacelle
III	Serious: - Insulation breakdown of the generator or transformer - Breakdown of the bearings
II	Moderate: - Breakdown of the earthing system - Insulation breakdown of the converter and other power-electronics devices
I	Minor: - Insulation breakdown of the monitoring, control, or communication device

2.3 Detection Techniques of the Disconnected Location of the Down Conductor in Wind Turbine Blades

The disconnection of the down conductor in the wind turbine blade can be due to aged deterioration, lightning current, or poor manufacturing, which can cause damage to the wind turbine blades. As suggested by the IEC-61400-24 standard [6], the down conductor system may be installed on the internal or external side of the blade's surfaces. However, manufacturers have chosen to

install the down conductors on the internal side of a blade surface to preserve their aerodynamic characteristics. This makes it difficult for maintenance engineers to observe the damage and to fix it. Thus, appropriate solutions for performing detections are necessary to be solved. Recently, the application of using the X-ray apparatus to detect the disconnected locations of the down conductor have been published [7]. Although that application provided a high efficiency, the constructed investigation systems were essential. This is because the blade was uninstalled from the ground for the investigation. Therefore, two detection techniques that use the change in the electrostatic capacitance and the half-wave dipole-antenna are proposed in this study.

2.3.1 Detection technique using the change in the electrostatic capacitance

Detection techniques using the change in the electrostatic capacitance between two down conductors in wind turbine blades and the capacitance between the wind turbine tower body and a down conductor in a wind turbine blade are proposed. By considering the concept of a capacitor, an object has the ability to store an electric charge, and the capacitance varies in shape and size. However, the basic configuration consists of two conductors that carry an equal but opposite charge, which is shown in Fig. 2.5 [12].

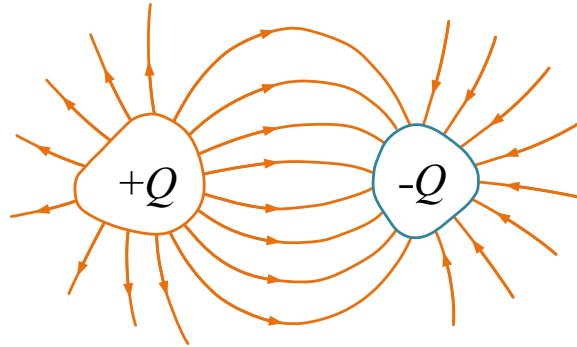


Fig. 2.5. Basic configuration of a capacitor [12].

In the case of an uncharged state, the charge on either one of the conductors is zero. On the other hand, the charge Q goes from one conductor to another conductor. A charge $+Q$ appears on one conductor, and the other capacitor has a charge of $-Q$, thereby producing a potential difference. The positively charged conductor produces a higher potential than the negatively charged conductor. Therefore, the capacitance of the system can be written as

$$C = \frac{Q}{|\Delta V|}, \quad (2.1)$$

where C is the capacitance,

Q is the charge,

and ΔV is the electric potential difference.

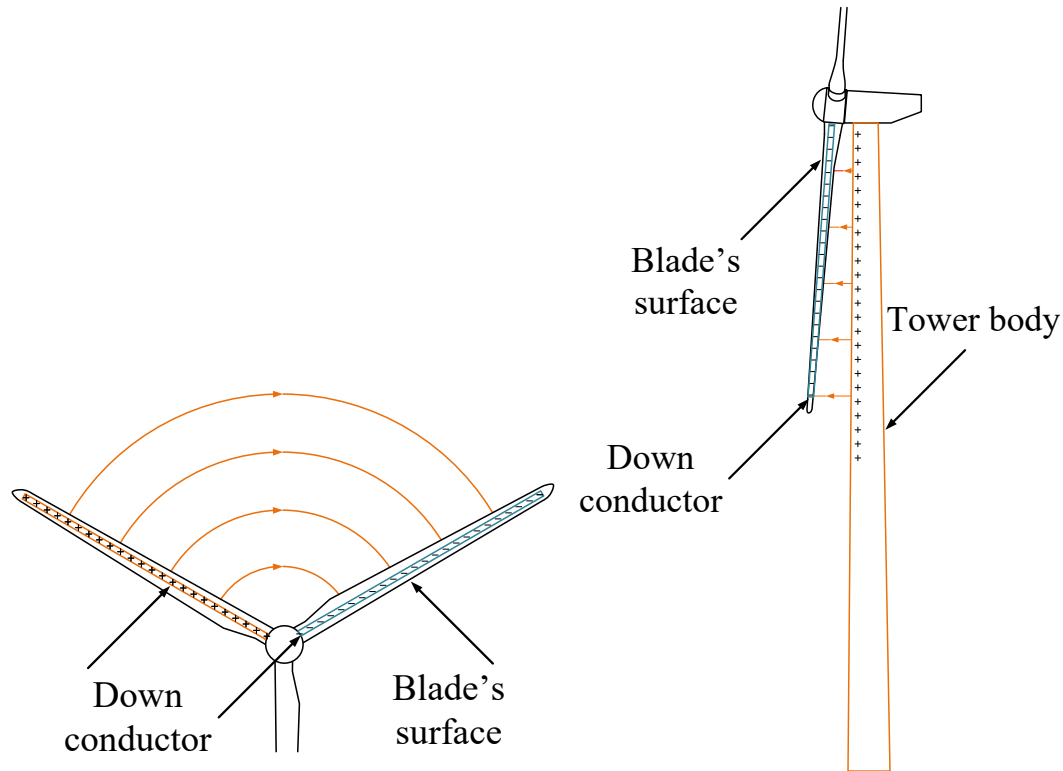


Fig. 2.6. Electric field between the two down conductors, and the electric field between the tower body and the down conductor.

From the basic concept as previously described, Fig. 2.6 shows two down conductors in the wind turbine blades, a tower body, and a down conductor that can be regarded as a capacitor. Therefore, if a disconnection appears in the down conductor, the capacitance will be lower than the completed down conductor.

2.3.2 Detection technique using the half-wave dipole-antenna theory

The linear wire or curved antennas, such as monopole antenna, a dipole-antenna, and a loop antenna, are some of the simplest and cheapest antennas that are employed in a wide range of applications. One of these, the dipole-antenna, has the most straight forward antenna alignment. As illustrated in Fig

2.7, the dipole-antenna consists of two thin metal rods with a continuous waveform difference between them. This study focuses the application on the half-wave dipole-antenna ($l = \lambda/2$) since it is the basis for most antennas. In addition, the peak of the current distribution along the length and the directional pattern are greater than the other dipole-antennas as illustrated in Fig 2.8 [13]. According to the geometry of the linear dipole-antenna displayed in Fig. 2.7, if the diameter of every conductor is small, the approximate resonance frequency of the half-wavelength dipole is as follows:

$$f = \frac{c}{2l}, \quad (2.2)$$

where f is the used frequency [Hz],

c is the speed of light [m/s],

and l is the length of the conductors [m].

As previously mentioned, two down conductors in wind turbine blades can be considered to act like a dipole-antenna by applying a CW source with the resonance frequency between them. If a disconnection appears in the down conductor, the current flowing in the conductor will decrease since no resonance can occur.

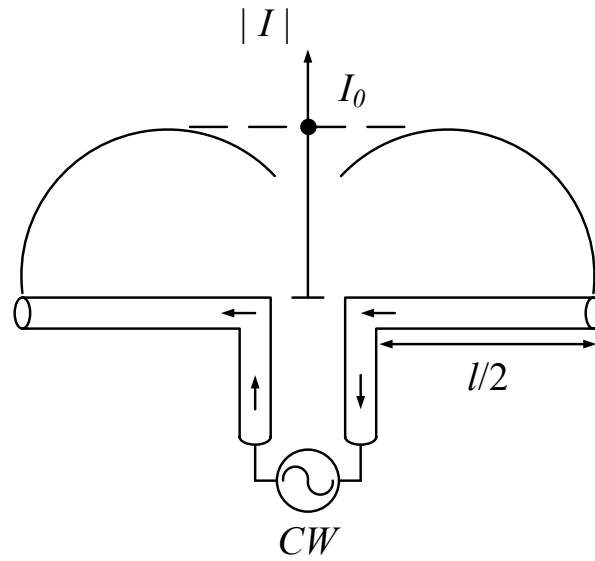


Fig. 2.7. Linear dipole-antenna [13].

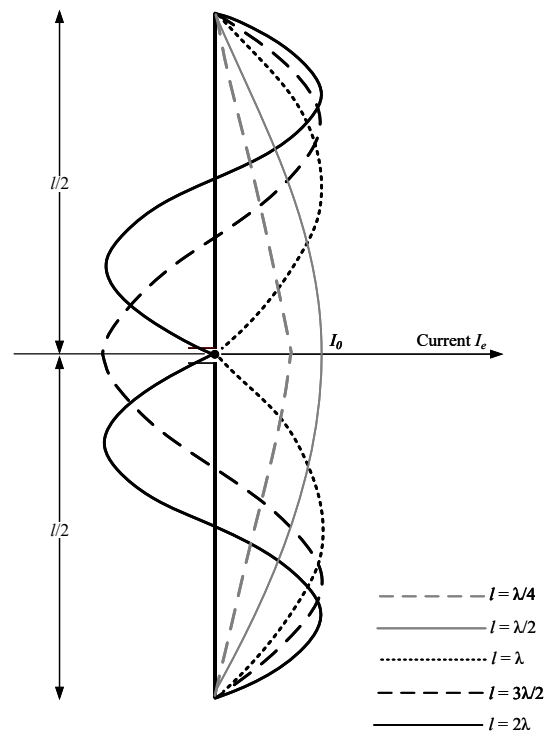


Fig. 2.8. Current distributions along the length of a linear wire antenna [13].

2.3.3 Detection technique using the wave propagation method

The wave propagation method based on the traveling wave is suitable to detect a disconnected location. This is because the end of the down conductor is considered as an open circuit. When a step voltage is propagated along the down conductor, there is a reflected wave that manifests itself by doubling the voltage of the open circuit and the current when the point is zero at all times, as shown in Fig. 2.9 [14]. If the traveling time for the propagated wave along the down conductor to the end is τ seconds, the traveling time, which includes the reflected wave toward the source with the reflected voltage, can be determined for 2τ seconds.

As mentioned above, if there is a disconnection that appears in the down conductor, the time 2τ will be shorter than the normal down conductor.

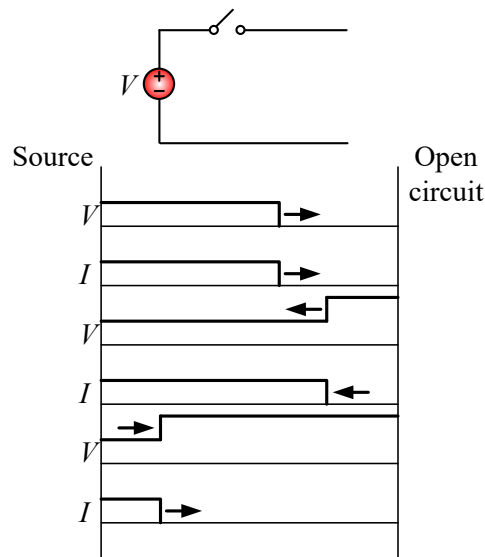


Fig. 2.9. Traveling waves initiated by energizing an open-circuited line [14].

2.4 Finite-Difference Time-Domain (FDTD)

Computational electromagnetics (CEM) has evolved to the point where it can be accurately predict a variety of electromagnetic problems. The computational electromagnetics method is usually classified into two categories that consists of the differential equation method (DE) and the integral equation method (IE). To solve these problems, DE and IE are based on the applications of Maxwell's equations with the appropriate boundary conditions. In terms of the finite sums, the IE methods provide approximations for the IE and the DE methods provides estimates for finite-differences. In the past, numerical electromagnetic analysis has emerged in the frequency-domain with an assumed time-harmonic behavior. Thus, the frequency-domain was admired over the time-domain. This is because the frequency-domain is more appropriate to obtain analytical solutions. However, the developed computational resources allows for more advanced time-domain CEM models. Therefore, the DE time-domain approaches are more convenient for adapting the computer simulation models without complicated mathematics.

As mentioned above, the capabilities of computational resources have been improved. The FDTD method has gained momentum as a tool for solving Maxwell's equations in the partial differential form. This is generally considered to be a convenient technique that can be implemented. To start the development of the FDTD method, Maxwell's time-domain equations with a specified field behavior over time can be performed as follows:

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}, \quad (2.3)$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} + \vec{M}, \quad (2.4)$$

$$\nabla \cdot \vec{D} = \rho_e, \quad (2.5)$$

$$\nabla \cdot \vec{B} = \rho_m, \quad (2.6)$$

where $\vec{E}$ is the electric field strength vector [V/m],

$\vec{D}$ is the electric displacement vector [C/m²],

$\vec{H}$ is the magnetic field strength vector [A/m],

$\vec{B}$ is the magnetic flux density vector [Wb/m² or T],

$\vec{J}$ is the electric current density vector [A/m²],

$\vec{M}$ is the magnetic current density vector [V/m²],

ρ_e is the electric charge density [C/ m³],

and ρ_m is the electric charge density [Wb/ m³].

Constitutive relations for linear, isotropic materials, and nondispersive materials can be written as below:

$$\vec{D} = \varepsilon \vec{E}, \quad (2.7)$$

$$\vec{B} = \mu \vec{H}, \quad (2.8)$$

where ε is the permittivity,

and μ is the permeability of the material.

In the free space:

$$\varepsilon = \varepsilon_0 \approx 8.854 \times 10^{-12} \text{ [F/m]},$$

$$\mu = \mu_0 = 4\pi \times 10^{-7} \text{ [H/m]}.$$

To decompose the current densities in Equations (2.3) to (2.6), the constructive relations in Equations (2.7) and (2.8) are substituted. Thus, Maxwell's curl equations can be rewritten as

$$\nabla \times \vec{H} = \varepsilon \frac{\partial \vec{E}}{\partial t} + \sigma^e \vec{E} + \vec{J}_i, \quad (2.9)$$

$$\nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} - \sigma^m \vec{H} + \vec{M}_i. \quad (2.10)$$

where σ^e is the electric conductivity [S/m],

σ^m is the magnetic conductivity [Ω /m],

$$\vec{J}_i = \vec{J} - \vec{J}_c,$$

$$\vec{J}_c = \sigma^e \vec{E},$$

$$\vec{J}_i = \vec{J} - \vec{J}_c,$$

$$\text{and } \vec{M}_c = \sigma^m \vec{H}.$$

The vector equations (2.9) and (2.10) are composed into three scalar equations for three-dimensional space. Therefore, Maxwell's curl equations can be represented with a system of six scalar equations with the Cartesian coordination (x, y, z) , which can be expressed as

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon_x} \left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} - \sigma_x^e E_x - J_{ix} \right), \quad (2.11)$$

$$\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon_y} \left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} - \sigma_y^e E_y - J_{iy} \right), \quad (2.12)$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon_z} \left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - \sigma_z^e E_z - J_{iz} \right), \quad (2.13)$$

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu_x} \left(\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} - \sigma_x^m H_x - M_{ix} \right), \quad (2.14)$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu_y} \left(\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} - \sigma_y^m H_y - M_{iy} \right), \quad (2.15)$$

$$\frac{\partial H_z}{\partial t} = \frac{1}{\mu_z} \left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x} - \sigma_z^m H_z - M_{iz} \right), \quad (2.16)$$

In 1966, Yee introduced a set of finite-difference equations for the time-dependent Maxwell's curl equations (Equations (2.11) to (2.16)) for the lossless materials cases [15], [16]. For a space point, the notations are repeated here and are generalized to three spatial dimensions. The space point in a uniform, rectangular lattice is denoted as

$$(i, j, k) = (i\Delta x, j\Delta y, k\Delta z) \quad (2.17)$$

The function u for space and time was evaluated at a discrete point in the grid and at a discrete point in time, which is denoted as

$$u_{i,j,k}^n = u(i\Delta x, j\Delta y, k\Delta z, n\Delta t) \quad (2.18)$$

where Δx , Δy , and Δz are the lattice space increments in the x , y , and z coordinate direction, respectively,

Δt is the time increment,

and i, j, k , and n are integers.

The centered finite-difference (central-difference) expressions for the space and time derivatives have a second-order accuracy. When considering the expression for the first partial space derivative of u in the x -direction, this was evaluated at the fixed time $t_n = n\Delta t$:

$$\frac{\partial u}{\partial x}(i\Delta x, j\Delta y, k\Delta z, n\Delta t) = \frac{u_{i+1/2,j,k}^n - u_{i-1/2,j,k}^n}{\Delta x} + O[(\Delta x)^2] \quad (2.19)$$

$$\frac{\partial u}{\partial t}(i\Delta x, j\Delta y, k\Delta z, n\Delta t) = \frac{u_{i,j,k}^{n+1/2} - u_{i,j,k}^{n-1/2}}{\Delta t} + O[(\Delta t)^2] \quad (2.20)$$

Equation (2.17) can be applied to all the space derivatives in Equations (2.11) to (2.16). The Yee positions of the components of E and H for a lattice cubic cell are shown in Fig. 2.10.

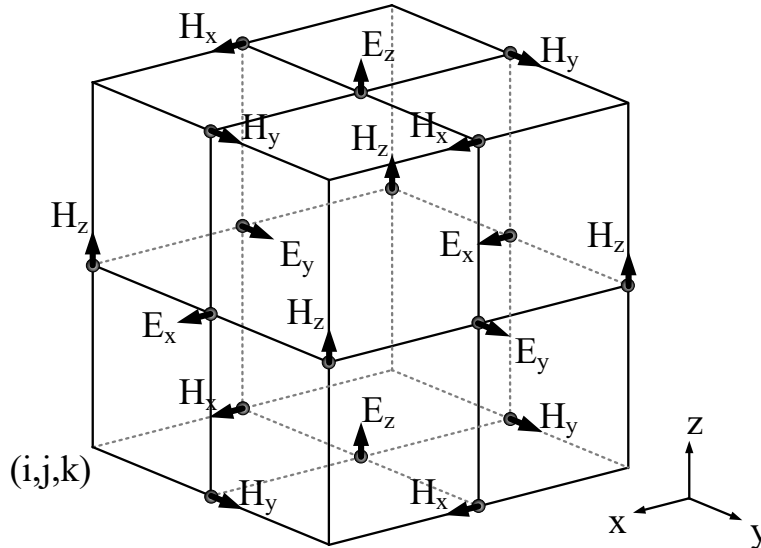


Fig. 2.10. Position of the electric and magnetic field vector components about a cubic cell for Yee's space lattice.

By combining Equation (2.18), the components of E and H are evaluated at alternate half-time steps. Thus, the explicit finite-difference approximation of Equations (2.11) to (2.16) can be expressed as

$$\begin{aligned}
E_x \Big|_{i,j+1/2,k+1/2}^{n+1/2} &= \left(\frac{1 - \frac{\sigma^e_{i,j+1/2,k+1/2} \Delta t}{2\varepsilon_{i,j+1/2,k+1/2}}}{1 + \frac{\sigma^e_{i,j+1/2,k+1/2} \Delta t}{2\varepsilon_{i,j+1/2,k+1/2}}} \right) E_x \Big|_{i,j+1/2,k+1/2}^{n-1/2} \\
&+ \left(\frac{\Delta t}{\varepsilon_{i,j+1/2,k+1/2}} \right) \left(\frac{H_z \Big|_{i,j+1,k+1/2}^n - H_z \Big|_{i,j,k+1/2}^n}{\Delta y} \right. \\
&\quad \left. - \frac{H_y \Big|_{i,j+1/2,k+1}^n - H_y \Big|_{i,j+1/2,k}^n}{\Delta z} - J_{ix} \Big|_{i,j+1/2,k+1/2}^n \right)
\end{aligned} \tag{2.21}$$

$$\begin{aligned}
E_y \Big|_{i-1/2,j+1,k+1/2}^{n+1/2} &= \left(\frac{1 - \frac{\sigma^e_{i-1/2,j+1,k+1/2} \Delta t}{2\varepsilon_{i-1/2,j+1,k+1/2}}}{1 + \frac{\sigma^e_{i-1/2,j+1,k+1/2} \Delta t}{2\varepsilon_{i-1/2,j+1,k+1/2}}} \right) E_y \Big|_{i-1/2,j+1,k+1/2}^{n-1/2} \\
&+ \left(\frac{\Delta t}{\varepsilon_{i-1/2,j+1,k+1/2}} \right) \left(\frac{H_x \Big|_{i-1/2,j+1,k+1}^n - H_x \Big|_{i-1/2,j+1,k}^n}{\Delta z} \right. \\
&\quad \left. - \frac{H_z \Big|_{i,j+1,k+1/2}^n - H_z \Big|_{i-1,j+1,k+1/2}^n}{\Delta x} - J_{iy} \Big|_{i-1/2,j+1,k+1/2}^n \right)
\end{aligned} \tag{2.22}$$

$$\begin{aligned}
E_z \Big|_{i-1/2, j+1/2, k+1}^{n+1/2} &= \left(\frac{1 - \frac{\sigma^e_{i-1/2, j+1/2, k+1} \Delta t}{2\varepsilon_{i-1/2, j+1/2, k+1}}}{1 + \frac{\sigma^e_{i-1/2, j+1/2, k+1} \Delta t}{2\varepsilon_{i-1/2, j+1/2, k+1}}} \right) E_z \Big|_{i-1/2, j+1/2, k+1}^{n-1/2} \\
&+ \left(\frac{\frac{\Delta t}{\varepsilon_{i-1/2, j+1/2, k+1}}}{1 + \frac{\sigma^e_{i-1/2, j+1/2, k+1} \Delta t}{2\varepsilon_{i-1/2, j+1/2, k+1}}} \right) \left(\frac{H_y \Big|_{i, j+1/2, k+1}^n - H_y \Big|_{i-1, j+1/2, k+1}^n}{\Delta x} \right. \\
&\quad \left. - \frac{H_x \Big|_{i-1/2, j+1, k+1}^n - H_x \Big|_{i-1/2, j, k+1}^n}{\Delta y} - J_{iz} \Big|_{i-1/2, j+1/2, k+1}^n \right)
\end{aligned} \tag{2.23}$$

$$\begin{aligned}
H_x \Big|_{i-1/2, j+1, k+1}^{n+1} &= \left(\frac{1 - \frac{\sigma^m_{i-1/2, j+1, k+1} \Delta t}{2\mu_{i-1/2, j+1, k+1}}}{1 + \frac{\sigma^m_{i-1/2, j+1, k+1} \Delta t}{2\mu_{i-1/2, j+1, k+1}}} \right) H_x \Big|_{i-1/2, j+1, k+1}^n \\
&+ \left(\frac{\frac{\Delta t}{\mu_{i-1/2, j+1, k+1}}}{1 + \frac{\sigma^m_{i-1/2, j+1, k+1} \Delta t}{2\mu_{i-1/2, j+1, k+1}}} \right) \left(\frac{E_y \Big|_{i-1/2, j+1, k+3/2}^{n+1/2} - E_y \Big|_{i-1/2, j+1, k+1/2}^{n+1/2}}{\Delta z} \right. \\
&\quad \left. - \frac{E_z \Big|_{i-1/2, j+3/2, k+1}^{n+1/2} - E_z \Big|_{i-1/2, j+1/2, k+1}^{n+1/2}}{\Delta y} - M_{ix} \Big|_{i-1/2, j+1, k+1}^{n+1/2} \right)
\end{aligned} \tag{2.24}$$

$$\begin{aligned}
H_y \Big|_{i, j+1/2, k+1}^{n+1} &= \left(\frac{1 - \frac{\sigma^m_{i, j+1/2, k+1} \Delta t}{2\mu_{i, j+1/2, k+1}}}{1 + \frac{\sigma^m_{i, j+1/2, k+1} \Delta t}{2\mu_{i, j+1/2, k+1}}} \right) H_y \Big|_{i, j+1/2, k+1}^n \\
&+ \left(\frac{\frac{\Delta t}{\mu_{i, j+1/2, k+1}}}{1 + \frac{\sigma^m_{i, j+1/2, k+1} \Delta t}{2\mu_{i, j+1/2, k+1}}} \right) \left(\frac{E_z \Big|_{i+1/2, j+1/2, k+1}^{n+1/2} - E_z \Big|_{i-1/2, j+1/2, k+1}^{n+1/2}}{\Delta x} \right. \\
&\quad \left. - \frac{E_x \Big|_{i, j+1/2, k+3/2}^{n+1/2} - E_x \Big|_{i, j+1/2, k+1/2}^{n+1/2}}{\Delta z} - M_{iy} \Big|_{i, j+1/2, k+1}^{n+1/2} \right)
\end{aligned} \tag{2.25}$$

$$\begin{aligned}
H_z \Big|_{i,j+1,k+1/2}^{n+1} &= \left(\frac{1 - \frac{\sigma_{i,j+1,k+1/2}^m \Delta t}{2\mu_{i,j+1,k+1/2}}}{1 + \frac{\sigma_{i,j+1,k+1/2}^m \Delta t}{2\mu_{i,j+1,k+1/2}}} \right) H_z \Big|_{i,j+1,k+1/2}^n \\
&+ \left(\frac{\frac{\Delta t}{\mu_{i,j+1,k+1/2}}}{1 + \frac{\sigma_{i,j+1,k+1/2}^m \Delta t}{2\mu_{i,j+1,k+1/2}}} \right) \left(\frac{E_x \Big|_{i,j+3/2,k+1/2}^{n+1/2} - E_x \Big|_{i,j+1/2,k+1/2}^{n+1/2}}{\Delta y} \right. \\
&\quad \left. - \frac{E_y \Big|_{i,+1/2,j+1,k+1/2}^{n+1/2} - E_y \Big|_{i-1/2,j+1,k+1/2}^{n+1/2}}{\Delta x} - M_{iz} \Big|_{i,j+1,k+1/2}^{n+1/2} \right)
\end{aligned} \tag{2.26}$$

From the systems of the finite-difference expressions as stated in Equations (2.19) to (2.26), the new value of the electromagnetic field vector component at any lattice point depends on its previous value. Thus, at any execution time step, the computation of a field vector can proceed one point at a time.

