MODIFIED FINITE DIFFERENCE TIME DOMAIN MODELLING OF LIGHTNING PROPAGATION CONSIDERING NON-UNIFORM AND FREQUENCY DEPENDENT SOIL

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ABSTRACT

When cloud-ground lightning occurs, electromagnetic waves, known as electromagnetic pulses (EMPs) propagate within the earth’s atmosphere. Consequently, they may interfere with many man-made systems such as electric power lines and telecommunication networks. Several theoretical lightning return stroke models had been previously proposed. However, these models can still be improved in terms of the accuracy of the electromagnetic field (EMF) generated, the applicability for nonlinear conditions for EMP propagation, such as frequency dependence of soil parameters, the applicability for complex geometries for EMP interference with surrounding objects, and the efficiency of computation. In this research, an improvement to the finite-difference timedomain (FDTD) method was made to solve Maxwell equations in dispersive media. This includes the utilization of the recursive convolution for the solution of Ampere's law-Maxwell equations for the nonlinear conditions faced when considering the frequency dependency of soil permittivity and conductivity. Due to the relationship between the total current density and the total admittance of the soil, the convolution operator will be only used between the electric field and a time-dependent admittance. A C++ programming language was utilised to build a 3D constant recursive convolution finite-difference time-domain (CRC-FDTD) model. The proposed CRC-FDTD method had made it possible to study the effects of various factors, such as soil structures, water content, distance, and return strokes parameters, on the behaviour of lightning EMF propagation. The main EMFs considered are the vertical and horizontal electric fields, and the azimuthal magnetic field, the magnitudes of which were measured both above and underground. The results obtained from the proposed method were compared to those using the finite element analysis (FEA) based on COMSOL and the previous results adopted Delfino’s expressions. This study has successfully developed a time-domain analysis of frequency dependency by combining the CRC and FDTD techniques. The CRC-FDTD method could determine electromagnetic radiation over frequency-dependent soil in the time domain with less simulation duration, lower computational requirements, a simpler procedure, and better applicability compared to its predecessors. This has enabled us to improve the accuracy and efficiency of lightning EMF modelling and computation and investigate the effects of the soil model on electromagnetic propagation through a comparison between frequency dependent soil (FDS) model and frequency independent soil (FIS) model. The CRC-FDTD has enabled these effects such as observation distance, soil moisture, soil structure, and parameters of lightning current, to be accurately studied and analysed. CRC-FDTD is comparable to Delfino’s expressions with a slight difference in tail time, and to FEA with mean differences of 3.2% for the peak magnitude, 3.3 % for the front time, and 7.6 % for the tail time. These mean differences are considered acceptable and the validation of the CRC-FDTD can be said to be accomplished.