CHAPTER 3

THE PROPOSED CONCEPT

It is difficult for the maintenance engineer to observe and detect the disconnected location of a down conductor in wind turbine blades without the trial-and-error approach. This chapter explains the proposed concept, which consists of the proposed techniques that uses the change in the electrostatic capacitance and the half-wave dipole-antenna theory. With the help of the FDTD, simulation models of the down conductors are employed to calculate the capacitance values and the current distributions along the down conductors while changing their disconnected locations. In both techniques, the VSTL software is employed to simulate the simulation models. One of the down conductor's lengths varies from the root to the maximum length to simulate the disconnected location. Then, the capacitance values are obtained by solving Equation (3.9) and the resonant peak currents from the half-wave dipole-antenna are used to create the length–current and length–capacitance coordination curves. The procedure and the model configurations are described in Sections 3.2 and 3.3.

3.1 Effect of the Characteristic Impedance

The characteristic impedance for tall towers should be considered when applying the proposed techniques to create the FDTD simulation model. This is because the characteristic impedance of the towers can affect the accuracy of

the capacitance. In addition, the peak of the resonance current of the dipole-antenna is based on calculations. It is known that the FDTD simulation model slices the analyzed space into cubic cells. Thus, it is impossible to produce a conical tower of the wind turbine with precise dimensions. To study the characteristic impedance, the well-known equations of a vertical line above the earth's surface, as illustrated in Fig. 3.1, represents the wind turbine tower. It is focused and the accuracies of these formulas are compared with the measured results from the tower models.

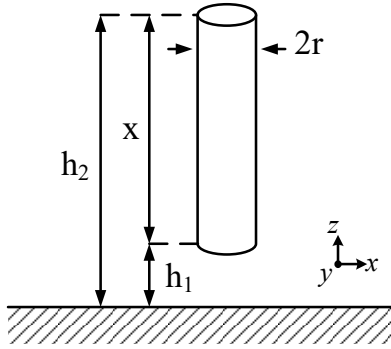


Fig. 3.1. A vertical line.

From Fig. 3.1, the well-known equations, when the bottom height of the line (h_1) is equal to zero (and it stands on the perfectly conducting earth with $\rho_e = 0 \Omega m$), are as follows:

(1) Sargent and Darveniza [17]:

$$Z_s = 60 \ln \left(\sqrt{2} \frac{ct}{r} \right) - 60, \quad (3.1)$$

where $t = 2h/c$ gives the value for two travel times.

(2) Menemenlis/Chun [18]:

$$Z_m = 50 + 35\sqrt{h} \quad (3.2)$$

(3) Hara et al. [19], [20]:

$$Z_h = 60[\ln(h/r) - 1] + 2.4 \quad (3.3)$$

(4) Jordan [21]:

$$Z_J = 60[\ln(h/r) - 1] + 90r/h \quad (3.4)$$

(5) Takahashi [22]:

$$Z_T = 60[\ln(4h/r) - 1] \quad (3.5)$$

(6) Gutierrez et al. [23]:

$$Z_G = 30\ln(2h/r) \quad (3.6)$$

(7) Conti et al. [24]:

$$Z_c = 60 \left[\ln \frac{2h + \sqrt{4h^2 + r^2}}{r} - \sqrt{1 + \left(\frac{r}{2h} \right)^2} + \frac{r}{2h} \right] \quad (3.7)$$

(8) Rogers and White [25]:

$$Z_r = 60 \left[\ln \frac{\left(\sqrt{r^2 + h^2} + h \right)^2}{r \left(\sqrt{r^2 + (2h)^2} + 2h \right)} + \frac{1}{2h} \left(3r + \sqrt{r^2 + (2h)^2} - 4\sqrt{r^2 + h^2} \right) \right] \quad (3.8)$$

When applying the aforementioned equations to calculate the preliminary characteristic impedance, a comparison of the mentioned equations with the measured results are given in Table 3.1.

Table 3.1 Comparison of the measured and theoretical surge impedances

Measured				Calculated surge impedances by existing formulas							
Ref	Height h [m]	Radius [mm]	Impedance Z [Ω]	Sargent	Menemenlis	Hara	Jordan	Takahashi	Gutierrez	Conti	Rogers
[17]	0.608	1.175	310	377.3	77.3	317.3	315.1	398.1	208.3	398.2	315.1
	0.608	3.113	250	318.9	77.3	258.9	256.9	339.7	179.0	339.8	256.9
	0.608	9.45	180	252.2	77.3	192.2	191.2	273.0	145.7	273.5	191.2
	0.608	43.375	112	160.8	77.3	100.8	104.8	181.6	100.0	183.7	104.7
[19]	2	0.25	481	541.6	99.5	481.6	479.2	562.4	290.4	562.4	479.2
	2	2.5	345	403.5	99.5	343.5	341.2	424.3	221.3	424.3	341.2
	3	0.25	514	566.0	110.6	506.0	503.6	586.7	302.6	586.7	503.6
	3	2.5	373	427.8	110.6	367.8	365.5	448.6	233.5	448.6	365.5
	3	15	250	320.3	110.6	260.3	258.3	341.1	179.7	341.2	258.3
	3	25	235	289.6	110.6	229.6	228.0	310.4	164.4	310.7	228.0
	3	50	181	248.1	110.6	188.1	187.2	268.8	143.6	269.3	187.2
	15	2.5	0.0025	459	524.4	185.6	462.0	545.1	281.8	545.2	462.0
	15	25.4	0.0254	320	385.3	185.6	323.0	406.0	212.2	406.1	323.0
Average difference [%]				23.9	60.0	3.0	2.9	31.9	30.5	32.1	2.6

From the comparison results in Table 3.1, it is determined that there is a slightly different radius at the same height, thus resulting in a minimal variation in the impedance, which is acceptable. Therefore, the calculation results from the FDTD method still provides a good accuracy. However, if the comparison

results are considered, some of the equations are not sufficiently accurate. From this achievement, it is useful for this study to predict the surge impedance of the wind turbine structures in the future with a more rigorous model, such as the two-stair tower model based on the ABCD parameters [26].

3.2 Application of the Detection Technique Using the Change in the Electrostatic Capacitance

The detection techniques using the change in the electrostatic capacitance between two down conductors for the wind turbine blades and the electrostatic capacitance between the tower body and the down conductor can be used for detecting the disconnected location of the down conductor. This can be achieved by applying the concept of the object that can store the electric charge as mentioned in the previous chapter. However, because the capacitance cannot be directly obtained from a simulation through a software program, a direct current (*DC*) source and a resistor connected in series must be inserted between two down conductors. In addition, a *DC* source and a resistor connected in series needs to be placed between the wind turbine tower body and a down conductor. This configuration can be viewed as a capacitor. The complete circuit can be regarded as a resistor-capacitor circuit as shown in Fig. 3.2.

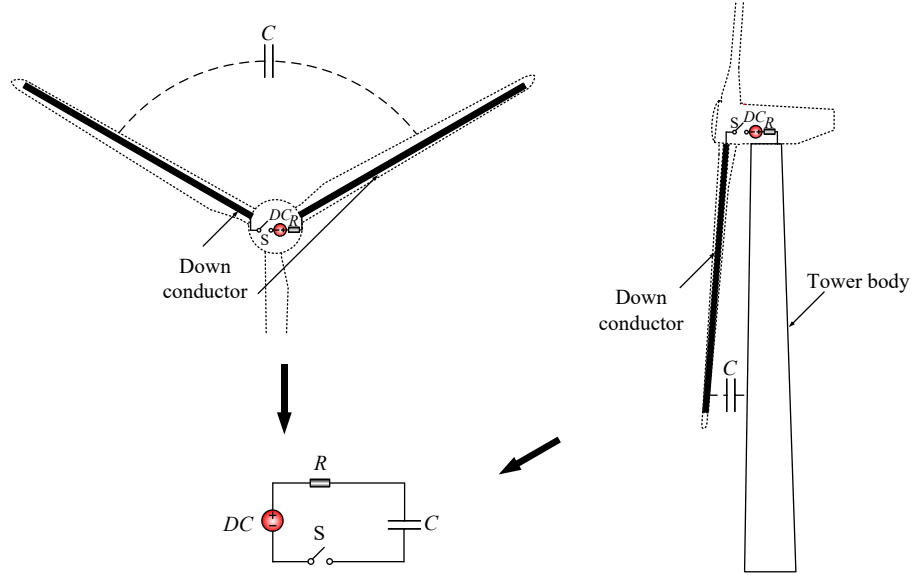


Fig. 3.2. Equivalent circuit of the RC series circuit.

According to Fig. 3.2, the capacitance can be obtained by solving the transient current that flows through the circuit by using the solution of the Gauss-Newton method. This method minimizes the sum squares of the residuals between the simulation results and the transient current equation [27]. The transient current of the RC series circuit can be explained by:

$$i(t) = \frac{E}{R} e^{-\frac{t}{RC}}, \quad (3.9)$$

where $i(t)$ is the current flowing through the circuit [A],

E is the supply voltage [V],

R is the resistance value of the series resistor [Ω],

and C is the capacitance value [F].

Thus, the capacitance value can be approached by:

$$\left[\left[Z_j \right]^T \left[Z_j \right] \right] \{ \Delta A \} = \left\{ \left[\left[Z_j \right]^T \{ D \} \right] \right\}, \quad (3.10)$$

where $[Z_j]$ is the vector of the partial derivatives of the function evaluated at the initial guess j ,

$\{ \Delta A \}$ is the vector of the changes in the parameter values,

and $\{ D \}$ is the vector of the differences between the measurements and the function values.

Because Equation (3.9) is a nonlinear equation, the solution must proceed iteratively. The iteration is stopped when Equation (3.11) falls below the acceptable stopping criterion, then the solution of Equation (3.9) is obtained.

$$|\varepsilon_a| = \left| \frac{a_{j+1} - a_j}{a_{j+1}} \right| 100\%, \quad (3.11)$$

As aforementioned, the simulation models of the four types of wind turbines were performed to show the validity of this proposed technique.

3.2.1 Reduced scale model

In Fig. 3.3, the procedure for applying the presented techniques to determine the disconnected locations is shown. The dimensions of the analytical space and the spatial step size are set to $1 \text{ m} \times 2 \text{ m} \times 1 \text{ m}$ and 0.01 m , respectively. The down conductor's radii were set to 1.3 mm . To simulate the

disconnected location, the length of the down conductor B varies between 0.0 m to 0.9 m, and the length of the down conductor A is fixed to 0.9 m. The charging voltage and resistance were set to 100 V and 10 k Ω , respectively. However, because of the FDTD method, the analyzed space was divided into cubic cells and the electromagnetic field was calculated for every discrete cell [15], [16]. Therefore, the down conductors were reproduced by employing a staircase function, as illustrated in Fig. 3.4.

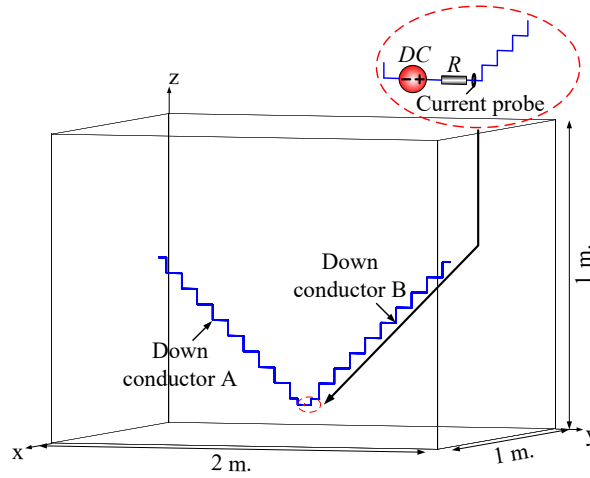


Fig. 3.3. Analytical space of the reduced scale model when applying the electrostatic capacitance between two down conductors.

The straight line that passes through the center of the approximated step function is the down conductor. The length of the straight line is considered to be the length of the down conductor.

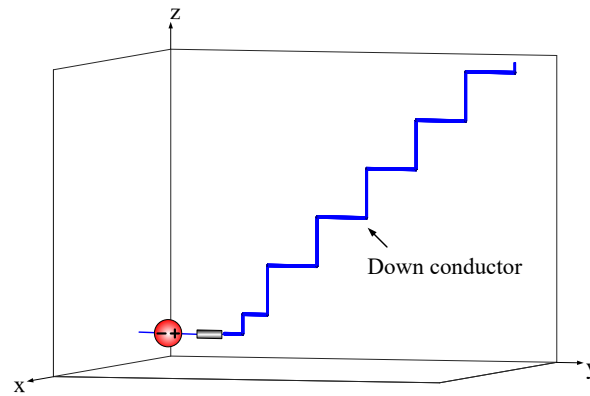


Fig. 3.4. Staircase approximation for the down conductor.

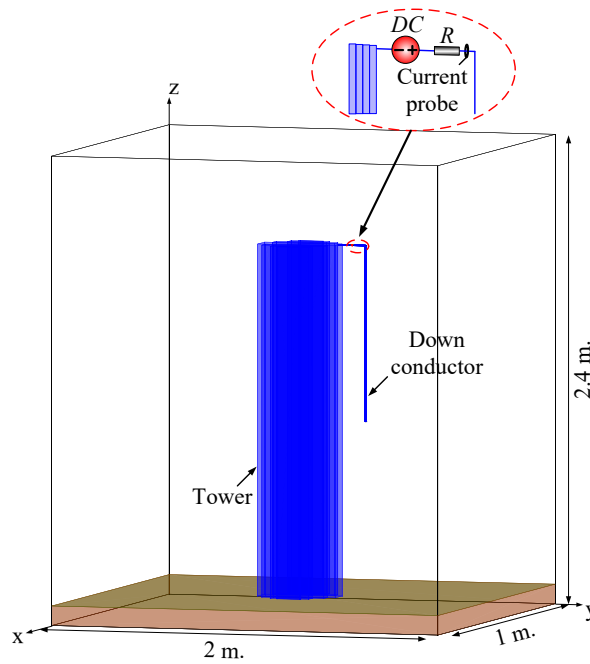


Fig. 3.5. Analytical space of the reduced-scale model when applying the electrostatic capacitance between the tower body and a down conductor.

For the proposed technique that uses the electrostatic capacitance between the tower body and the down conductor, the simulation model of the

down conductor was set in parallel to the tower body, as presented in Fig. 3.5. The analytical space and the spatial step size were set to $1\text{ m} \times 1\text{ m} \times 2.4\text{ m}$ and 0.01 m , respectively. The *DC* input voltage was set to 100 V , and the resistor had a resistance of $10\text{ k}\Omega$. The resistivity of the earth and the relative permittivity were set to $100\text{ }\Omega\text{m}$ and 10 , respectively. The tower height of 1.8 m was modeled by using rectangular objects. The length of the down conductor that is parallel to the tower body varied between 0.0 m to 0.9 m .

3.2.2 Small wind turbine

The down conductors and the tower body were modeled using the FDTD method (analogous to the previous part) to calculate the transient current that flows through the RC circuits. In these simulations, the down conductors (with a radius of 1.3 mm) were set in all cases. As illustrated in Fig. 3.6, the analytical space of $20\text{ m} \times 40\text{ m} \times 10\text{ m}$ was divided into $100 \times 200 \times 50$ cells, and there was a spatial step size of 0.2 m in the x , y , and z directions. The input peak voltage of the *DC* charging voltage and the series resistor were 100 V and $5\text{ k}\Omega$, respectively.

Fig. 3.7 shows the analytical space of the small wind turbine when applying an electrostatic capacitance between the tower body and the down conductor. The analytical space and the spatial step size were set to $6.5\text{ m} \times 10\text{ m} \times 39\text{ m}$ and 0.1 m , respectively. The tower height of 35 m was reproduced. The resistivity of the earth was $100\text{ }\Omega\text{m}$ and a relative permittivity of 10 were set in the simulation model. In a similar manner, the length of the down conductor varied from its root to the maximum length to simulate the disconnected location.

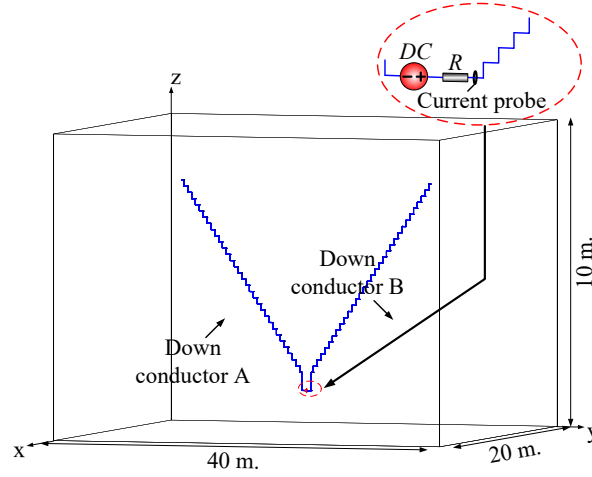


Fig. 3.6. Analytical space of the small wind turbine when applying an electrostatic capacitance between the two down conductors.

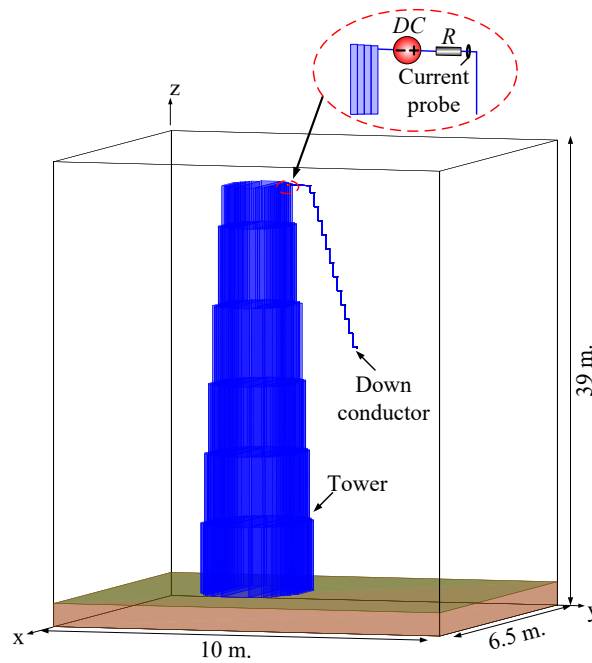


Fig. 3.7. Analytical space of a small wind turbine when applying an electrostatic capacitance between a tower body and a down conductor.

3.2.3 Mitsubishi MWT-1000A

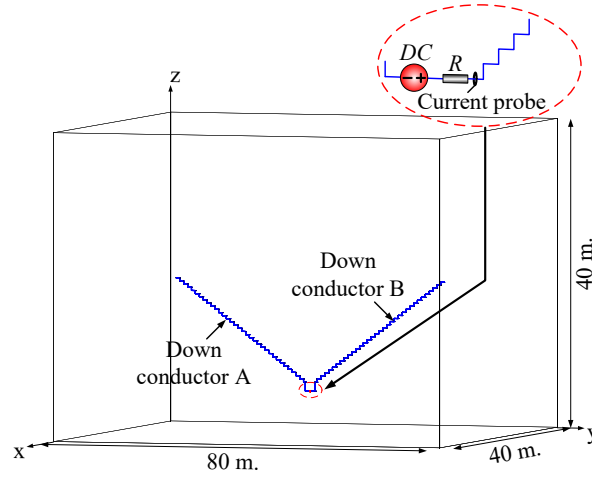


Fig. 3.8. Analytical space of the Mitsubishi MWT-1000A when applying the electrostatic capacitance between the two down conductors.

Similarly, the FDTD method was employed to model the down conductors and the tower body to calculate the transient current. With the Mitsubishi manufacturer data [28], the down conductors and the tower body of the wind turbine were reproduced. The dimensions of the analytical space were set to $40 \text{ m} \times 80 \text{ m} \times 40 \text{ m}$ and it was divided into the cells with a side length of 0.4 m, as shown in Fig. 3.8. In the simulation, the *DC* voltage of 100 V and a resistor of $5 \text{ k}\Omega$ were connected between two down conductors. The down conductor's radii were set to 5.4 mm to reproduce the down conductor of the wind turbine. The length of down conductor B varied from 0 m to 29.5 m, and the length of down conductor A was 29.5 m.

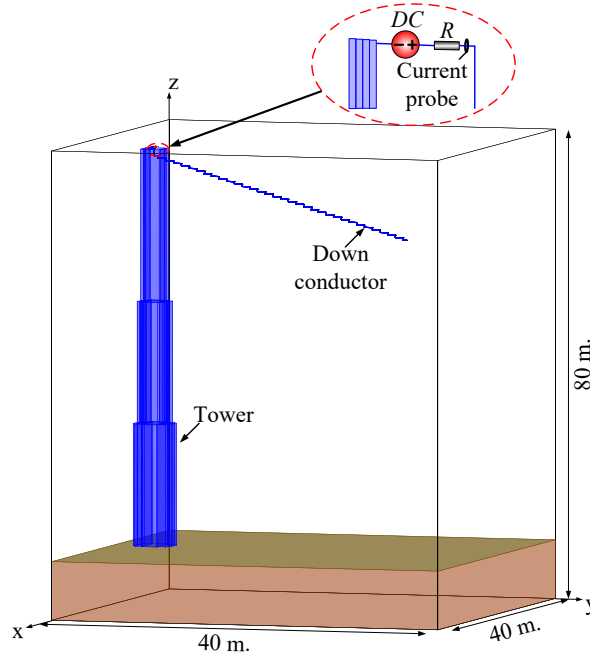


Fig. 3.9. Analytical space of the Mitsubishi MWT-1000A when applying the electrostatic capacitance between the tower body and the down conductor.

As depicted in Fig. 3.9, the analytical space and the spatial step size were set to $40\text{ m} \times 40\text{ m} \times 80\text{ m}$ and 0.4 m , respectively. Due to the configuration of the wind turbine [28], the tower body and the down conductor were set up at a 60-degree angle in the simulation. The input peak voltage of the *DC* charging voltage, series resistance, soil resistivity, and the relative permittivity of the soil were 100 V , $5\text{ k}\Omega$, $100\text{ }\Omega\text{m}$, and 10 , respectively. The length of the down conductor varied from the root to the maximum length.

3.2.4 Gamesa G80-2.0 MW

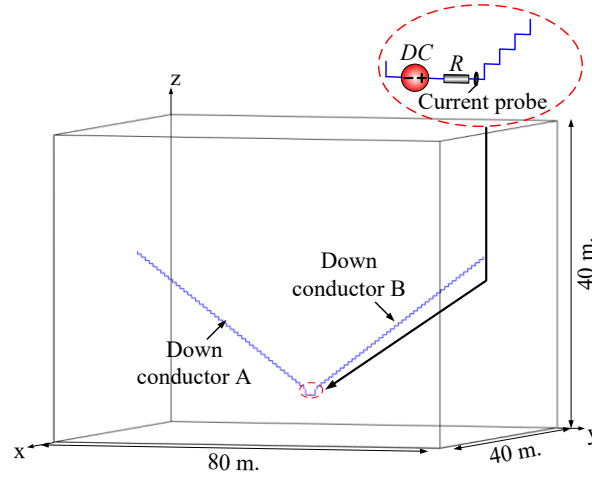


Fig. 3.10. Analytical space of the Gamesa G80-2.0 MW when applying the electrostatic capacitance between two down conductors.

The simulation models that used the Gamesa G80-2.0 MW [29] (with a tower height of 60 m, a blade length of 39 m, and the down conductor's radii of 5.4 mm) wind turbines are displayed in Figs. 3.10 and 3.11. From Fig. 3.10, the dimensions of the analytical space were set to $40 \text{ m} \times 80 \text{ m} \times 40 \text{ m}$, and it was divided into the cells with a spatial step size of 0.4 m. Similarly, the *DC* voltage source of 100 V and a resistance of 5 k Ω were placed between the down conductors. The length of down conductor B varied from 0 m to 39 m, and the length of down conductor A was 39 m. Fig. 3.11 presents the dimensions of the analytical space of $40 \text{ m} \times 40 \text{ m} \times 80 \text{ m}$ with the spatial step size of 0.4 m. The resistivity of the earth was set to 100 Ωm , and the soil permittivity was equal to 10. The length of the down conductor that is parallel to the tower body varied from the root to the maximum length.

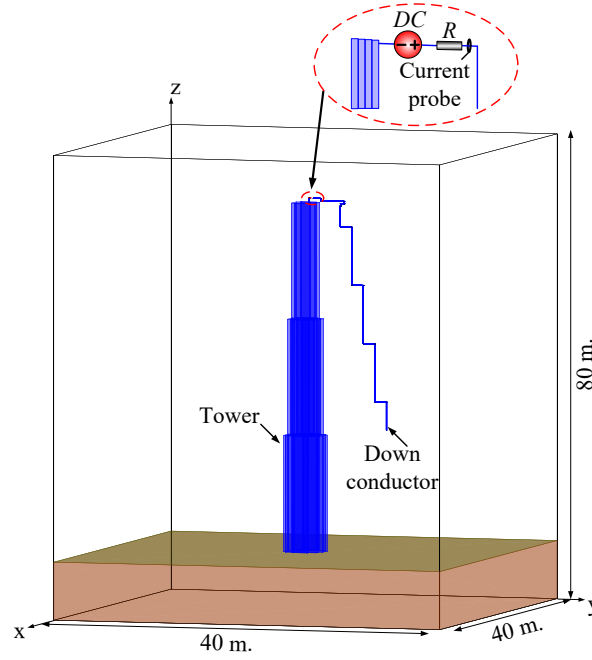


Fig. 3.11. Analytical space of the Gamesa G80-2.0 MW when applying the electrostatic capacitance between the tower body and the down conductor.

3.3 Application of the Detection Technique Using the Half-Wave Dipole-antenna Theory

As mentioned in the previous chapter, the pair of down conductors can be considered to act as a dipole-antenna. This is because the pair of down conductors applies a continuous waveform (*CW*) source with the resonance frequency between them.

3.3.1 Reduced scale model

The analytical setup is shown in Fig. 3.12. The dimensions of the analytical space and the spatial step size were set to $1 \text{ m} \times 2 \text{ m} \times 1 \text{ m}$ and 0.01

m, respectively. The input peak voltage was set to 1.4 V, and the resonance frequency was estimated using Equation (2.2). Then, the trial-and-error approach was employed to select the appropriate resonance frequency for the maximum length of the down conductors. The obtained frequency was set as the input frequency for the *CW* source for all simulations. To simulate the disconnected location, the length of the down conductor B varied between 0.0 m to 0.9 m, and the length of the down conductor A was set to 0.9 m.

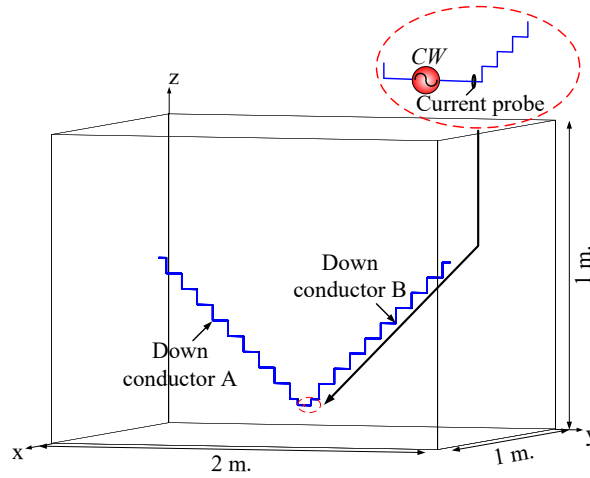


Fig. 3.12. Analytical space of the reduced-scale model when applying the half-wave dipole-antenna theory.

3.2.2 Small wind turbine

The analytical setup is presented in Fig. 3.13. The dimensions of the analytical space and spatial step size were set to $20 \text{ m} \times 40 \text{ m} \times 10 \text{ m}$ and 0.2 m, respectively. In the simulation, the input peak voltage of the *CW* source was set to 14 V. The obtained frequency from the trial-and-error approach of 3.7

MHz was set to the source frequency. In a similar manner, the length of down conductor B varied from 0 m to 14 m to simulate the disconnected location.

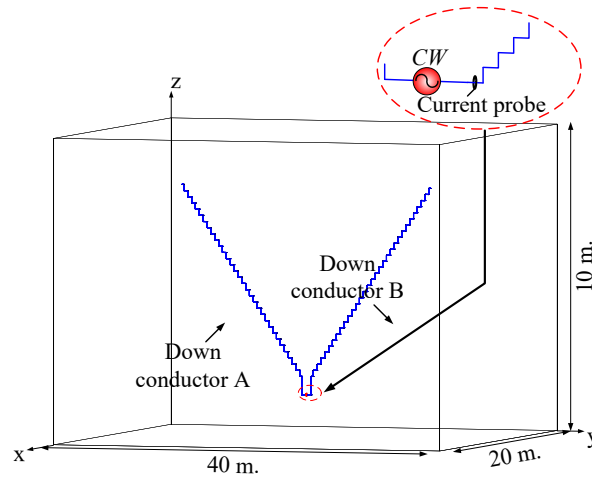


Fig. 3.13. Analytical space of the small wind turbine when applying the half-wave dipole-antenna.

3.3.3 Mitsubishi MWT-1000A

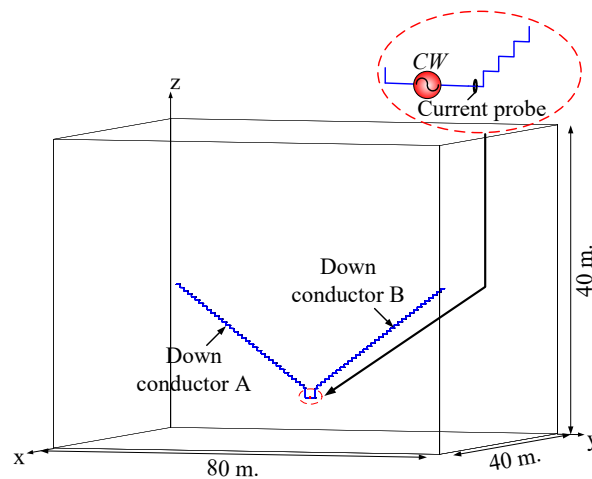


Fig. 3.14. Analytical space of the Mitsubishi MWT-1000A when applying the half-wave dipole-antenna.

As demonstrated in Fig. 3.14, the dimensions of the analytical space was configured to $40 \text{ m} \times 80 \text{ m} \times 40 \text{ m}$ with a spatial step size of 0.4 m . The input peak voltage of the *CW* source and the resonance frequency were set to 14 V and 1.89 MHz , respectively. The length of down conductor B varied from 0 m to 29.5 m , and the other had its maximum length fixed [28].

3.3.4 Gamesa G80-2.0 MW

According to the dimensions of the wind turbine [29], the dimensions of the analytical space of $40 \text{ m} \times 80 \text{ m} \times 40 \text{ m}$ and the spatial step size of 0.4 m were modeled as depicted in Fig. 3.15. Similarly, the length of down conductor B varied from 0 m to 39 m to simulate the disconnected location. The peak voltage of 14 V and the resonance frequency of 1.49 MHz were set to the *CW* source.

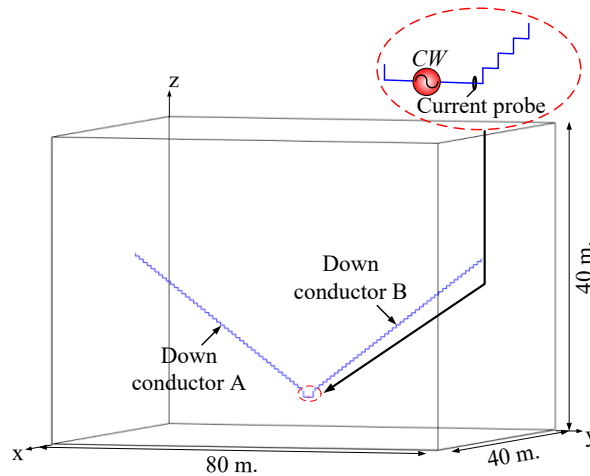


Fig. 3.15. Analytical space of the Gamesa G80-2.0 MW when applying the half-wave dipole-antenna.

3.4 Application of the Detection Technique Using the Propagation Method

Wave propagation is a simple and a highly efficient technique to check the disconnection or the failure of the conductors. In this study, this propagation method was used to detect the disconnection of the down conductors in the wind turbine blades by applying a high-steepness front-wave and a long duration to the down conductor. According to the behavior traveling wave, an open circuit at the end of a conductor demands that the current at that point is equal to zero at all times. In addition, the traveling time includes the reflected wave that travels towards the source with the reflected voltage. This can be determined as 2τ . Therefore, if there is a disconnection, the traveling time is shorter than the normal conductor. In the experiment, a long duration with a high-steepness wave-front from a pulse generator was used to inject the down conductor. Then, the waveform, which includes the reflected wave, was measured. The pulse generator has two terminals: positive polarity and negative polarity. Therefore, the effect of the grounding wire length must be considered because the measured waveform has a possibility that it might be canceled. This is because the same traveling time and the magnitude of the reflected waveform from the two polarities meet at the measured point. The FDTD simulation models were employed to study the effect of the grounding wire length. For this investigation, three cases of the FDTD simulation models were considered. First, the simulation model had two down conductors that connected to the pulse generator and they were not connected to the ground. In this simulation, one of the conductor lengths varied from the root to a length that was longer than the other conductor. As demonstrated in Fig. 3.16, the dimensions of the analytical space were configured to $80\text{ m} \times 40\text{ m} \times 80\text{ m}$ with a spatial step size of 0.4 m .

The input peak voltage of the pulse waveform was set to 40 V. The length of conductor B varied from 0 m to 58.8 m and the other was fixed to 39.2 m.

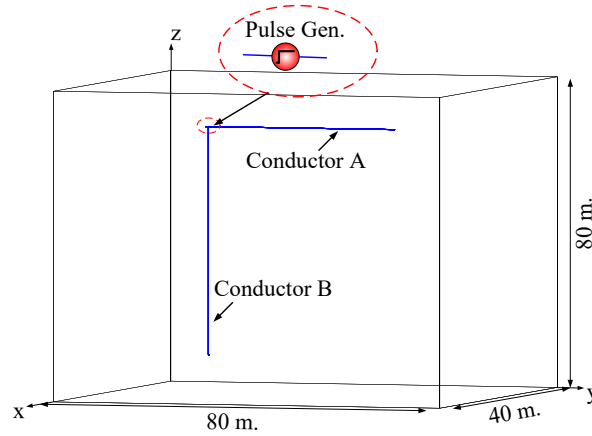


Fig. 3.16. Analytical space for the injected step waveform for two conductors (open circuit of both conductors).

In the second simulation case, the FDTD simulation model was like the previous case; however, conductor B was connected to the ground. For the analytical space as displayed in Fig. 3.17, the dimensions of the analytical space and the spatial step size were set to $40 \text{ m} \times 80 \text{ m} \times 80 \text{ m}$ and 0.4 m, respectively. The resistivity of the earth was set to $100 \Omega\text{m}$ and the permittivity was set to 10, respectively. The length of conductor B varied from 0 m to 58.8 m and the length of conductor A was fixed as 39.2 m.

In the third simulation case, the FDTD simulation model had a similar performance as the wind turbine towers. Conductor A was set in parallel to the tower body and conductor B was connected to the tower. In this simulation, the tower was created in the shape of a cylinder that has a hole in the middle. Conductor B passed through the hole to check the effect of the conductor length.

In the same manner, conductor B varied from 0 to 58.8 m. As illustrated in Fig. 3.18, the analytical space of $40\text{ m} \times 40\text{ m} \times 80\text{ m}$ was divided into $100 \times 100 \times 200$ cells, with a step size of 0.4 m in the x , y , and z directions. The input peak voltage of the pulse voltage, the resistivity of the earth, and the permittivity were 40 V , $100\ \Omega\text{m}$, and 10 , respectively.

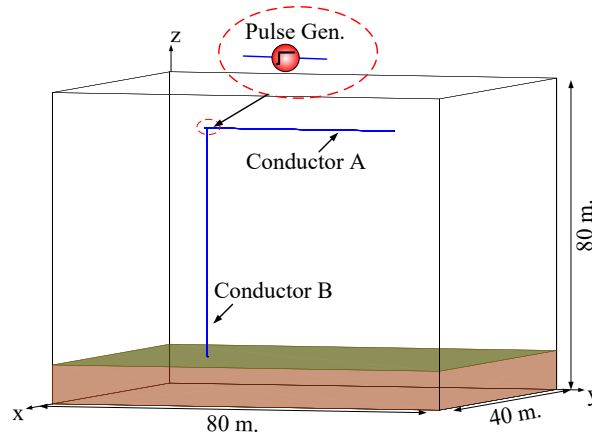


Fig. 3.17. Analytical space for the injected step waveform in two conductors (conductor B is connected to the ground).

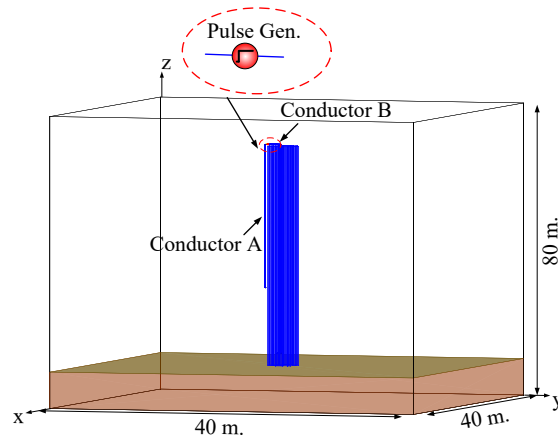


Fig. 3.18. Analytical space for the step waveform in two conductors (conductor B is connected to the tower).

CHAPTER 4

SIMULATION AND EXPERIMENTAL RESULTS

This chapter includes the simulation and the experimental results when applying the proposed techniques for the electrostatic capacitance and the half-wave dipole-antenna. The experiments were carried out on the reduced scale model. The small wind turbine was used to examine the performance of the presented techniques. Moreover, these techniques were employed to detect the disconnected locations of the down conductors in the wind turbine blades of the Mitsubishi MWT-1000A and the Gamesa G80-2.0 MW. The propagation method was used to confirm the validity of the estimated results.

4.1 Reduced Scale Model

To apply the proposed techniques, as mentioned in Sections 2.3.1 and 2.3.2, the FDTD simulation models described in Sections 3.2.1 and Section 3.3.1 were considered. In the case of the electrostatic capacitance between the two down conductors, the FDTD simulation model (Fig. 3.3) was employed to calculate the transient current waveforms when the length of the down conductor B varied from 0.0 m to 0.9 m. As illustrated in Fig. 4.1, the transient current waveforms obtained by the FDTD simulation and the approximated transient current waveforms obtained by solving Equations (3.9) to (3.11) for approaching the capacitance from the simulation results are represented by the solid blue line and the dotted red line, respectively.

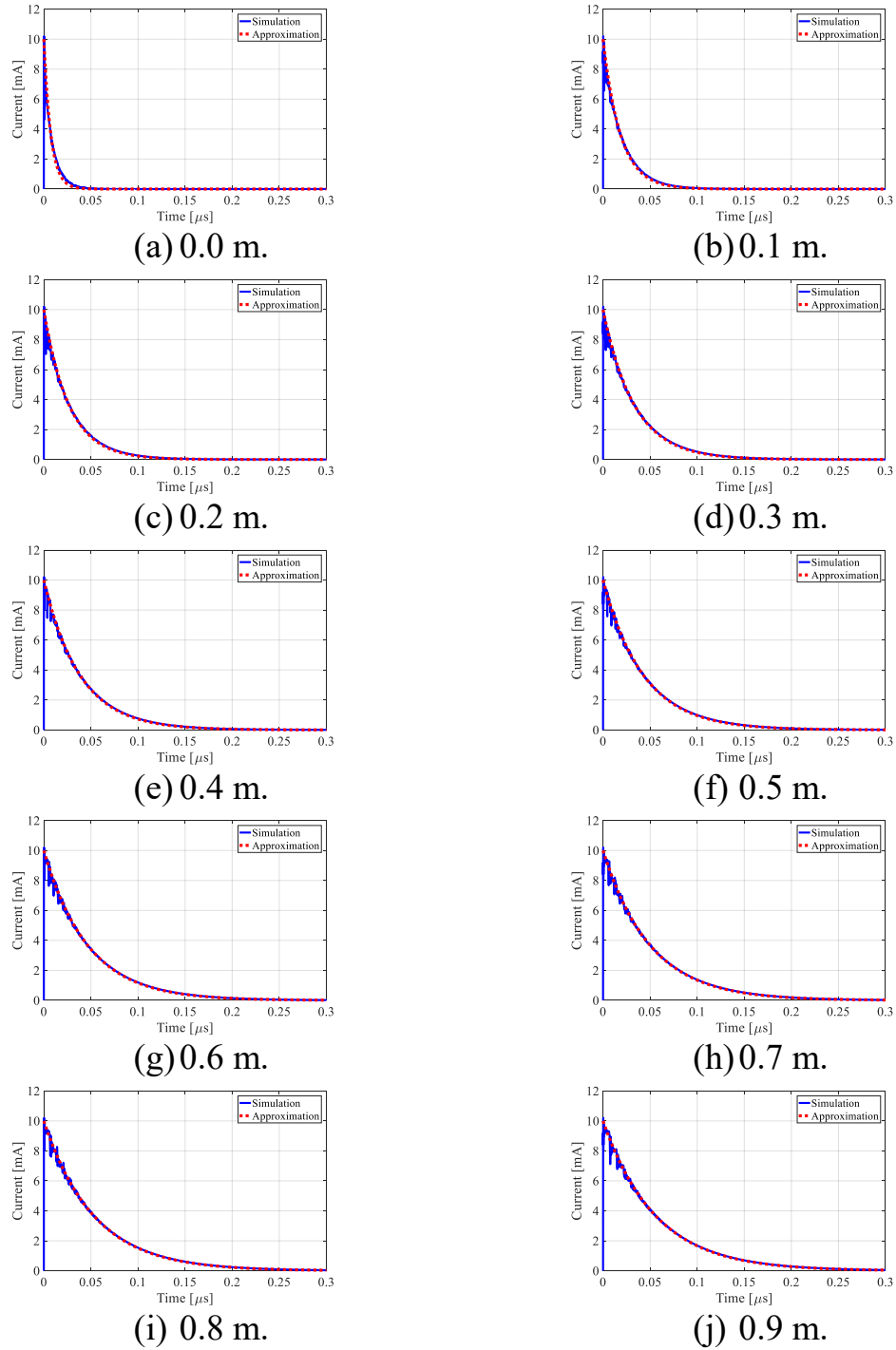


Fig. 4.1. Transient current waveforms: the length of down conductor B, the charging voltage, and the series resistance varied from 0.0 m to 0.9 m, 100 V, and 10 k Ω , respectively.