ABSTRAK

Apabila kilat awan-bumi berlaku, gelombang elektromagnetik yang dikenali sebagai denyutan elektromagnetik (EMP) merambat dalam atmosfera bumi. Akibatnya ia mungkin mengganggu banyak sistem buatan manusia seperti talian kuasa elektrik dan rangkaian telekomunikasi. Beberapa model panahan balik kilat telah dicadangkan sebelum ini. Walau bagaimanapun, model ini masih boleh dipertingkatkan dari segi ketepatan medan elektromagnetik (EMF) yang dijana, kebolehgunaan untuk penyebaran EMP bagi keadaan tak linear seperti penyandaran parameter tanah pada frekuensi, kebolehgunaan untuk geometri kompleks bagi menentukan gangguan EMP kepada objek persekitaran, dan dari segi kecekapan pengiraan. Dalam penyelidikan ini, penambahbaikan kepada kaedah perbezaan terhingga domain masa (FDTD) telah dibuat untuk menyelesaikan persamaan Maxwell dalam bahantara serakan. Ini termasuk penggunaan lingkaran rekursif bagi penyelesaian hukum Maxwell-persamaan Ampere untuk keadaan tak linear yang dihadapi apabila mempertimbangkan penyandaran kebertelusan dan keberaliran tanah pada frekuensi. Disebabkan oleh hubungan antara ketumpatan arus total dan admitans total tanah, pengendali lingkaran hanya akan digunakan antara medan elektrik dan admitans bersandar masa. Bahasa pengaturcaraan C++ telah digunakan untuk membina model 3D lingkaran rekursif berterusan-perbezaan terhingga domain masa (CRC-FDTD). Kaedah CRC-FDTD yang dicadangkan telah membolehkan kajian kesan pelbagai faktor, seperti struktur tanah, kandungan air, jarak, dan parameter panahan balik, ke atas tingkah laku perambatan EMF kilat. EMF utama yang dipertimbangkan ialah medan elektrik menegak dan mendatar, dan medan magnetik azimut, di mana semua magnitud diukur di atas dan di bawah tanah. Keputusan yang diperoleh daripada kaedah yang dicadangkan telah dibandingkan dengan analisis unsur terhingga (FEA) berdasarkan COMSOL dan dengan keputusan terdahulu menggunakan persamaan Delfino. Kajian ini telah berjaya membangunkan analisis domain masa bersandar frekuensi dengan menggabungkan teknik CRC dan FDTD. Kaedah CRC-FDTD boleh menentukan sinaran elektromagnetik ke atas tanah bersandar frekuensi dalam domain masa dengan tempoh simulasi lebih kecil, keperluan pengiraan lebih rendah, prosedur lebih mudah dan kebolehgunaan yang lebih baik berbanding dengan pendahulunya. Ini telah membolehkan peningkatan ketepatan dan kecekapan pemodelan dan pengiraan EMF kilat serta penyiasatan kesan model tanah terhadap perambatan elektromagnetik melalui perbandingan antara model tanah bersandar frekuensi (FDS) dan model tanah tak bersandar frekuensi (FIS). Kaedah CRC-FDTD telah membolehkan kesan seperti jarak cerapan, kelembapan tanah, struktur tanah dan parameter arus kilat, dikaji dan dianalisis dengan tepat. Kaedah CRC-FDTD adalah setanding persamaan Delfino dengan sedikit perbezaan pada masa ekor, dan setanding kaedah FEA dengan min perbezaan 3.2% untuk magnitud puncak, 3.3 % untuk masa hadapan dan 7.6% untuk masa ekor. Perbezaan min ini dianggap boleh diterima dan pengesahsahihan CRC-FDTD boleh dikatakan tercapai.

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Figure 4.50 Variation of the H_ϕ with water percentage for five different soil models determined at 50 meters from the lightning location: a) 10 meters aboveground and b) 10 meters subsurface. 179

LIST OF ABBREVIATIONS

Uniform soil - All layers have same water content
H_ϕ - Azimuthal magnetic field
CRC-FDTD - Constant Recursive Convolution Finite-Difference Time-Domai
EM - Electromagnetic
EMF - Electromagnetic Field
EMR - Electromagnetic Radiation
FEA - Finite Element Analysis
FDTD - Finite-Difference Time-Domain
FD - Frequency Dependence
FDS - Frequency dependent soil
FIS - Frequency independent soil
Non-uniform soil - Layers have different water content
LEMP - Lightning Electromagnetic Pulse
PML - Perfect Match Layer
E_r - Radial electric field
RSC - Return stroke current
S - Scott soil model
SL - Smith & Longmire soil model
Observation distance - The distance from lightning channel
E_z - Vertical electric field

LIST OF SYMBOLS

DC - Direct Current

E - Electric Field

H - Magnetic Field

c - Propagation Velocity of Light

μ_r - Relative Permeability

ε_r - Relative Permittivity

σ - Electric Conductivity

ω - Angular Frequency

B - Magnetic Flux Densities

D - Electric Flux Densities

ρ_v Volume Charge Density

J_T Total Current Density

dt Time Interval

J_s Surface Current Density

Y_T Total Soil Admittance

J_f Free Current Density

J_d Bound Current Density

Y_{fd} Frequency Dependence Admittance

Y_c Constant Soil Admittance

CHAPTER 1

INTRODUCTION

1.1 Background

Lightning is a vigorous natural phenomenon that has a significant presence in, and effects on, human lives and man-made systems. The electrical discharge with high current passes through the air for up to several kilometres. Several types of lightning include the cloud-to-ground, cloud-to-cloud, and intro-cloud discharges. However, cloud-to-ground lightning is the most important type since it can severely affect man-made systems such as the electric power system [1, 2]. The lightning electric discharge, normally called a flash, consists of twelve stages, starting from the point when the charges are distributed inside the cloud and ending with the occurrence of the last subsequent return stroke [3-5]. The return-stroke phase of a flash has garnered the most attention for its potential use for protection objectives. Uman estimates that the duration of a lightning flash is 63 milliseconds, and each of the phases described above lasts for a certain amount of time [3]. The term "lightning return-stroke model" refers to a definition of the time and height-dependent current in the return-stroke channel (RSC) that allows the computation of the resulting distant electromagnetic fields [6].