To evaluate the performance of the simulation results, the experiments were carried out in a laboratory that was set up with the same scale as the simulations (a down conductor length of 0.9 m and a down conductor's radii of 1.3 mm). An LCR-meter at a frequency of 10 kHz was used to measure the capacitance between the two down conductors. A comparison of the capacitance values from the simulation and the experiment with the varying down conductor lengths is provided in Table 4.1. The simulation and experimental results are denoted by the blue and red dots, respectively. The trends were obtained through the best-fit curves of these results, as illustrated in Fig. 4.2.

Table 4.1 Comparison of the capacitance values obtained by the simulation and the experiment when applying the electrostatic capacitance between the two down conductors for the reduced scale model

Length [m]	Capacitance [pF]	
	Simulation	Experiment
0.0	0.74	1.33
0.1	1.84	2.36
0.2	2.64	2.76
0.3	3.28	3.43
0.4	3.81	3.85
0.5	4.26	4.17
0.6	4.65	4.47
0.7	4.99	4.78
0.8	5.29	5.07
0.9	5.57	5.43

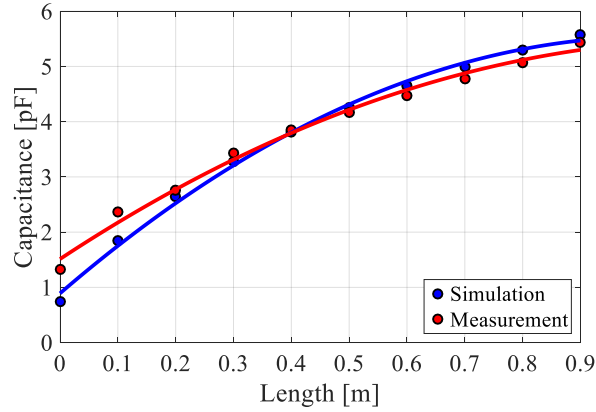
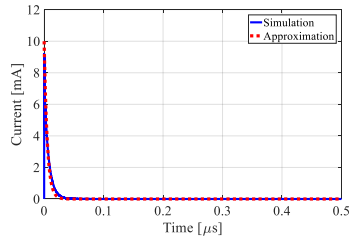
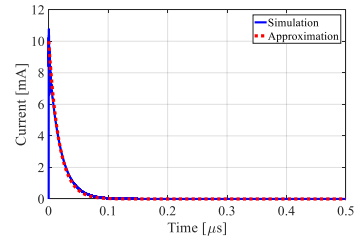


Fig. 4.2. Simulation and experimental results: comparison of the capacitance between the two down conductors.

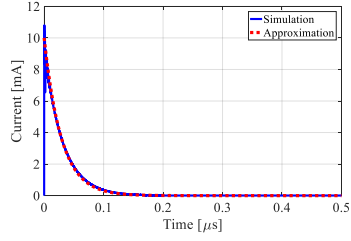
As displayed in Fig. 3.5 in the previous section, the FDTD simulation of the electrostatic capacitance between the tower body and the down conductor was calculated. The down conductor varied from 0.0 m to 0.9 m to simulate the disconnected location. Similarly, the approximated transient current waveforms can be received from the simulation results by solving Equations (3.9) to (3.11). Fig. 4.3 displays the transient current waveforms from the FDTD simulation while changing their disconnected locations and the approximated transient current waveforms. The experimental results that were obtained by using a reduced scale (with a tower height of 1.8 m, a down conductor length of 0.9 m, and a 1.3 mm radius for the down conductor) were compared to the simulation results to confirm the validity of this proposed technique. Table 4.2 and Fig 4.4 presents the comparison of the capacitance values obtained by the simulation and the experiment while the length of the down conductor varied.



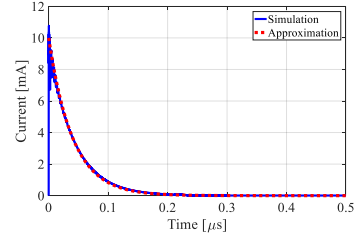
(a) 0.0 m.



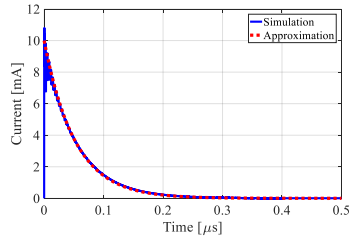
(b) 0.1 m.



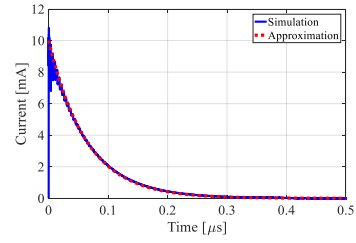
(c) 0.2 m.



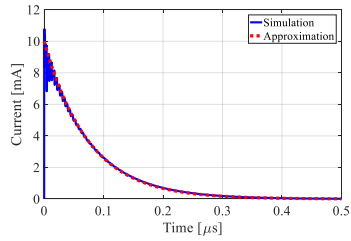
(d) 0.3 m.



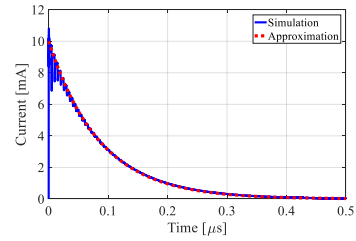
(e) 0.4 m.



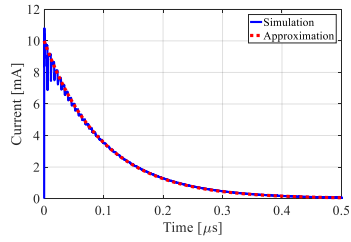
(f) 0.5 m.



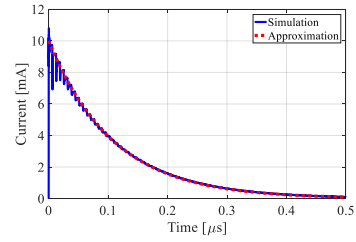
(g) 0.6 m.



(h) 0.7 m.



(i) 0.8 m.



(j) 0.9 m.

Fig. 4.3. Transient current waveforms: the down conductor's length, the charging voltage, and the series resistance varied from 0.0 m to 0.9 m, 100 V, and 10 k Ω , respectively.

Table 4.2 Comparison of the capacitance values obtained by the simulation and the experiment when applying the electrostatic capacitance between the tower body and the down conductor for the reduced scale model

Length [m]	Capacitance [pF]	
	Simulation	Experiment
0.0	0.53	1.56
0.1	1.73	2.28
0.2	2.88	3.71
0.3	4.02	4.59
0.4	5.15	5.30
0.5	6.28	6.12
0.6	7.41	7.82
0.7	8.54	9.33
0.8	9.67	10.90
0.9	10.79	12.10

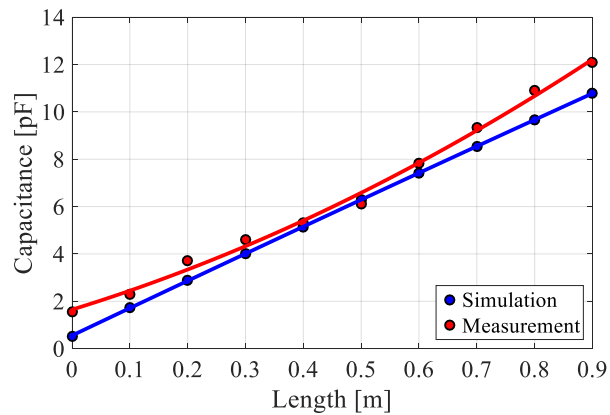
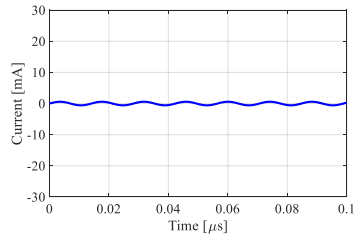
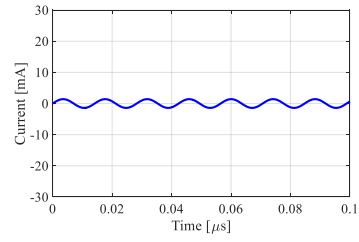


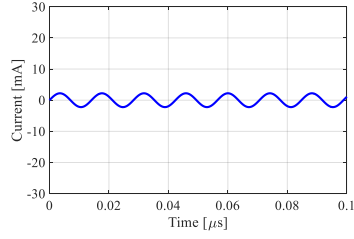
Fig. 4.4. Simulation and experimental results: comparison of the capacitance between the tower body and the down conductor.



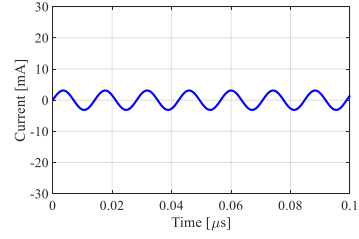
(a) 0.0 m.



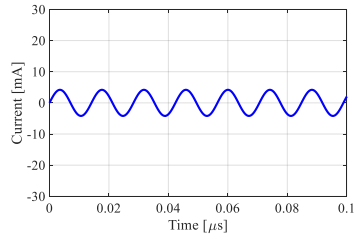
(b) 0.1 m.



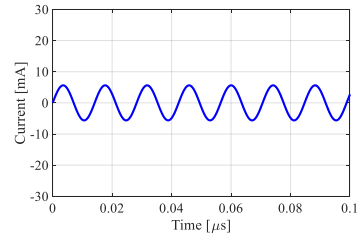
(c) 0.2 m.



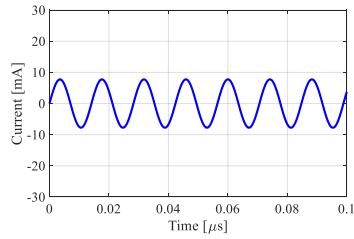
(d) 0.3 m.



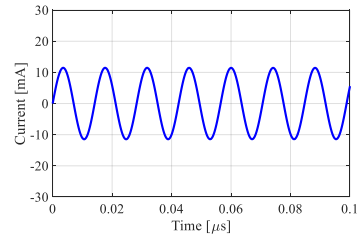
(e) 0.4 m.



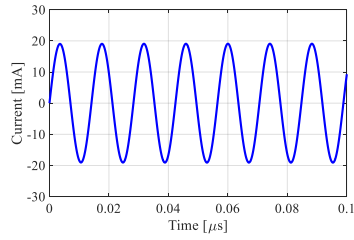
(f) 0.5 m.



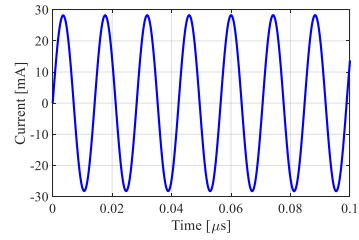
(g) 0.6 m.



(h) 0.7 m.



(i) 0.8 m.



(j) 0.9 m.

Fig. 4.5. Resonant current waveforms: the length of down conductor B, the peak alternating voltage, and the resonance frequency varied from 0.0 m to 0.9 m, 1.4 V, and 70.8 MHz, respectively.

The FDTD simulation model of the proposed technique using the half-wave dipole-antenna (Fig. 3.12) was used to calculate the resonance current when the length of down conductor B varied from 0.0 m to 0.9 m. The resonant current waveforms obtained by the simulation are shown in Fig. 4.5. To evaluate the performance of the simulation results, a *CW* source with an input peak voltage of 1.4 V and an appropriate frequency were applied to the down conductors in the experiment. A current probe was used to measure the resonant current waveform in the down conductors. A comparison of the simulation and the experimental results for each down conductor length is listed in Table 4.3. Fig. 4.6 shows a comparison of the resonant peak current for each down conductor length.

Table 4.3 Comparison of the resonant peak current values obtained by the simulation and the experiment when applying the half-wave dipole-antenna for the reduced scale model

Length [m]	Current [mA]	
	Simulation	Experiment
0.0	0.57	0.47
0.1	1.40	0.54
0.2	2.22	1.25
0.3	3.11	2.10
0.4	4.19	2.85
0.5	5.62	4.08
0.6	7.76	6.35
0.7	11.47	10.68
0.8	19.08	15.54
0.9	28.28	26.22

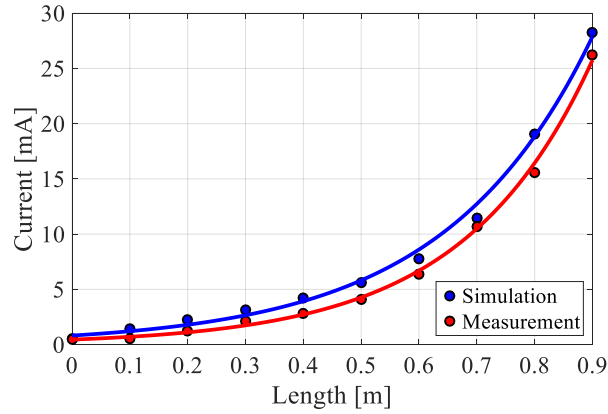


Fig. 4.6. Simulation and experimental results: comparison of the peak current for each down conductor length when applying the half-wave dipole-antenna. N. Triruttanapiruk, et. al., (2019). A simplified technique for detecting disconnections along down conductors in wind turbine, *ELECTR. POW. SYST. RES.*, 172, 177-182. DOI: 10.1016/j.epsr.2019.03.011

According to Figs. 4.2, 4.4, and 4.6, the simulation and experimental results are in good agreement.

4.2 Small Wind Turbine

Following the success of the application of the proposed techniques to the reduced scale model, experiments were conducted on a small wind turbine to reconfirm the validity. First, the down conductors and the tower body were modeled using the FDTD method (analogous to the previous) to calculate the transient current and the resonant current. The FDTD simulation models, as illustrated in Figs. 3.6, 3.7, and 3.13, were considered for the calculations. In the case of the electrostatic capacitance between the two down conductors, the

transient current waveforms obtained by the FDTD simulation and the approximated transient current waveforms are described in Fig. 4.7.

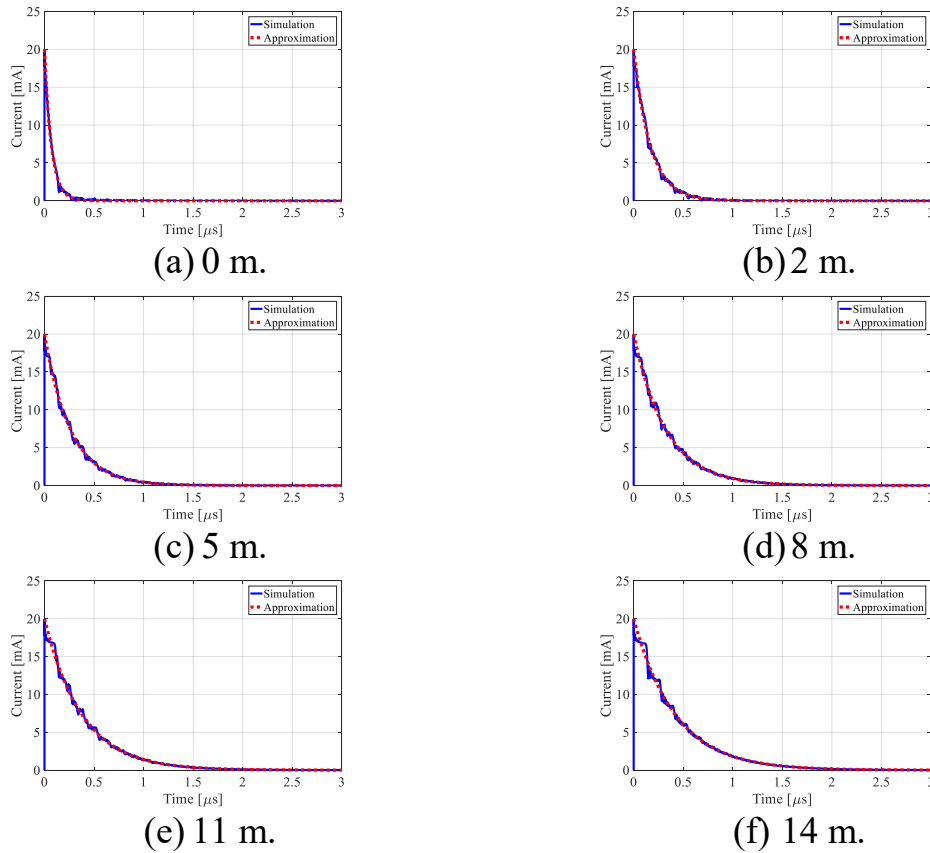


Fig. 4.7. Transient current waveforms: the length of down conductor B, the charging voltage, and the series resistance varied from 0 m to 14 m, 100 V, and 5 kΩ, respectively.

The experiments that were carried out on the small wind turbine were employed to examine the validity of the simulation results. The down conductors (with a radius of 1.3 mm) were installed along the surface of the wind turbine blades to simulate the down conductors. One of the down

conductors' lengths varied from 0 m to 14 m. A comparison of the simulation and experimental results is provided in Table 4.4. Fig. 4.8 shows the comparison results between the simulation and the experiment.

Table 4.4 Comparison of the capacitance values obtained by the simulation and the experiment when applying the electrostatic capacitance between the two down conductors for the small wind turbine

Length [m]	Capacitance [pF]	
	Simulation	Experiment
0	13.96	22.00
2	33.48	39.00
5	52.59	51.00
8	65.14	67.00
11	75.43	74.00
14	83.76	83.00

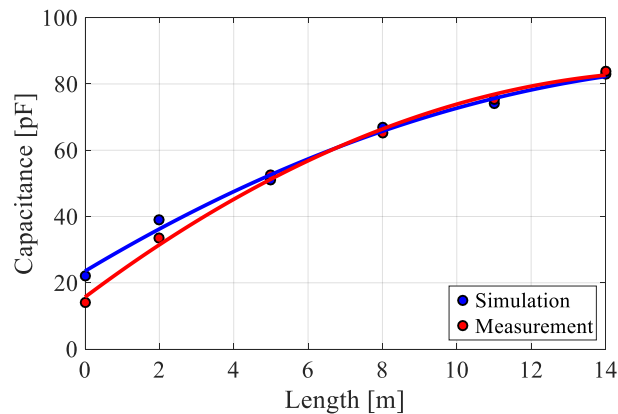


Fig. 4.8. Simulation and experimental results: comparison of the capacitance between the two down conductors for each length.

Fig. 4.9 shows the transient current waveforms obtained by the FDTD simulation and the approximated transient current waveforms when applying the capacitance between the tower body and the down conductor. In the same

manner, the down conductor length varied from its root to the maximum length to simulate the disconnected location.

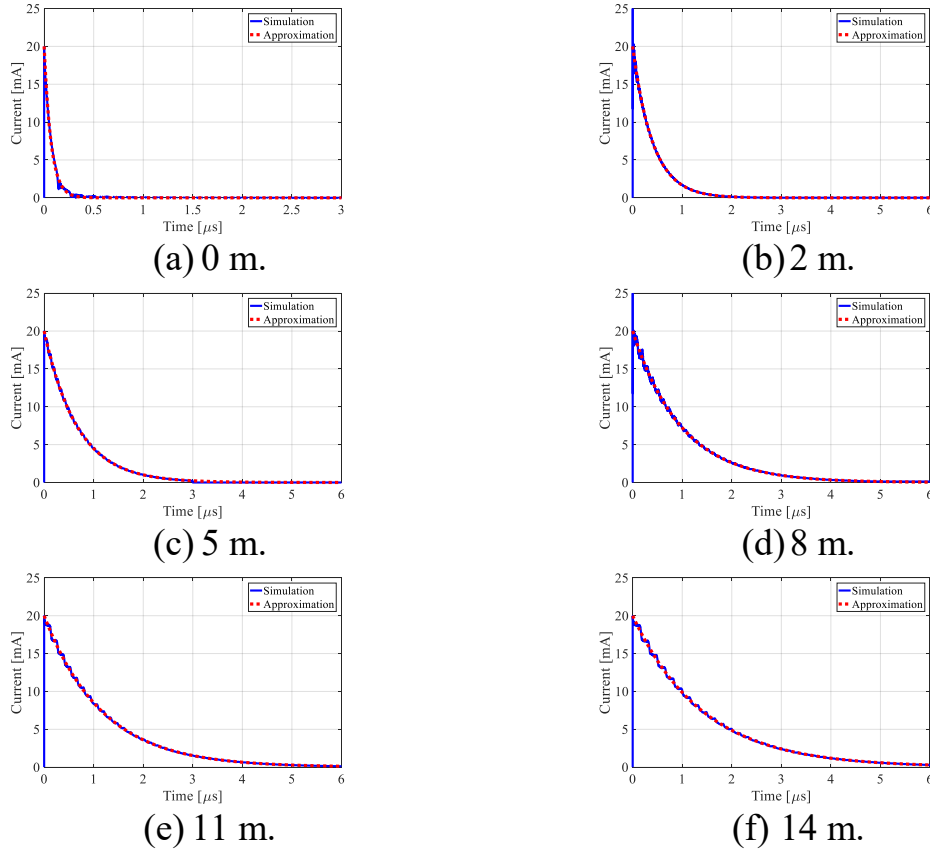


Fig. 4.9. Transient current waveforms: the down conductor's length, the charging voltage, and the series resistance varied from 0 m to 14 m, 100 V, and 5 k Ω , respectively.

Table 4.5 and Fig. 4.10 show a comparison of the simulation and the experimental results from the proposed technique of the electrostatic capacitance between the tower body and the down conductor of the small wind turbine.

Table 4.5 Comparison of the capacitance values obtained by the simulation and the experiment when applying the electrostatic capacitance between the tower body and the down conductor for the small wind turbine

Length [m]	Capacitance [pF]	
	Simulation	Experiment
0	37.63	40.00
2	80.38	103.00
5	134.15	149.00
8	196.6	177.00
11	233.65	234.00
14	283.06	290.00

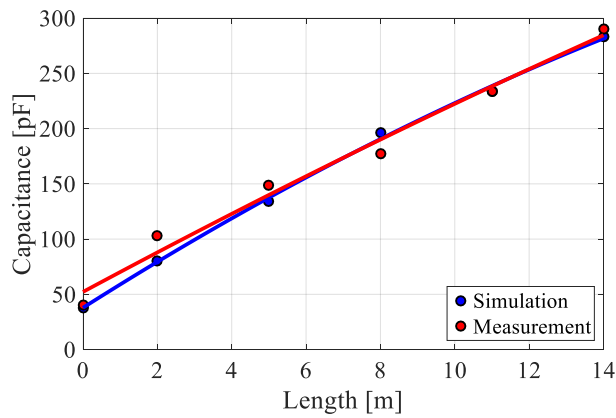


Fig. 4.10. Simulation and experimental results: comparison of the capacitance between the tower body and the down conductor at each length.

The resonant current waveforms obtained by the FDTD simulation of the proposed technique using the half-wave dipole-antenna are shown in Fig 4.11

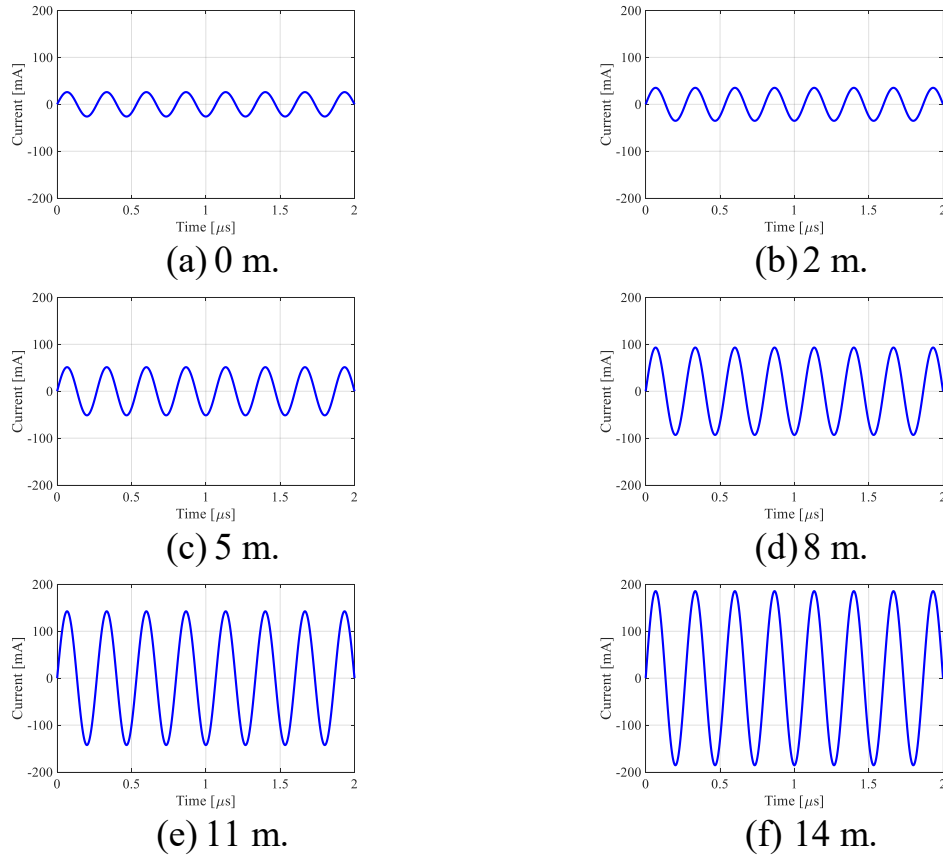


Fig. 4.11. Resonant current waveforms: the length of down conductor B, the peak alternating voltage, and the resonance frequency varied from 0 m to 14 m, 14 V, and 3.7 MHz, respectively.

A comparison of the peak resonant current from the simulation and the experimental results using the proposed technique as shown in Table 4.6 and Fig. 4.12.

Table 4.6 Comparison of the resonant peak current values obtained by the simulation and the experiment when applying the half-wave dipole-antenna for the small wind turbine

Length [m]	Current [mA]	
	Simulation	Experiment
0	26.00	35.84
2	35.15	40.80
5	51.30	46.40
8	71.25	55.20
11	93.11	75.83
14	185.50	177.10

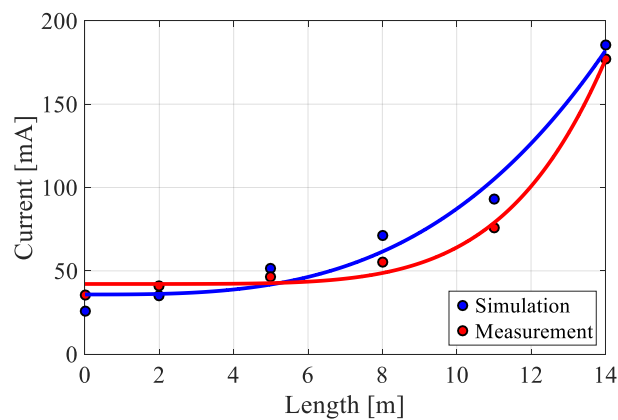


Fig. 4.12. Half-wave dipole-antenna: comparison of the simulation and the experimental values of the peak current for each down conductor length.

N. Triruttanapiruk, et al., (2019). A simplified technique for detecting disconnections along down conductors in wind turbine blades, *ELECTR. POW. SYST. RES.*, 172, 177-182. DOI: 10.1016/j.epsr.2019.03.011

The simulation and experimental results, which were obtained by using the application of the electrostatic capacitance, are in good agreement. However, the results obtained using the application of the half-wave dipole-antenna

exhibits deviations due to electrical noise. Nevertheless, as far as the experiments are concerned, small deviations are acceptable. Combining this technique with other techniques would be useful in detecting the disconnected locations.

4.3 Mitsubishi MWT-1000A

When considering the comparison results of the proposed techniques when they are applied to the reduced scale model and the small wind turbine, it was determined that the proposed techniques are efficient. The proposed techniques start with the calculations of the FDTD simulation. As shown in Figs. 3.8, 3.9, and 3.14, with the help of the manufacturer's data [28], the length of the down conductors and the tower body of the Mitsubishi MWT-1000A were created to calculate the transient current waveforms and the resonant current waveforms while the down conductor's lengths varied from their roots to the maximum length. In the case of the electrostatic capacitance between the two down conductors and the electrostatic capacitance between the tower body and the down conductor, the transient current waveforms and their approximated waveforms are shown in Figs. 4.13, and 4.15. The capacitance values for each down conductor length is described in Tables 4.7 to 4.8 and the trend curves that were obtained through the best-fit of these results are shown in Figs. 4.14 and 4.16.

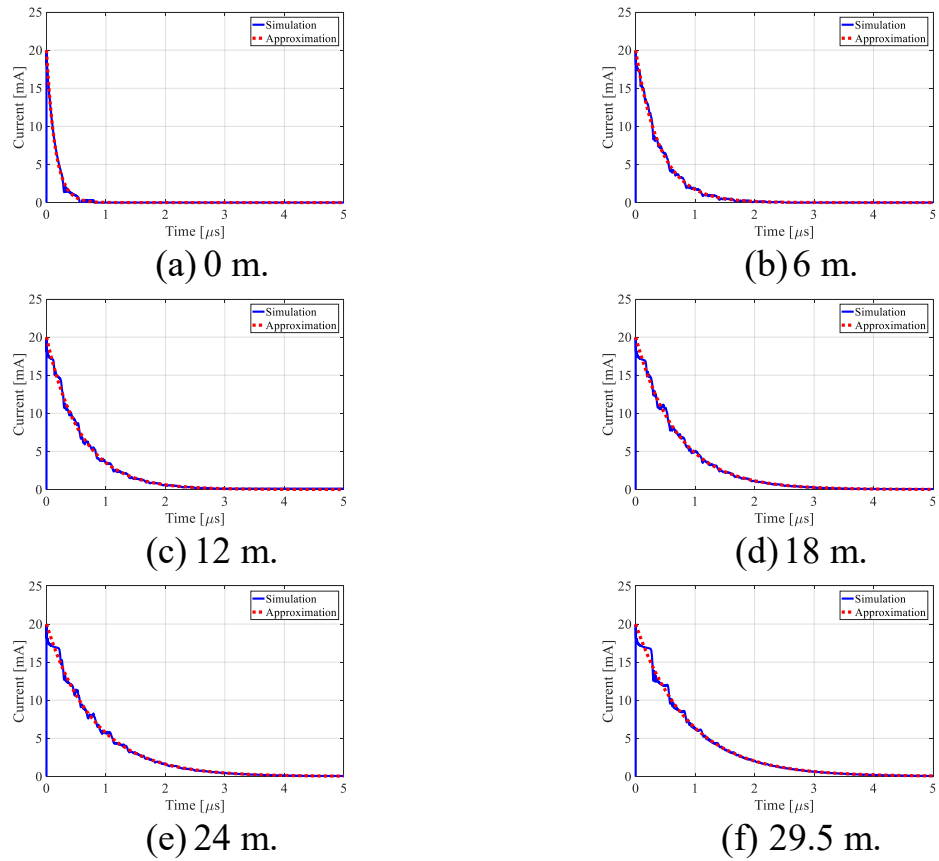


Fig. 4.13. Transient current waveforms: the length of down conductor B, the charging voltage, and the series resistance varied from 0 m to 29.5 m, 100 V, and 5 k Ω , respectively.

Table 4.7 Capacitance values obtained by the simulation when applying the electrostatic capacitance between the two down conductors for the Mitsubishi MWT-1000A

Length [m]	Capacitance [pF]
0	26.00
6	35.15
12	51.30
18	71.25
24	93.11
29.5	185.50

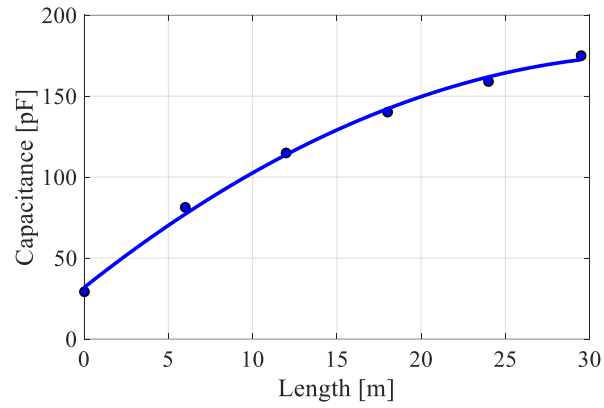


Fig. 4.14. Simulation results: trend curve of the capacitance between the two down conductors at each length.

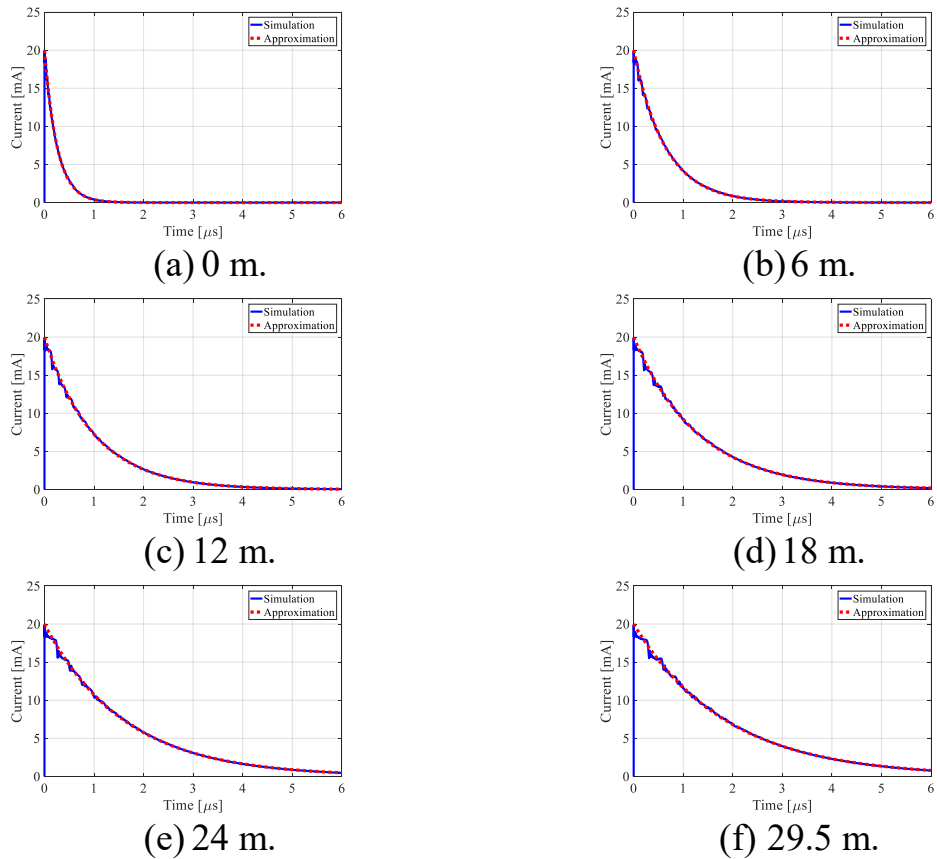


Fig. 4.15. Transient current waveforms: the length of the down conductor, the charging voltage, and the series resistance varied from 0 m to 29.5 m, 100 V, and 5 k Ω , respectively.

Table 4.8 Capacitance values obtained by the simulation when applying the electrostatic capacitance between the tower body and the down conductor for the Mitsubishi MWT-1000A

Length [m]	Capacitance [pF]
0	51.02
6	126.91
12	197.27
18	257.73
24	321.00
29.5	370.91

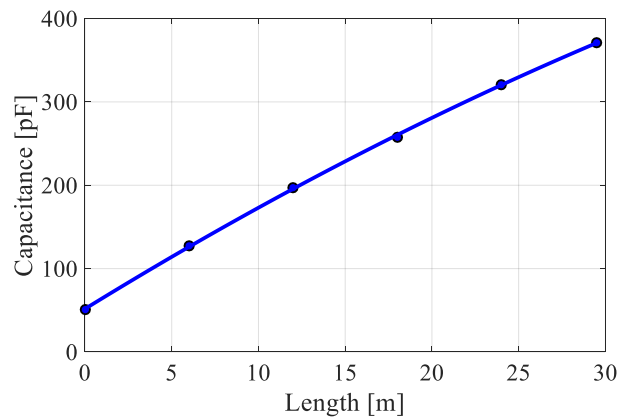


Fig. 4.16. Simulation results: trend curve of the capacitance between the tower body and the down conductor at each length.

The resonant current waveforms obtained by the FDTD simulation of the proposed technique when applying the half-wave dipole-antenna is shown in Fig. 4.17. The trend curve of the peak current for each down conductor length is illustrated in Fig. 4.18 and they are also described in Table 4.9.

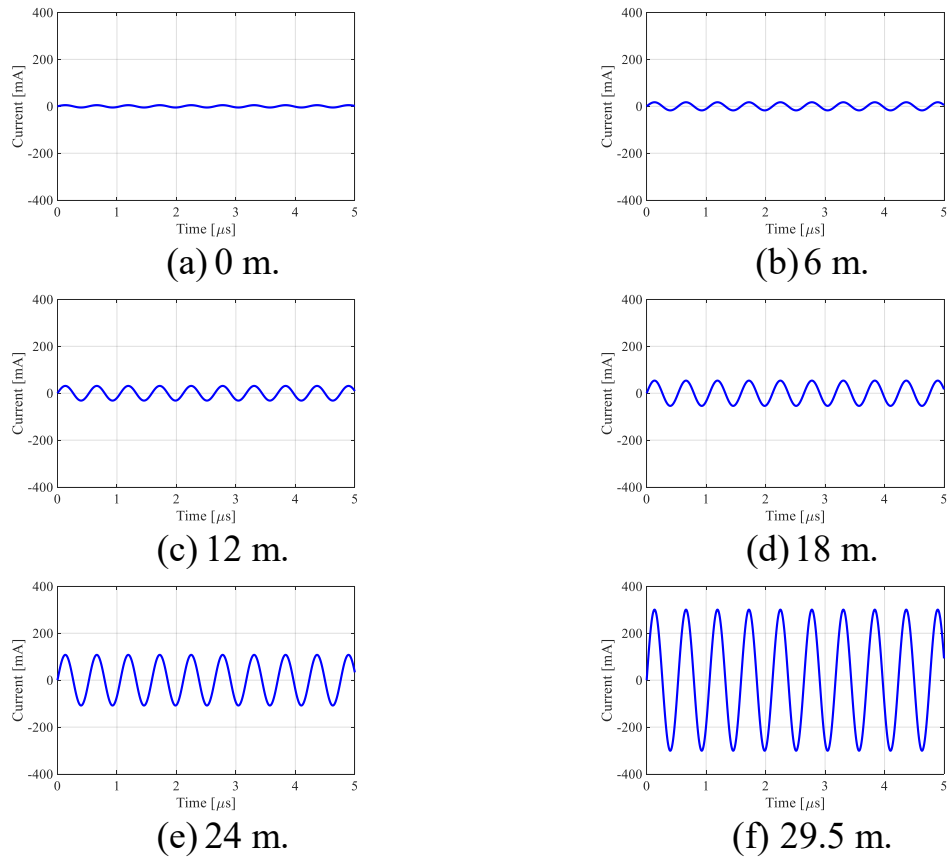


Fig. 4.17. Resonant current waveforms: the length of down conductor B, the peak alternating voltage, and the resonance frequency varied from 0 m to 29.5 m, 14 V, and 1.89 MHz, respectively.

Table 4.9 Resonant peak current values obtained by the simulation when applying the half-wave dipole-antenna for the Mitsubishi MWT-1000A

Current [mA]	Current [mA]
0	5.06
6	17.31
12	31.26
18	53.83
24	107.89
29.5	300.57

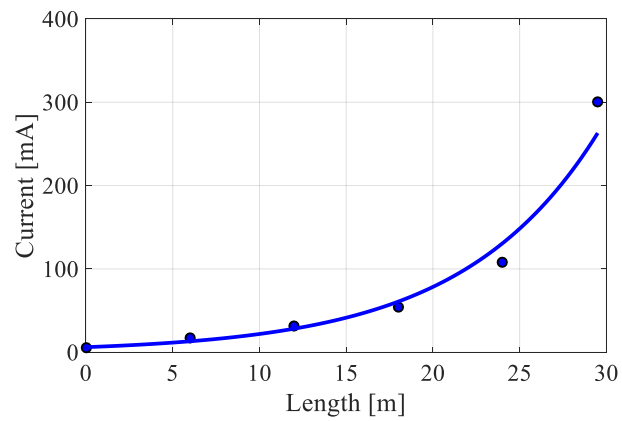


Fig. 4.18. Simulation results: trend curve of the peak resonant current at each length of the down conductor.

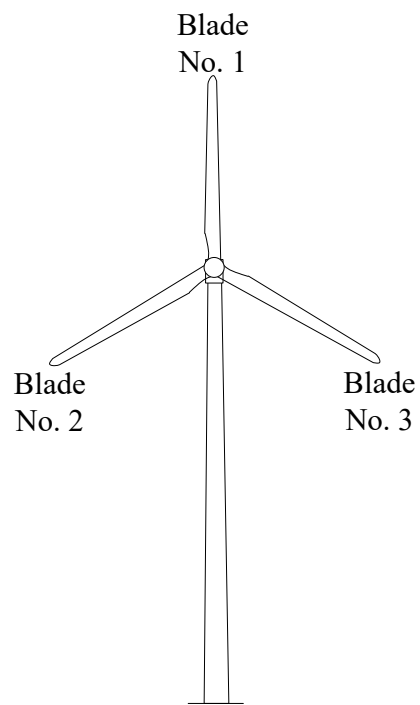


Fig. 4.19. Positioning of the blades during the test.

The simulations were applied to estimate the disconnected locations of the down conductors and they were compared with the experimental results. In the experiments, five wind turbine machines with disconnections that appeared on the down conductors were examined to find the disconnected locations. Due to the configuration of the Mitsubishi MWT-1000A, the proposed techniques were applied to the wind turbine hub and the position of the wind turbine blades were set as shown in Fig. 4.19. As demonstrated, blade No. 2 and blade No. 3 were set up at a 60-degree angle to the tower. Before performing measurements, wind turbine owners would provide data of the blade numbers, which features disconnections in the down conductors. According to the simulation models of the proposed techniques, the electrostatic capacitance between the tower body and the down conductor were excluded because one of the down conductor lengths was fixed to the maximum length and the other varied from the root to the maximum length. Therefore, if both pairs of down conductors had disconnections, their capacitance values and resonant current waveforms would not be measured.

The measured results were obtained by applying the electrostatic capacitance between the two down conductors, the capacitance between the tower body and the down conductor, and the resonant peak current when applying the half-wave dipole-antenna for each machine. This is described in further detail in Tables 4.10 to 4.12.

Table 4.10 Capacitance values obtained by the experiment when applying the electrostatic capacitance between the two down conductors of the wind turbines during testing

Sample No.	Combination of blade	Capacitance [pF]
1	Blade No. 1 and Blade No. 2.	165.0
	Blade No. 2 and Blade No. 3.	-
	Blade No. 3 and Blade No. 1.	163.0
2	Blade No. 1 and Blade No. 2.	178.3
	Blade No. 2 and Blade No. 3.	183.7
	Blade No. 3 and Blade No. 1.	177.5
3	Blade No. 1 and Blade No. 2.	207.4
	Blade No. 2 and Blade No. 3.	202.4
	Blade No. 3 and Blade No. 1.	193.0
4	Blade No. 1 and Blade No. 2.	-
	Blade No. 2 and Blade No. 3.	182.7
	Blade No. 3 and Blade No. 1.	185.5
5	Blade No. 1 and Blade No. 2.	189.1
	Blade No. 2 and Blade No. 3.	183.2
	Blade No. 3 and Blade No. 1.	180.0

-: Cannot measure due to both blades occurred disconnection.

Table 4.11 Capacitance values obtained by the experiment when applying the electrostatic capacitance between the tower body and the down conductor of the wind turbines during testing

Sample No.	Combination	Capacitance [pF]
1	Blade No. 2 and Tower body	355.0
	Blade No. 3 and Tower body	367.0
2	Blade No. 2 and Tower body	_*
	Blade No. 3 and Tower body	_*
3	Blade No. 2 and Tower body	408.0
	Blade No. 3 and Tower body	356.3
4	Blade No. 2 and Tower body	360.0
	Blade No. 3 and Tower body	376.0
5	Blade No. 2 and Tower body	382.0
	Blade No. 3 and Tower body	353.0

_*: Not necessary to measure.

Table 4.12 Resonant peak current values obtained by the experiment when applying the half-wave dipole-antenna of the wind turbines during testing

Sample No.	Combination of blade	Current [mA]
1	Blade No. 1 and Blade No. 2.	203.2
	Blade No. 2 and Blade No. 3.	-
	Blade No. 3 and Blade No. 1.	257.2
2	Blade No. 1 and Blade No. 2.	289.4
	Blade No. 2 and Blade No. 3.	-
	Blade No. 3 and Blade No. 1.	271.6
3	Blade No. 1 and Blade No. 2.	320.1
	Blade No. 2 and Blade No. 3.	122.6
	Blade No. 3 and Blade No. 1.	136.7
4	Blade No. 1 and Blade No. 2.	-
	Blade No. 2 and Blade No. 3.	237.3
	Blade No. 3 and Blade No. 1.	269.9
5	Blade No. 1 and Blade No. 2.	320.4
	Blade No. 2 and Blade No. 3.	130.7
	Blade No. 3 and Blade No. 1.	133.5

-: Cannot measure due to both blades occurred disconnection.

To estimate the disconnected location of the down conductor of the wind turbine during testing, the measured results were compared to the trend curves obtained by the simulation results. The procedures to estimate the disconnected location started with the trend performance curves from the simulation results. The maximum capacitance values and the maximum resonant peak current values from the simulation results were multiplied by the ratio factor. This was done so they had the same value as the measured results from the experiments obtained by the complete condition of the down conductors. Then, the other simulation results would be multiplied by the same ratio factor. Thus, the trend curves were redone from the new simulation results. However, wind turbine No. 1 and No. 4 during the test had more than one down conductor with a

disconnection. Thus, these were not the maximum values of the proposed techniques. As a result, the maximum values from wind turbine No. 5 were used since it was located close to the wind turbines. Fig. 4.20 describes the procedure to apply the proposed techniques for the real case of wind turbines.

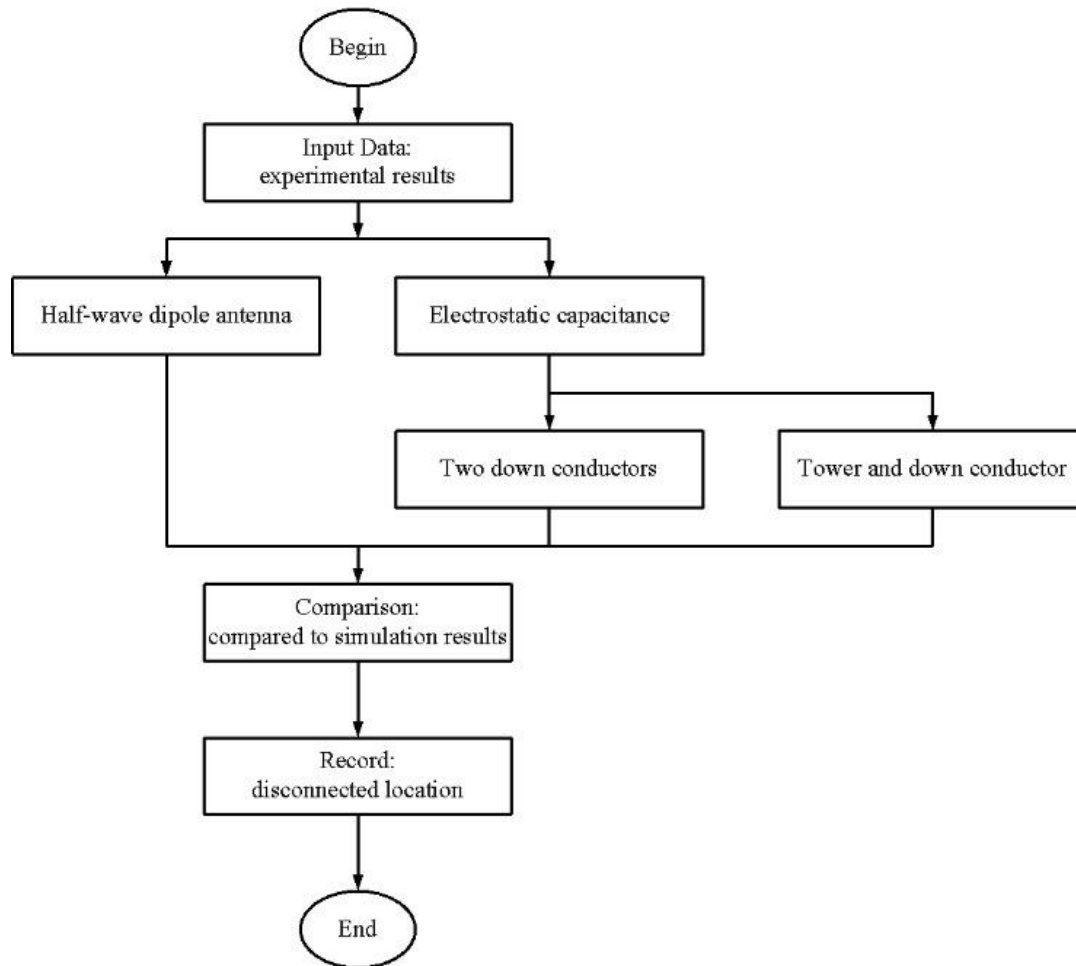
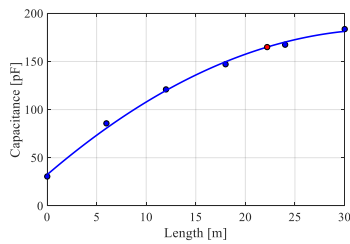


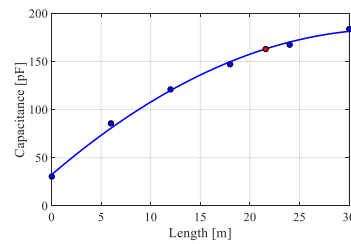
Fig. 4.20. Process of the proposed techniques.

N. Triruttanapiruk, et. al., (2019). A simplified technique for detecting disconnections along down conductors in wind turbine, *ELECTR POW SYST RES.*, 172, 177-182. DOI: 10.1016/j.epsr.2019.03.011

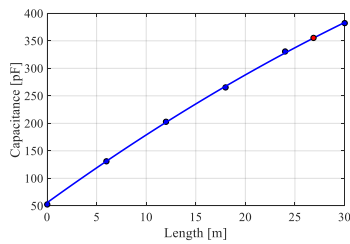
The estimated results and the measured results were compared to the new trend curves as shown in Figs. 4.21 to 4.25. The blue dots, the blue line, and the red dots represent the simulation results that were multiplied by the ratio factor, the trend curves, and the estimated locations, respectively, that were obtained by performing measurements.



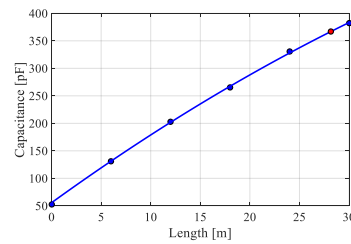
(a) Capacitance between blades No. 1 and No. 2.



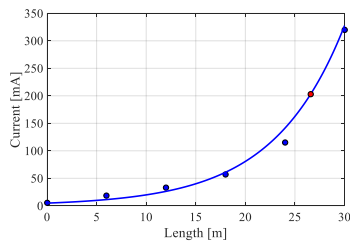
(b) Capacitance between blades No. 3 and No. 1.



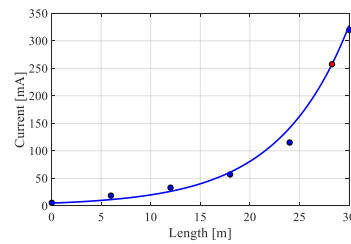
(c) Capacitance between the tower body and blade No. 2.



(d) Capacitance between the tower body and blade No. 3.

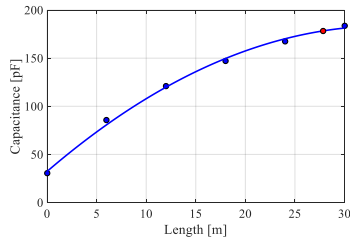


(e) Resonant peak current of blades No. 1 and No. 2.

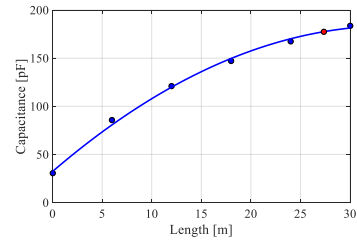


(f) Resonant peak current of blades No. 3 and No. 1.

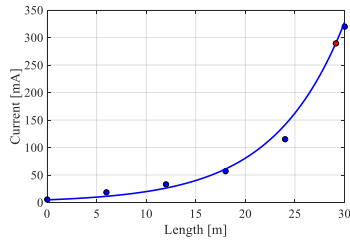
Fig. 4.21. Estimated locations when comparing the simulation results of wind turbine No. 1.



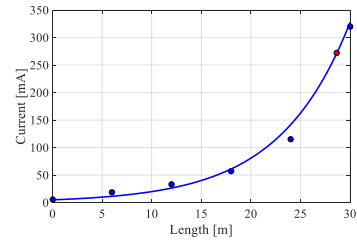
(a) Capacitance between blades No. 1 and No. 2.



(b) Capacitance between blades No. 3 and No. 1.

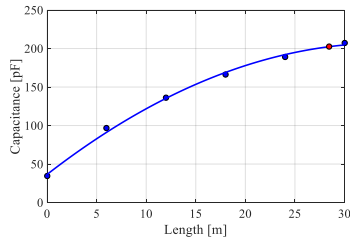


(c) Resonant peak current of blades No. 1 and No. 2.

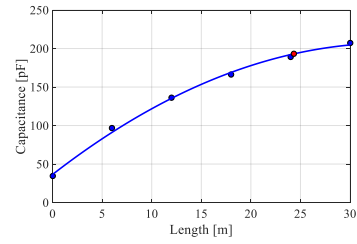


(d) Resonant peak current of blades No. 3 and No. 1.

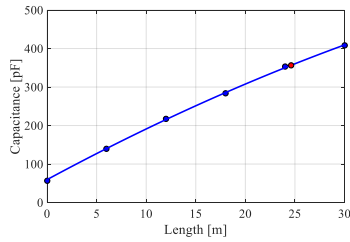
Fig. 4.22. Estimated locations when comparing the simulation results of wind turbine No. 2.



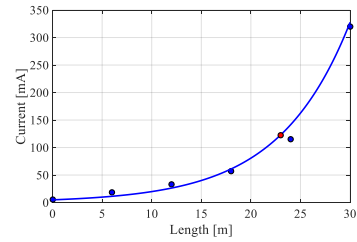
(a) Capacitance between blades No. 2 and No. 3.



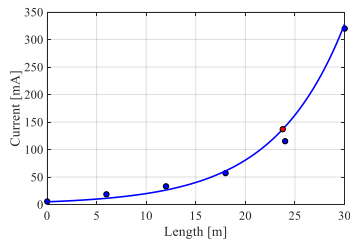
(b) Capacitance between blades No. 3 and No. 1.



(c) Capacitance between the tower body and blade No. 3.

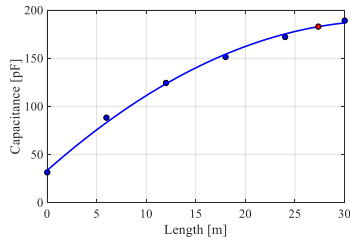


(d) Resonant peak current of blades No. 2 and No. 3.

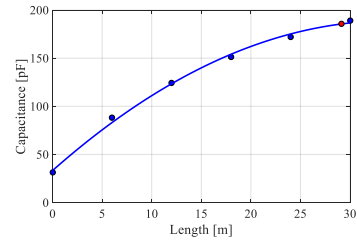


(e) Resonant peak current of blades No. 3 and No. 1.

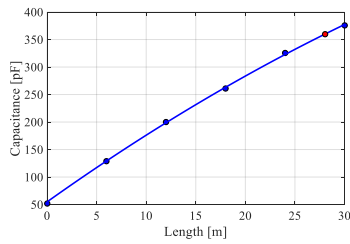
Fig. 4.23. Estimated locations when comparing the simulation results of wind turbine No. 3.



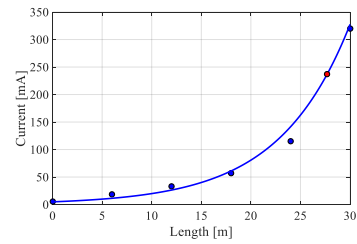
(a) Capacitance between blades No. 2 and No. 3.



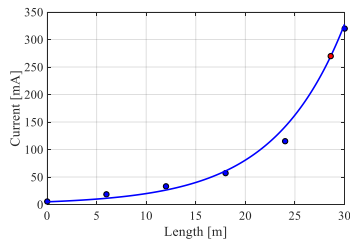
(b) Capacitance between blades No. 3 and No. 1.



(c) Capacitance between the tower body and blade No. 2.

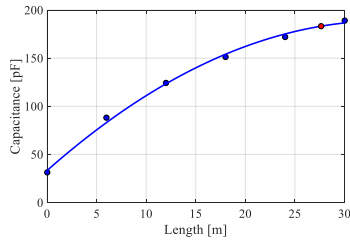


(d) Resonant peak current of blades No. 2 and No. 3.

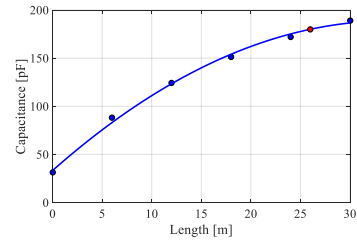


(e) Resonant peak current of blades No. 2 and No. 3.

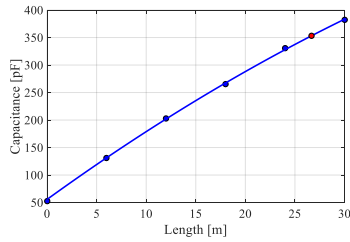
Fig. 4.24. Estimated locations when comparing the simulation results of wind turbine No. 4.



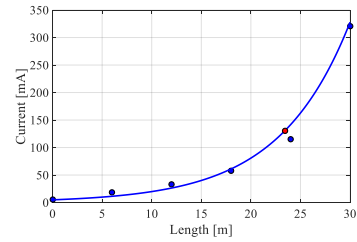
(a) Capacitance between blades No. 2 and No. 3.



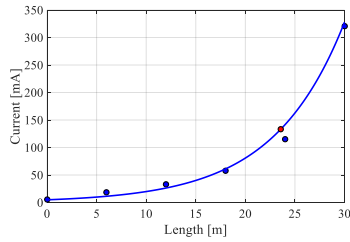
(b) Capacitance between blades No. 3 and No. 1.



(c) Capacitance between the tower body and blade No. 2.



(d) Resonant peak current of blades No. 2 and No. 3.



(e) Resonant peak current of blades No. 3 and No. 1.

Fig. 4.25. Estimated locations when comparing the simulation results of wind turbine No. 5.

To evaluate the validity of the approximation of the estimated locations, a pulse waveform with a high-steepness wave-front was injected into the down conductor during testing to measure the traveling time of the waveform. However, the length of the grounding wire was considered since the pulse generator has two terminals (positive and negative polarity). Thus, one terminal

of the pulse generator was connected to the down conductor. The second terminal must be connected to the ground by the wind turbine tower for safety purposes due to the possibility of an electrical emergency. As shown in Figs. 3.17 to 3.18, the FDTD simulation models were calculated to check the effect of the grounding wire length. The simulation results from those models are shown in Figs. 4.26 to 4.28.

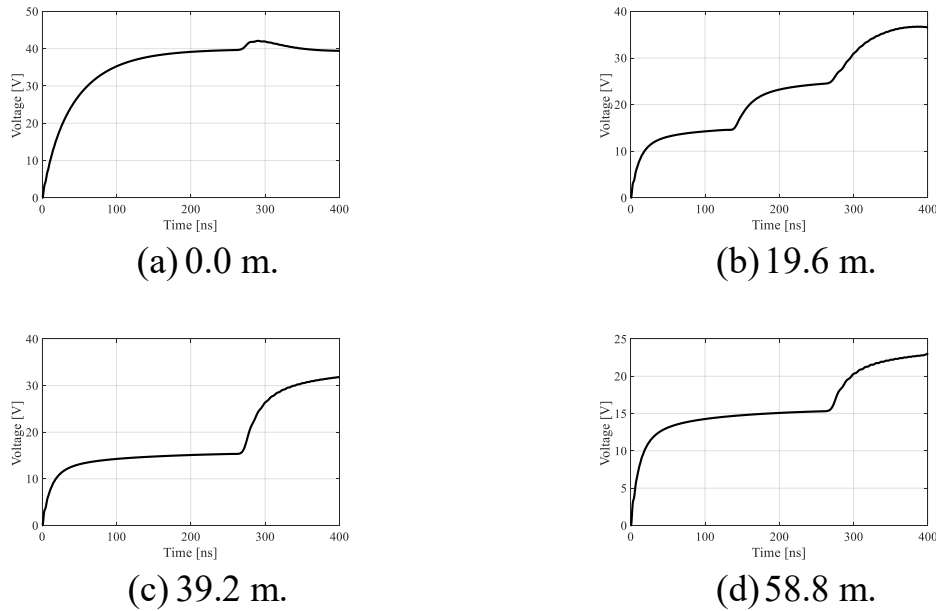
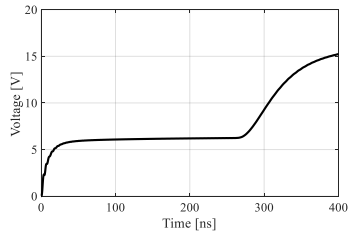
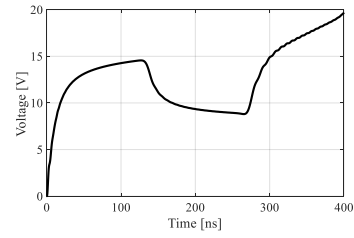


Fig. 4.26. Simulation results for the injected step waveform for the two conductors (open circuit of both conductors).

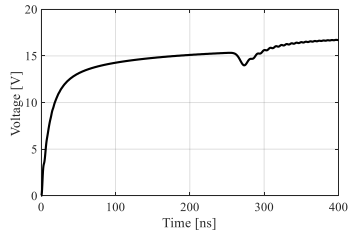
From the simulation results, it was determined that when the waveform length of conductor B is equal to the length of conductor A, this provides the best-reflected waveform. On the other hand, if the length of conductor B was set to 0 m, the reflected waveform for the most part was not observed.



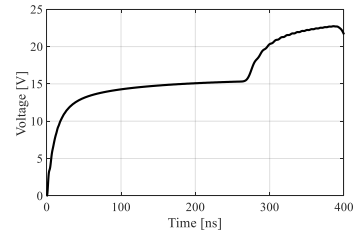
(a) 0.0 m.



(b) 19.6 m.

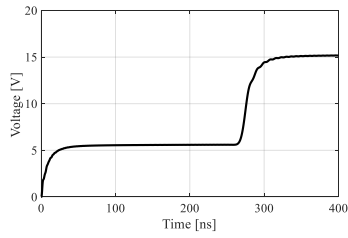


(c) 39.2 m.

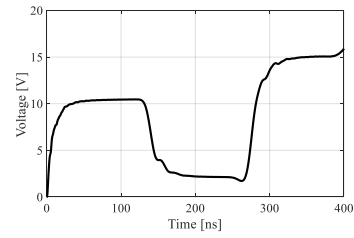


(d) 58.8 m.

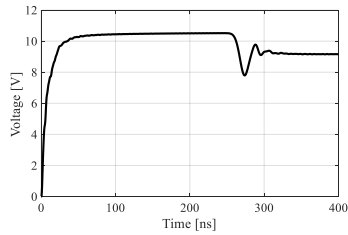
Fig. 4.27. Simulation results for the injected step waveform for two conductors (conductor B was connected to the ground).



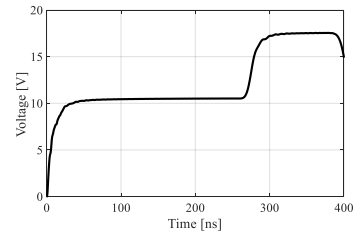
(a) 0.0 m.



(b) 19.6 m.



(c) 39.2 m.



(d) 58.8 m.

Fig. 4.28. Simulation results for the injected step waveform for two conductors (conductor B was connected to the tower).

From Fig. 4.27, the simulation results show that the best-reflected waveform was found when conductor B was equal to 0 m. In contrast, the worst reflected waveform appears when conductor B was set to 39.2 m, which is the same as conductor A.

As shown in Fig. 4.28, it can be determined that the reflected waveform when conductor B equals 0 m provides the best-reflected waveform. In addition, the obtained reflected waveform is challenging to observe when the length of conductor B is like conductor A. However, if it is considered in real practice for detecting the disconnected location of the down conductor, the laceration of the down conductors has the possibility of appearing at the root. Therefore, it is difficult to estimate where a disconnection location may have occurred. For this reason, the grounding wire length was longer than the down conductor's length. This is because it covers the entire length of the down conductor. Although it does not provide the best-reflected waveform, the reflected waveform is still easy to observe.

Figs. 4.29 to 4.33 show the measured results of the traveling time when the high-steepness wave-front was injected in the down conductors of the wind turbines during testing. The solid black line, solid grey line, and the black dotted line represent the reflected waveform of blade No. 1, No. 2, and No. 3, respectively. To estimate the disconnected location from the reflected waveform, the traveling time from the normal blade was set to 100 %, and it was compared to the longest length of the down conductor. Then, the disconnected location can be estimated from the time ratio when comparing the traveling time with the normal blade.

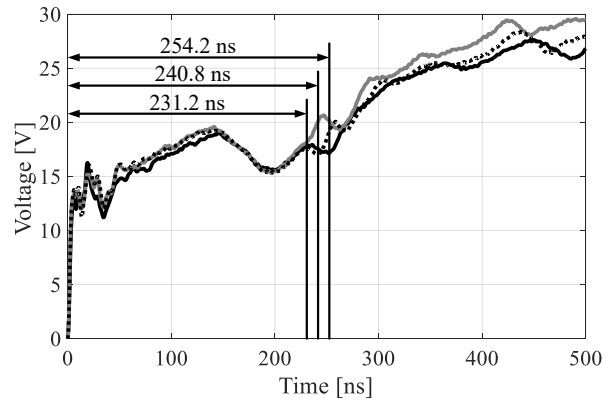


Fig. 4.29. Measured results of the traveling time of the reflected waveform for wind turbine No. 1.

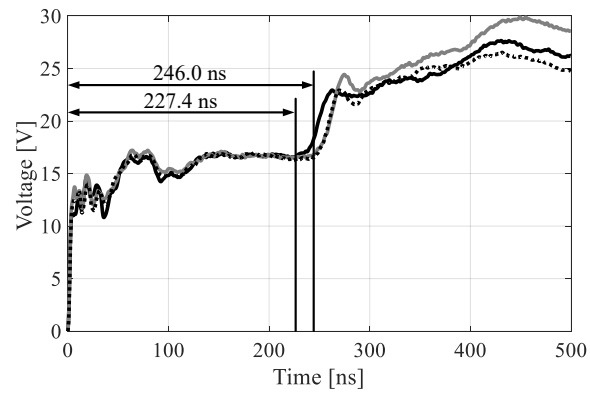


Fig. 4.30. Measured results of the traveling time of the reflected waveform for wind turbine No. 2.

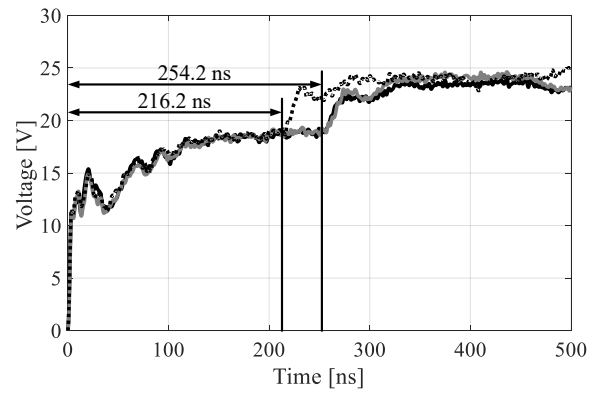


Fig. 4.31. Measured results of the traveling time of the reflected waveform for wind turbine No. 3.

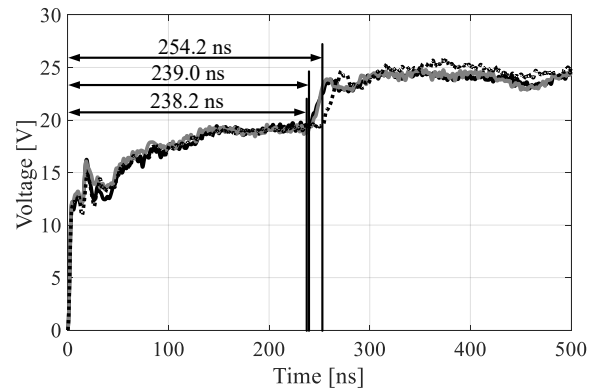


Fig. 4.32. Measured results of the traveling time of the reflected waveform for wind turbine No. 4.

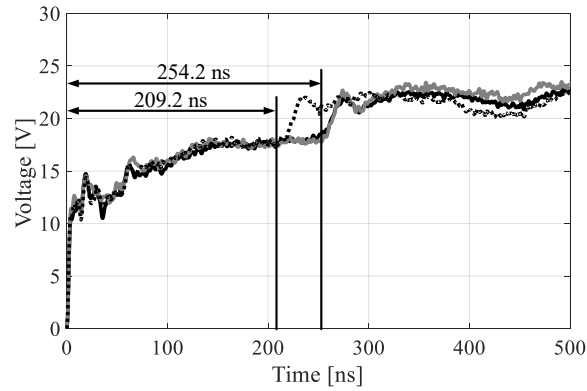


Fig. 4.33. Measured results of the traveling time of the reflected waveform for wind turbine No. 5.

From the results based on the proposed techniques, the estimated locations of the disconnections from the roots of the down conductors are listed in Table. 4.13.

Table 4.13 Disconnected locations from the estimations

Sample No.	Blade No.	Disconnected locations [m]			
		Two down conductors	Tower body and the down conductor	Half-wave dipole-antenna	Propagation method
1	2	22.21	26.87	26.60	26.83
	3	21.59	28.18	28.27	27.95
2	1	27.36	-	28.66	27.27
		27.83		29.11	
3	3	24.35	24.60	22.98	25.09
		28.45		23.76	
4	1	29.11	-	28.62	27.73
	2	27.34	28.04	27.70	27.64
5	3	26.00	26.65	23.43	24.28
		27.63		23.59	

4.4 Gamesa G80-2.0 MW

Similar to the previous section, the procedure of the proposed techniques starts with the creation of the FDTD simulation models (Figs. 3.10, 3.11, and 3.15) by using the manufacturer's data [30]. In the simulations, the down conductors and the tower body were created to calculate the transient current waveforms and the resonant current waveforms when the down conductor's lengths were changed from the roots to the maximum length.

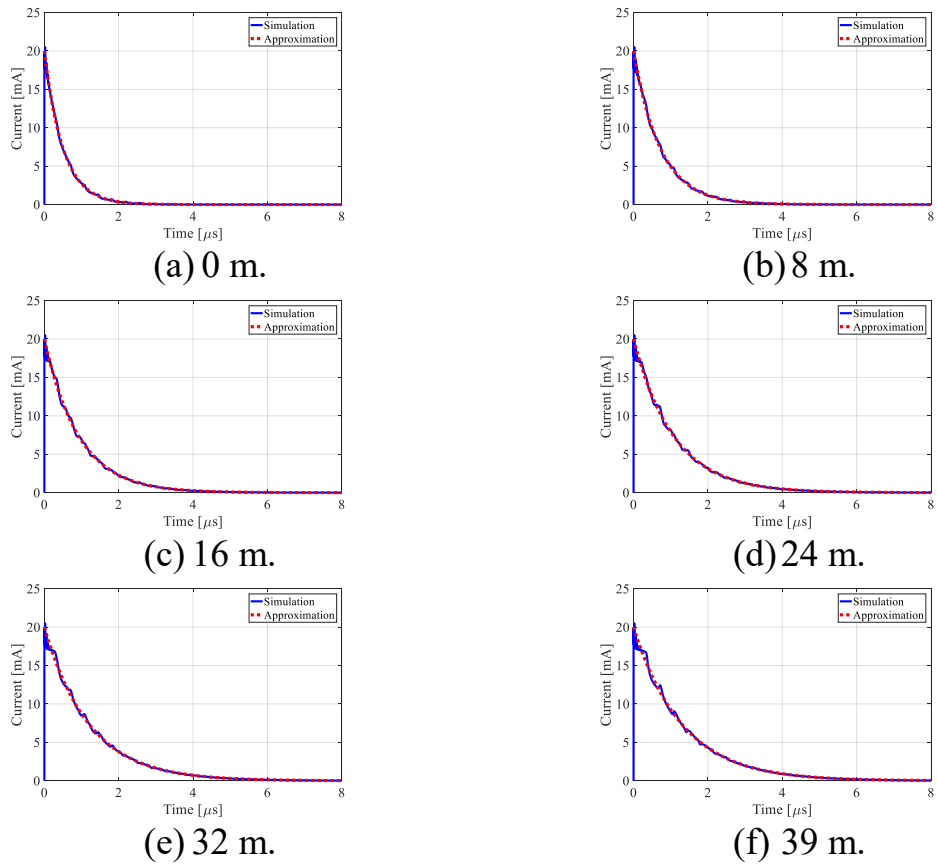


Fig. 4.34. Transient current waveforms: the length of down conductor B, the charging voltage, and the series resistance varied from 0 m to 39 m, 100 V, and 5 k Ω , respectively.

In the case of the electrostatic capacitance between the two down conductors, the electrostatic capacitance between the tower body and the down conductor, the transient current waveforms, and their approximated waveforms are shown in Figs. 4.34 and 4.36. The capacitance values for each down conductor length are listed in Tables 4.14 and 4.15. The trend curves were obtained through the best-fit of these results and are shown in Figs. 4.35 and 4.37.

Table 4.14 Capacitance values obtained by the simulation when applying the electrostatic capacitance between the two down conductors for the Gamesa G80-2.0 MW

Length [m]	Capacitance [pF]
0	100.03
8	143.39
16	184.51
24	215.82
32	240.98
39	259.94

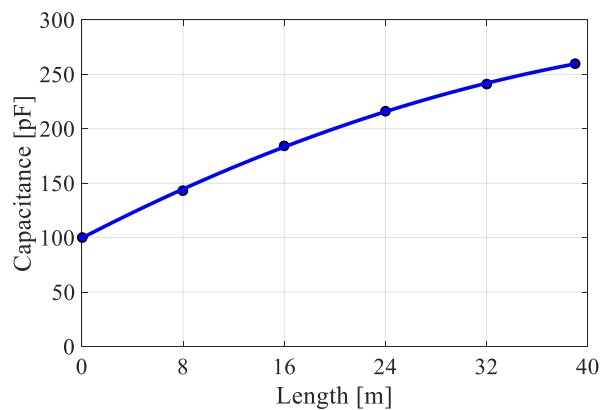


Fig. 4.35. Simulation results: best-fit curve of the capacitance between two down conductors for each length.

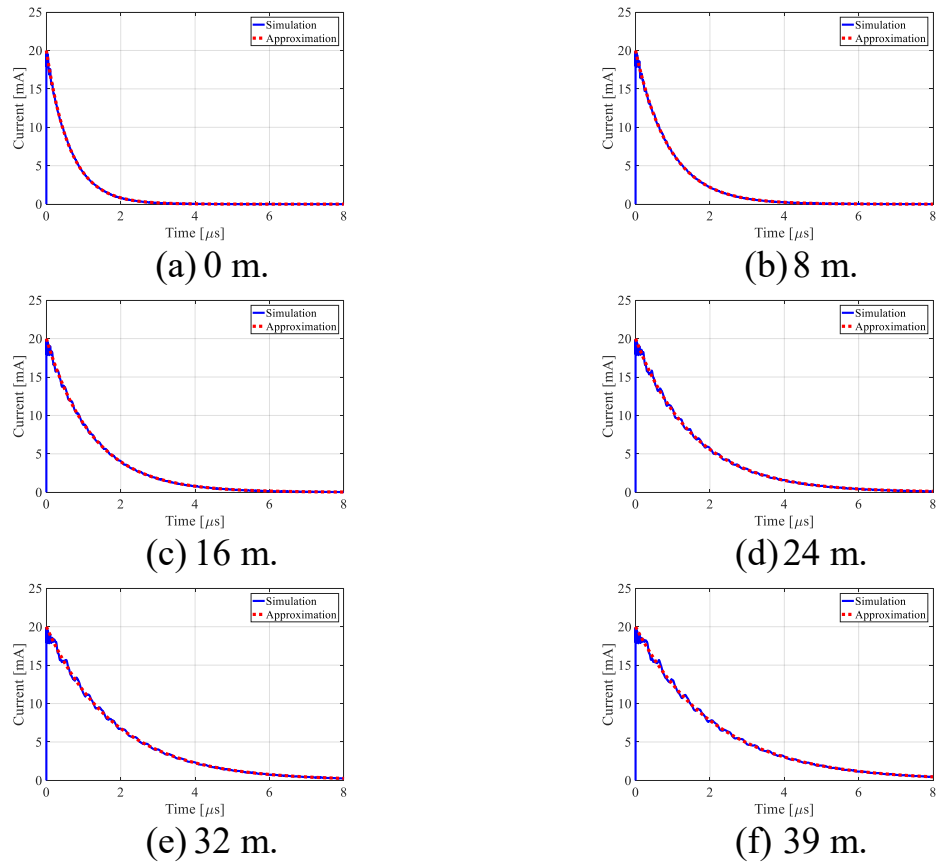


Fig. 4.36. Transient current waveforms: the down conductor length, the charging voltage, and the series resistance varied from 0 m to 39 m, 100 V, and 5 k Ω , respectively.

Table 4.15 Capacitance values obtained by the simulation when applying the electrostatic capacitance between the tower body and the down conductor for the Gamesa G80-2.0 MW

Length [m]	Capacitance [pF]
0	125.35
8	181.09
16	247.77
24	313.09
32	368.87
39	424.91

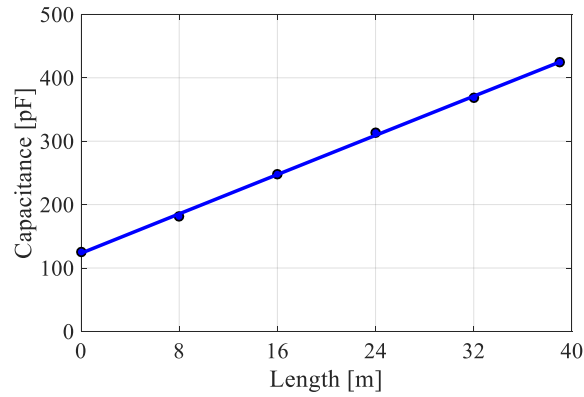


Fig. 4.37. Simulation results: best-fit curve of the capacitance between the tower body and the down conductor for each length.

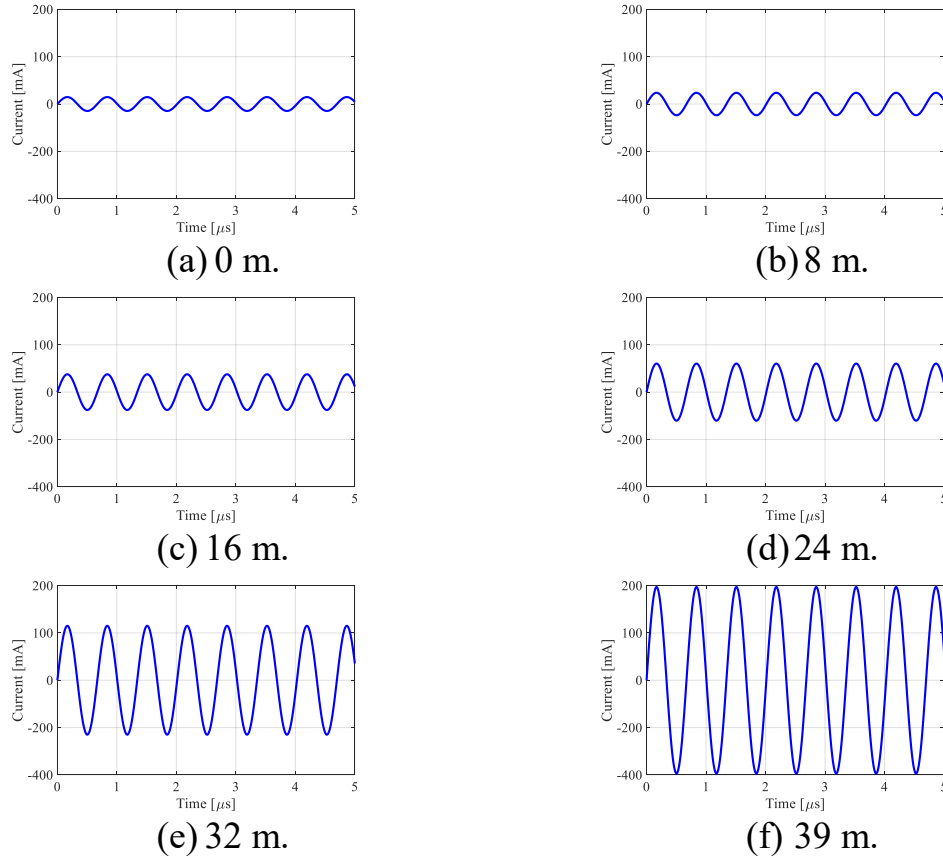


Fig. 4.38. Transient current waveforms: the down conductor length, the charging voltage, and the series resistance varied from 0 m to 39 m, 100 V, and 5 k Ω , respectively.

Fig. 4.38 illustrates the resonant current waveforms from the FDTD simulation of the proposed technique when applying the half-wave dipole-antenna. The trend curve of the peak current for each down conductor length is illustrated in Fig. 4.39 and they are described in Table 4.16.

Table 4.16 Resonant peak current values obtained by the when applying the half-wave dipole-antenna for the Gamesa G80-2.0 MW

Length [m]	Current [mA]
0	14.67
8	23.7
16	37.7
24	60.28
32	114.97
39	196.97

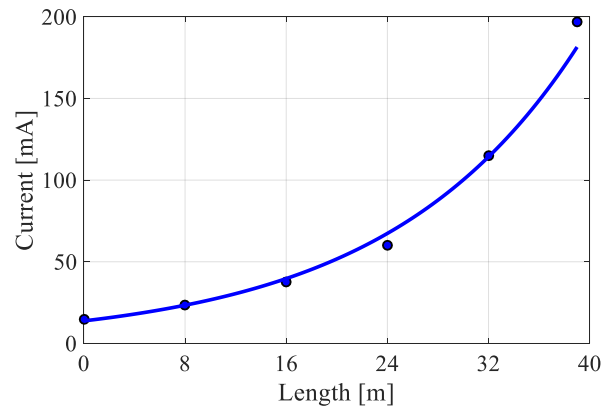


Fig. 4.39. Simulation results: best-fit curve of the peak resonant current at each length of the down conductor.

From the owner's information, the disconnection for the down conductor was discovered on blade No. 2. This estimated the disconnected location based on the experiments that used the application of the proposed techniques. In the

first experiments, the positioning of blade No. 1 and blade No. 2 were set up 120-degrees and -120-degrees to the tower body. Blade No. 3 was set up parallel to the tower body as shown in Fig. 4.40 to measure the high-frequency current. This was flowing in blade No.1 and blade No. 2 when applying the half-wave dipole-antenna. Furthermore, the LCR-meter was used to measure the capacitance between blade No. 1 and blade No. 2 as well as the capacitance between the tower body and blade No. 3.

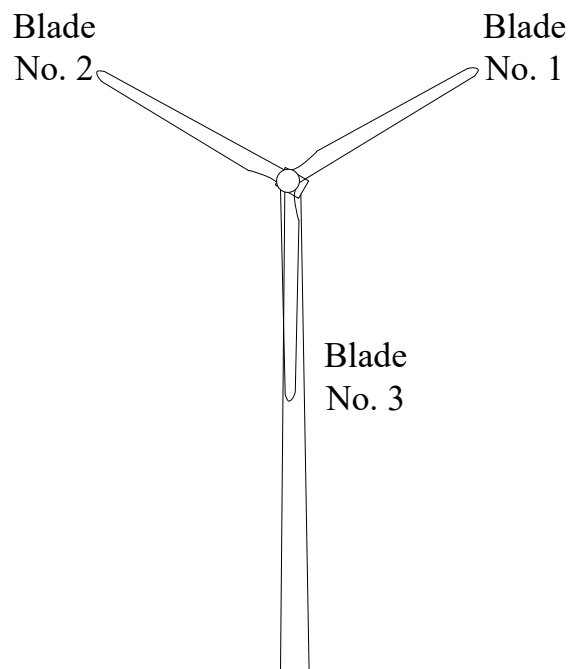


Fig. 4.40. Positioning of the wind turbine blades during testing.

In the second experiment, the wind turbine's blades were rotated 120-degrees counterclockwise to measure the high-frequency current and the

capacitance of blade No. 1 and blade No. 3 and the capacitance between the tower body and blade No. 2.

Table 4.17 Capacitance values obtained by the experiment when applying the electrostatic capacitance between the two down conductors of the wind turbine

Sample No.	Combination of blade	Capacitance [pF]
1	Blade No. 1 and Blade No. 2.	-*
	Blade No. 2 and Blade No. 3.	224.0
	Blade No. 3 and Blade No. 1.	230.0

-*: Not necessary to measure.

Table 4.18 Capacitance values obtained by the experiment when applying the electrostatic capacitance between the tower body and the down conductor of the wind turbine

Sample No.	Combination of blade	Capacitance [pF]
1	Blade No. 1 and Tower body	-*
	Blade No. 2 and Tower body	531.0
	Blade No. 3 and Tower body	551.0

-*: Not necessary to measure.

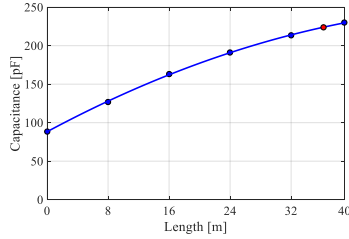
Table 4.19 Resonant peak current values obtained by the experiment when applying the half-wave dipole-antenna of the wind turbine

Sample No.	Combination of blade	Current [mA]
1	Blade No. 1 and Blade No. 2.	-*
	Blade No. 2 and Blade No. 3.	200.6
	Blade No. 3 and Blade No. 1.	240.8

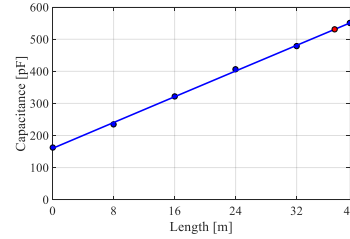
-*: Not necessary to measure.

In the same manner, the measured results were compared to the new trend curves to estimate the disconnected location of the down conductor of the wind turbine during testing. The estimated locations are demonstrated in Figs. 4.41. The blue dots, the blue line, and the red dots represent the simulation results

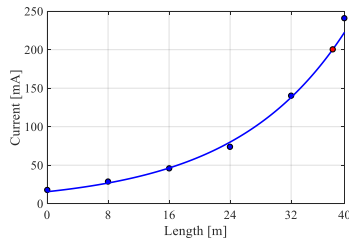
that were multiplied by the ratio factor, the trend curves, and the estimated locations, which were obtained by performing measurements.



(a) Capacitance between blades No. 2 and No. 3.



(b) Capacitance between the tower and blade No. 2.



(c) Resonant peak current of blades No. 2 and No. 3.

Fig. 4.41. Estimated locations when compared to the simulation results.

To confirm the validity of the proposed techniques, the estimated results were compared with the measured results of the traveling time when the high-steepness wave-front was injected in the down conductors during the test. Fig. 4.42 shows the traveling time while the high-steepness wave-front was injected in the down conductors of the wind turbines. The estimated results that were obtained by the proposed techniques are presented in Table 4.20.

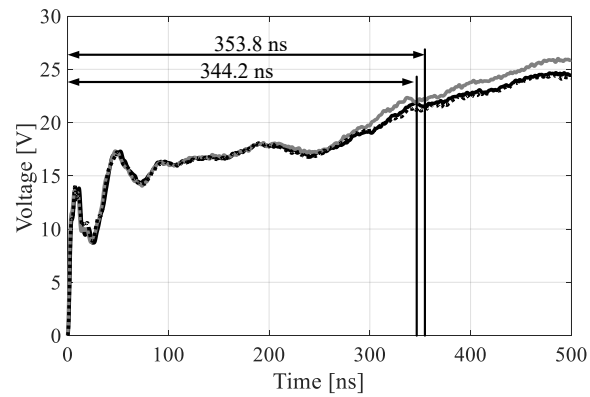


Fig. 4.42. Measured results of the reflected waveform's time for a wind turbine during testing.

Table 4.20 Disconnected locations obtained by the estimation

Sample No.	Blade No.	Disconnected locations [m]			
		Two down conductors	Tower body and the down conductor	Half-wave dipole-antenna	Propagation method
1	2	37.84	38.60	39.00	37.94

CHAPTER 5

CONCLUSIONS

This study has presented simplified and accurate testing techniques to detect the disconnection point of the down conductor by using applications of electrostatic capacitance, a half-wave dipole-antenna, and propagation phenomena of a surge waveform. With the help of the FDTD method, the simulation models can be employed to calculate the simulation models as shown in this research. To validate the proposed techniques, four types of wind turbines were used. These include: a reduced scale model, a small wind turbine, the Mitsubishi MWT-1000A, and the Gamesa G80-2.0 MW. Experiments were performed on these four types of wind turbines and the measured results were compared with the FDTD simulation results.

From the comparison results of the reduced scale model, the proposed techniques that used the electrostatic capacitance and the half-wave dipole-antenna that changed with the down conductor length had a good agreement. This might have occurred because the experiments were carried out in the laboratory where there are good conditions for testing such as a low disturbance from the electrical noise. As a result, the techniques that used the electrostatic capacitance and the half-wave dipole-antenna were applied to the small wind turbine to verify the performance to detect the disconnected location.

The simulation and experimental results from the small wind turbine, which were obtained using the application of the electrostatic capacitance, are

still in good agreement. However, the results obtained using the application of the half-wave dipole-antenna has deviations due to electrical noise. However, small deviations are acceptable. In addition, consolidating this technique with other techniques would be sufficient to determine the disconnection points.

The proposed techniques were applied to detect the disconnection points of the down conductor for practice. The proposed techniques were carried out on the Mitsubishi MWT-1000A and the Gamesa G80-2.0 MW. To confirm the validity of the proposed techniques, the traveling time of the reflected waveform was used to compare the estimated location from the proposed techniques. The comparison results revealed that there are some deviations of the estimated location that were obtained by the proposed techniques. As far as estimations are concerned, the proposed techniques can be combined to identify the disconnection point of the down conductor.

Therefore, the proposed techniques are effective to detect the disconnection points of the down conductors. In addition, the proposed techniques are economical in practice and they can be adapted to help maintenance engineers to observe the disconnection points without a trial-and-error approach. However, there is still some uncomfortable in installing the system of measurement due to size dimensions and weights of the equipment, which can be improved to future work by designing and construction of small size and lightweight of special measurement equipment.

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APPENDIX A

M-FILES MATLAB SOURCE CODE

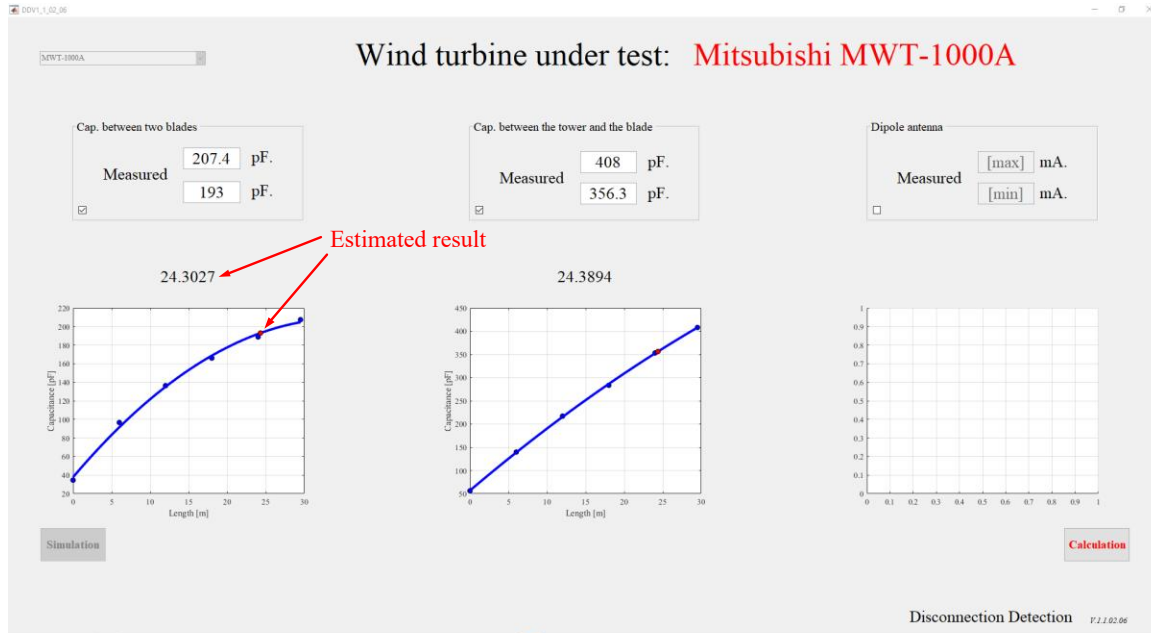


Fig. A.1. MATLAB GUI for the estimated locations of the disconnection.

A GUI (also known as a graphical user interface) is a user interface that allows users to communicate with electronic devices by using graphic icons. MATLAB is one of the world's most accessible software programs that allows user to create a GUI because it provides point-and-click control of the software to run the application. In this appendix, the M-file source code of the MATLAB GUI to estimate the disconnections of the down conductors using the proposed techniques are presented. In addition, the M-files of the associated programs to estimate the locations are presented as follows:

```

function varargout = DDV1_1_02_06(varargin)

% Begin initialization code - DO NOT EDIT

gui_Singleton = 1;

gui_State = struct('gui_Name',    mfilename, ...
                  'gui_Singleton', gui_Singleton, ...
                  'gui_OpeningFcn', @DDV1_1_02_06_OpeningFcn, ...
                  'gui_OutputFcn', @DDV1_1_02_06_OutputFcn, ...
                  'gui_LayoutFcn', [] , ...
                  'gui_Callback', []);

if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end

% End initialization code - DO NOT EDIT

```

```

% --- Executes just before DDV1_1_02_06 is made visible.

function DDV1_1_02_06_OpeningFcn(hObject, eventdata, handles, varargin)

handles.output = hObject;

guidata(hObject, handles);


% --- Outputs from this function are returned to the command line.

function varargout = DDV1_1_02_06_OutputFcn(hObject, eventdata,
handles)

varargout{1} = handles.output;


% Initial conditions of the program for estimating the disconnection.

set(handles.pushbutton1_Simulation,'Enable','off')

set(handles.pushbutton2_Cal,'Enable','off')

set(handles.WT,'String','NONE');

set(handles.edit2_BB,'Enable','off')

set(handles.edit3_BB,'Enable','off')

set(handles.edit4_TB,'Enable','off')

set(handles.edit5_TB,'Enable','off')

set(handles.edit6_DI,'Enable','off')

```

```

set(handles.edit7_DI,'Enable','off')

set(handles.checkbox1_BB,'Enable','off')

set(handles.checkbox2_TB,'Enable','off')

set(handles.checkbox3_DI,'Enable','off')


% --- Executes during object creation, after setting all properties.

function popupmenu1_Model_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),...

    get(0,'defaultUicontrolBackgroundColor'))

    set(hObject,'BackgroundColor','white');

end


% --- Executes on selection change in popupmenu1_Model.

function popupmenu1_Model_Callback(hObject, eventdata, handles)

contents = cellstr(get(hObject,'String'));

popChoice = contents{get(hObject,'Value')};

if (strcmp(popChoice,'-----Please select a model-----'))

    set(handles.WT,'String','NONE');

    set(handles.pushbutton1_Simulation,'Enable','off')

```

```

set(handles.pushbutton2_Cal,'Enable','off')

set(handles.checkbox1_BB,'Enable','off')

set(handles.checkbox2_TB,'Enable','off')

set(handles.checkbox3_DI,'Enable','off')

SIBB = 0;

SITB = 0;

SIRES = 0;

elseif (strcmp(popChoice,'MWT-1000A'))

    set(handles.WT,'String','Mitsubishi MWT-1000A');

    set(handles.pushbutton1_Simulation,'Enable','on')

    set(handles.checkbox1_BB,'Enable','on')

    set(handles.checkbox2_TB,'Enable','on')

    set(handles.checkbox3_DI,'Enable','on')

    % To load the simulation result of the Mitsubishi MWT-1000A.

    SIBB = load('MWT1000A_CAP_BB.txt');

    SITB = load('MWT1000A_CAP_TB.txt');

    SIRES = load('MWT1000A_CURRENT.txt');

else

    set(handles.WT,'String','Gamesa G80-2.0 MW');

```

```

set(handles.pushbutton1_Simulation,'Enable','on')

set(handles.checkbox1_BB,'Enable','on')

set(handles.checkbox2_TB,'Enable','on')

set(handles.checkbox3_DI,'Enable','on')

% To load the simulation result of the GAMESA G80-2.0 MW.

SIBB = load('G80_CAP_BB.txt');

SITB = load('G80_CAP_TB.txt');

SIRES = load('G80_CURRENT.txt');

end

setappdata(0,'SIBB_val',SIBB);

setappdata(0,'SITB_val',SITB);

setappdata(0,'SIRES_val',SIRES);


% --- Executes on button press in pushbutton1_Simulation.

function pushbutton1_Simulation_Callback(hObject, eventdata, handles)

SIBB = getappdata(0,'SIBB_val');

SITB = getappdata(0,'SITB_val');

SIRES = getappdata(0,'SIRES_val');

[XBB,YBB] = Polynomial_fitting(SIBB,2);

```

```

[XTB,YTB] = Polynomial_fitting(SITB,2);

[XRES,YRES] = Exponential_fitting(SIRES);

plot(handles.axes1,SIBB(:,1),SIBB(:,2),'MarkerFaceColor',[0 0
1],'Marker','o',...

    'LineStyle','none','Color',[0 0 0])

hold(handles.axes1,'on');

plot(handles.axes1,XBB,YBB,'LineWidth',3,'Color',[0 0 1]);

grid on

xlabel(handles.axes1,'Length [m]');

ylabel(handles.axes1,'Capacitance [pF]');

box(handles.axes1,'on');

set(handles.axes1,'FontName','Times New
Roman','XGrid','on','YGrid','on');

hold(handles.axes1,'off');

plot(handles.axes2,SITB(:,1),SITB(:,2),'MarkerFaceColor',[0 0
1],'Marker','o',...

    'LineStyle','none','Color',[0 0 0])

hold(handles.axes2,'on');

plot(handles.axes2,XTB,YTB,'LineWidth',3,'Color',[0 0 1]);

grid on

```

```

xlabel(handles.axes2,'Length [m]');

ylabel(handles.axes2,'Capacitance [pF]');

box(handles.axes2,'on');

set(handles.axes2,'FontName','Times New
Roman','XGrid','on','YGrid','on');

hold(handles.axes2,'off');

plot(handles.axes3,SIRES(:,1),SIRES(:,2),'MarkerFaceColor',...
      [0 0 1],'Marker','o','LineStyle','none','Color',[0 0 0])

hold(handles.axes3,'on');

plot(handles.axes3,XRES,YRES,'LineWidth',3,'Color',[0 0 1]);

grid on

xlabel(handles.axes3,'Length [m]');

ylabel(handles.axes3,'Current [mA]');

box(handles.axes3,'on');

set(handles.axes3,'FontName','Times New
Roman','XGrid','on','YGrid','on');

hold(handles.axes3,'off');

```

```

% --- Executes on button press in checkbox1_BB.

function checkbox1_BB_Callback(hObject, eventdata, handles)

CH1 = get(hObject,'Value');

CH123(1,1) = get(handles.checkbox1_BB,'Value');

CH123(2,1) = get(handles.checkbox2_TB,'Value');

CH123(3,1) = get(handles.checkbox3_DI,'Value');

SCH123 = sum(CH123);

if SCH123 == 0

    set(handles.pushbutton1_Simulation,'Enable','on')

    set(handles.pushbutton2_Cal,'Enable','off')

    set(handles.popupmenu1_Model,'Enable','on')

else

    set(handles.pushbutton1_Simulation,'Enable','off')

    set(handles.pushbutton2_Cal,'Enable','on')

    set(handles.popupmenu1_Model,'Enable','off')

end

if CH1 == 1

    set(handles.edit2_BB,'Enable','on')

    set(handles.edit3_BB,'Enable','on')

```

```

        cla(handles.axes1,'reset')
    else

        set(handles.edit2_BB,'Enable','off')

        set(handles.edit3_BB,'Enable','off')
    end

% --- Executes on button press in checkbox2_TB.

function checkbox2_TB_Callback(hObject, eventdata, handles)

CH2 = get(hObject,'Value');

CH123(1,1) = get(handles.checkbox1_BB,'Value');
CH123(2,1) = get(handles.checkbox2_TB,'Value');
CH123(3,1) = get(handles.checkbox3_DI,'Value');
SCH123 = sum(CH123);

if SCH123 == 0

    set(handles.pushbutton1_Simulation,'Enable','on')

    set(handles.pushbutton2_Cal,'Enable','off')

    set(handles.popupmenu1_Model,'Enable','on')
else

    set(handles.pushbutton1_Simulation,'Enable','off')

```

```

        set(handles.pushbutton2_Cal,'Enable','on')

        set(handles.popupmenu1_Model,'Enable','off')
    end

    if CH2 == 1

        set(handles.edit4_TB,'Enable','on')

        set(handles.edit5_TB,'Enable','on')

        cla(handles.axes2,'reset')
    else

        set(handles.edit4_TB,'Enable','off')

        set(handles.edit5_TB,'Enable','off')
    end

    % --- Executes on button press in checkbox3_DI.

    function checkbox3_DI_Callback(hObject, eventdata, handles)

    CH3 = get(hObject,'Value');

    CH123(1,1) = get(handles.checkbox1_BB,'Value');

    CH123(2,1) = get(handles.checkbox2_TB,'Value');

    CH123(3,1) = get(handles.checkbox3_DI,'Value');

    SCH123 = sum(CH123);

```

```

if SCH123 == 0

    set(handles.pushbutton1_Simulation,'Enable','on')

    set(handles.pushbutton2_Cal,'Enable','off')

    set(handles.popupmenu1_Model,'Enable','on')

else

    set(handles.pushbutton1_Simulation,'Enable','off')

    set(handles.pushbutton2_Cal,'Enable','on')

    set(handles.popupmenu1_Model,'Enable','off')

end

if CH3 == 1

    set(handles.edit6_DI,'Enable','on')

    set(handles.edit7_DI,'Enable','on')

    cla(handles.axes3,'reset')

else

    set(handles.edit6_DI,'Enable','off')

    set(handles.edit7_DI,'Enable','off')

end

```

% --- Executes during object creation, after setting all properties.

```
function edit2_BB_CreateFcn(hObject, eventdata, handles)
```

```
if ispc && isequal(get(hObject,'BackgroundColor'),...
```

```
    get(0,'defaultUicontrolBackgroundColor'))
```

```
    set(hObject,'BackgroundColor','white');
```

```
end
```

```
function edit2_BB_Callback(hObject, eventdata, handles)
```

% --- Executes during object creation, after setting all properties.

```
function edit3_BB_CreateFcn(hObject, eventdata, handles)
```

```
if ispc && isequal(get(hObject,'BackgroundColor'), ...
```

```
    get(0,'defaultUicontrolBackgroundColor'))
```

```
    set(hObject,'BackgroundColor','white');
```

```
end
```

```
function edit3_BB_Callback(hObject, eventdata, handles)
```

% --- Executes during object creation, after setting all properties.

```
function edit4_TB_CreateFcn(hObject, eventdata, handles)
```

```
if ispc && isequal(get(hObject,'BackgroundColor'), ...
```

```
    get(0,'defaultUicontrolBackgroundColor'))
```

```
    set(hObject,'BackgroundColor','white');
```

```
end
```

```
function edit4_TB_Callback(hObject, eventdata, handles)
```

% --- Executes during object creation, after setting all properties.

```
function edit5_TB_CreateFcn(hObject, eventdata, handles)
```

```
if ispc && isequal(get(hObject,'BackgroundColor'), ...
```

```
    get(0,'defaultUicontrolBackgroundColor'))
```

```
    set(hObject,'BackgroundColor','white');
```

```
end
```

```
function edit5_TB_Callback(hObject, eventdata, handles)
```

```

% --- Executes during object creation, after setting all properties.

function edit6_DI_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),...
    get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

```

```

function edit6_DI_Callback(hObject, eventdata, handles)

```

```

% --- Executes during object creation, after setting all properties.

function edit7_DI_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),...
    get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

```

```

function edit7_DI_Callback(hObject, eventdata, handles)

```

```

% --- Executes on button press in pushbutton2_Cal.

function pushbutton2_Cal_Callback(hObject, eventdata, handles)

SIBB = getappdata(0,'SIBB_val');

SITB = getappdata(0,'SITB_val');

SIRES = getappdata(0,'SIRES_val');

CB = zeros(3,1);

CB(1,1) = get(handles.checkbox1_BB,'Value');

CB(2,1) = get(handles.checkbox2_TB,'Value');

CB(3,1) = get(handles.checkbox3_DI,'Value');

%max

ED(1,1) = str2double(get(handles.edit2_BB,('string')));

ED(2,1) = str2double(get(handles.edit4_TB,('string')));

ED(3,1) = str2double(get(handles.edit6_DI,('string')));

%min

ED(1,2) = str2double(get(handles.edit3_BB,('string')));

ED(2,2) = str2double(get(handles.edit5_TB,('string')));

ED(3,2) = str2double(get(handles.edit7_DI,('string')));

for i = 1:3

    if i == 1

```

```

Ratio = (ED(i,1)/max(SIBB(:,2)));

SIBB(:,2) = SIBB(:,2).*Ratio;

elseif i == 2

Ratio = (ED(i,1)/max(SITB(:,2)));

SITB(:,2) = SITB(:,2).*Ratio;

else

Ratio = (ED(i,1)/max(SIRES(:,2)));

SIRES(:,2) = SIRES(:,2).*Ratio;

end

if (CB(i)) == 1

if i == 1

[X,Y,B] = Polynomial_fitting(SIBB,2);

B = flipud(B);

kB = B;

kB(3,1) = B(3,1)-ED(i,2);

SS = roots(kB);

if SS(1,1) >= 0 && SS(1,1) <= max(SIBB(:,1))

ANSW(i,1) = SS(1,1);

else

```

```

    ANSW(i,1) = SS(2,1);

end

plot(handles.axes1,SIBB(:,1),SIBB(:,2),'MarkerFaceColor',[0 0 1],...
    'Marker','o','LineStyle','none','Color',[0 0 0])

hold(handles.axes1,'on');

plot(handles.axes1,X,Y,'LineWidth',3,'Color',[0 0 1]);

plot(handles.axes1,ANSW(i,1),ED(i,2),'MarkerFaceColor',[1 0 0],...
    'Marker','o','LineStyle','none','Color',[0 0 0])

grid on

xlabel(handles.axes1,'Length [m]');

ylabel(handles.axes1,'Capacitance [pF]');

box(handles.axes1,'on');

set(handles.axes1,'FontName','Times New Roman','XGrid','on',...
    'YGrid','on');

hold(handles.axes1,'off');

elseif i == 2

[X,Y,B] = Polynomial_fitting(SITB,2);

B = flipud(B);

kB = B;

```

```

kB(3,1) = B(3,1)-ED(i,2);

SS = roots(kB);

if SS(1,1) >= 0 && SS(1,1) <= max(SITB(:,1))

    ANSW(i,1) = SS(1,1);

else

    ANSW(i,1) = SS(2,1);

end

plot(handles.axes2,SITB(:,1),SITB(:,2),'MarkerFaceColor',[0 0 1],...

    'Marker','o','LineStyle','none','Color',[0 0 0])

hold(handles.axes2,'on');

plot(handles.axes2,X,Y,'LineWidth',3,'Color',[0 0 1]);

plot(handles.axes2,ANSW(i,1),ED(i,2),'MarkerFaceColor',[1 0 0],...

    'Marker','o','LineStyle','none','Color',[0 0 0])

grid on

xlabel(handles.axes2,'Length [m]');

ylabel(handles.axes2,'Capacitance [pF]');

box(handles.axes2,'on');

set(handles.axes2,'FontName','Times New Roman','XGrid','on',...

    'YGrid','on');

```

```

        hold(handles.axes2,'off');
else
    [X,Y,B] = Exponential_fitting(SIRES);
    ANSW(i,1) = log(ED(i,2)/B(1,1))/B(2,1);
    plot(handles.axes3,SIRES(:,1),SIRES(:,2),'MarkerFaceColor',[0 0
1],...
        'Marker','o','LineStyle','none','Color',[0 0 0])
    hold(handles.axes3,'on');
    plot(handles.axes3,X,Y,'LineWidth',3,'Color',[0 0 1]);
    plot(handles.axes3,ANSW(i,1),ED(i,2),'MarkerFaceColor',[1 0 0],...
        'Marker','o','LineStyle','none','Color',[0 0 0])
    grid on
    xlabel(handles.axes3,'Length [m]');
    ylabel(handles.axes3,'Current [mA]');
    box(handles.axes3,'on');
    set(handles.axes3,'FontName','Times New Roman','XGrid','on',...
        'YGrid','on');
    hold(handles.axes3,'off');
end

```

```

else

    ANSW(i,1) = 0;

end

end

% To display estimated results.

if ANSW(1,1) == 0

    set(handles.AnsBB,'string','');

else

    set(handles.AnsBB,'string',ANSW(1,1));

end

if ANSW(2,1) == 0

    set(handles.AnsTB,'string','');

else

    set(handles.AnsTB,'string',ANSW(2,1));

end

if ANSW(3,1) == 0

    set(handles.AnsDI,'string','');

else

    set(handles.AnsDI,'string',ANSW(3,1));

```

```
end
```

```
% --- Executes when figure1 is resized.
```

```
function figure1_SizeChangedFcn(hObject, eventdata, handles)
```

```
function [X,Y,B] = Polynomial_fitting(DATA,deg)
```

```
%%
```

```
xi = DATA(:,1); % Down conductor length
```

```
yi = DATA(:,2); % Capacitance at each length
```

```
n = length(xi);
```

```
%%
```

```
A = zeros(deg+1,deg+1);
```

```
B = zeros(deg+1,1);
```

```
C = zeros(deg+1,1);
```

```
m = (-1:deg);
```

```
Sum_xi = zeros(2*deg,1);
```

```
A(1,1) = n;
```

```
for i = 1:2*deg
```

```
    Sum_xi(i,1) = sum(xi.^i);
```

```
end
```

```

for j = 1:deg
    A(j+1,j+1) = Sum_xi(j*2);

    for jj = j:deg
        A(jj+1,j) = Sum_xi(jj+m(j)+1);

        A(j,jj+1) = A(jj+1,j);

    end

end

for k = 1:deg+1

    C(k,1) = sum(yi.*xi.^(k-1));

end

B = A\C;

%%

X = linspace(min(xi),max(xi),500);

Y = zeros(500,deg+1);

for i = 1:deg+1

    Y(:,i) = B(i)*X.^(i-1);

end

Y = sum(Y,2);

```

```

function [X,Y,B] = Exponential_fitting(DATA)

%%

xi = DATA(:,1); % Down conductor length
yi = DATA(:,2); % Peak current at each length
n = length(xi);

%%

A = [n sum(xi);sum(xi) sum(xi.^2)];

B = zeros(2,1);

C = [sum(log(yi));sum(xi.*log(yi))];

B = A\C;

B(1,1) = exp(B(1,1));

%%

X = linspace(min(xi),max(xi),500);

Y = B(1)*exp(B(2)*X);

```

APPENDIX B

LIST OF PUBLISHED PAPERS

Transactions

EPSR Transactions

N. Triruttanapiruk, K. Yamamoto, S. Sumi, S. Yokoyama, “A simplified technique for detecting disconnections along down conductors in wind turbine blades,” *Electr. Pow. Syst. Res.*, Vol. 172, 2019, pp. 177-182.

IEEE Transactions

A. Ametani, N. Triruttanapiruk, K. Yamamoto, Y. Baba, F. Rachidi, “Impedance and Admittance Formulas for a Multi-Stair Model of Transmission Towers,” *IEEE Trans. Electromagn. Compat.* (accepted).

International Conference

ICLP

N. Triruttanapiruk, I. Koderu, K. Yamamoto, “Approach Techniques for Detecting Disconnected Locations of Down Conductors inside Wind Turbine Blades without Trial and Error,” *International Conference on Lightning Protection (ICLP)*, 2018, pp. 1-5.

APL

N. Triruttanapiruk, K. Yamamoto, “Application of Genetic Algorithm to Detect Disconnected Locations of Down Conductors along Wind Turbine Blades,” Asia-Pacific International Conference on Lightning (APL), 2019, pp. 1-4.

ISET&ISS

N. Triruttanapiruk, K. Yamamoto, “Numerical Simulation Studies of Simplified Techniques for Detecting Disconnected Locations of Down Conductors inside Wind Turbine Blades,” International Symposium on EMC and Transients in Infrastructures and International Student Session (ISET&ISS), 2018, pp. 1-4.

ISLH

T. Nishiyama, N. Triruttanapiruk, K. Yamamoto, A. Ametani, “Impedance/Admittance Formulas of Vertical Conductors for a Multi-Story Tower Model,” International Symposium on Lightning Protection and High Voltage Engineering (ISLH), 2019, pp. 1-4.