Much research has been performed to solve the difficulty of estimating the electromagnetic fields produced by lightning return strokes. Several current distribution models for the lightning strike channel have been presented [6, 7]. Several approaches to model and compute the lightning electromagnetic fields [8-10] were also described. In addition, comparisons between computed and measured fields were also made [11-13]. It is noted that, in these studies, the ground had been assumed either as a perfectly conducting plane, or as a soil having constant conductivity and permittivity, irrespective of the frequency of the propagating electromagnetic fields. In recent years, several attempts had been made to consider the influence of frequency on soil conductivity and permittivity, and hence their effects on the propagating waves [14-18].

1.2 Research Motivation

As previously stated, electromagnetic field radiation, also known as electromagnetic pulses (EMP), is generated by the lightning return stroke due to the enormous current traveling via the discharge channel initiated between cloud and ground. The electromagnetic field or the EMP propagates in all directions and over long distances. In fact, the electromagnetic wave may travel through different media, including the soil. Because of this, it may pose a threat to the stability and reliability of man-made systems such as the overhead electric power transmission and telecommunication systems, as well as buried or underground transmission systems. Therefore, it is important to be able to know exactly the interaction between the lightning EMP and these systems so that appropriate measures can be taken to minimise its effects [19-22]. It is noted that the lightning electromagnetic fields experience certain changes as they propagate through a given propagation medium due to phenomena such as wave attenuation, especially for the high-frequency signals when propagating over a finitely conducting ground, also known as a lossy ground. Thus, the measured lightning electromagnetic fields at a given observation location can be said to be dependent on the propagation distance as well as on the ground or soil conductivity. Key measured parameters of the fields include the peak, the rise time, and the time derivatives. An assumed lossless ground may therefore give underestimated magnitudes of the lightning fields and hence may underestimate their deleterious effects.

Because of its important effect on lightning electromagnetic field propagation, the soil or ground is usually modelled as lossy instead of lossless ground. Several lossy ground models have been previously proposed. However, a simplified version of the models, that is using constant values of soil conductivity and permittivity, was adopted [23-25]. Then, in 2009 [14], an improved model using frequency dependent soil conductivity and permittivity, was proposed. However, the proposed method has a drawback, namely, it is only applicable for a uniform soil condition. It did not cater for non-homogenous or non-uniform soil structures.

Apart from the soil model drawbacks, the computation of the lightning electromagnetic fields, which is primarily based on solving the relevant Maxwell equations, at a given observation point is also a challenge to many researchers. Recently, an improved numerical solver over its predecessors to compute lightning electromagnetic fields in frequency domain was proposed [26]. Thereafter, the frequency dependent soil was also incorporated in the frequency domain solvers [14, 15, 17, 18]. However, several limitations of the methods still exist, for example, in terms of accuracy, applicability, and computational requirements. Because of these limitations, alternative methods were further explored, including solving the field computation in the time domain. One promising method that can give superior performance is known as the finite difference time domain (FDTD) method [27]. Among the FDTD method's advantages are simplicity, suitability for non-homogeneous geometries, capable of incorporating nonlinear effects and components, and ability to handle wideband quantities from a single run [24, 28].

The challenge when using the FDTD technique is to solve the Maxwell equations in a lossy or dispersive propagation medium. This is because the resultant equations are rather complex, primarily due to the step which involves a recursive implementation of the convolution between the time-dependent electric susceptibility function and the electric field in the so-called Maxwell update equations [29]. The convolution is basically an integral that expresses the amount of overlap of the electric field as it is shifted over the electric susceptibility function. The electric field in the convolution integral form may be approximated by three main approaches that were previously proposed to solve this specific problem, namely, the Recursive Convolution

(RC), the auxiliary differential equation, and the Z-transform techniques [30]. It is to be noted, in the previous studies, the soil had been modelled as having a permittivity in a complex number format, and conductivity in a real number format and of constant value [31]. The main drawback of these studies is that the soil conductivity is actually treated as a constant parameter [28]. However, based on previous studies of return stroke models, the frequency dependence of soil conductivity is more significant since it has more effect on the lightning fields than that of the permittivity of the soil [14-16, 18].

In the above studies, the soil is modelled as having a uniform profile. The consideration of a non-homogeneous or non-uniform soil structure poses another challenge since not only the soil permittivity and conductivity have to be frequency dependent, the number of soil types or layers need also to be varied at the same time. Even though the effects of soil homogeneity on the lightning propagation have been studied for different cases such as vertical and horizontal straight layers [32-35], most of the studies did not consider the frequency dependency of the soil permittivity and conductivity. In addition, several studies were also previously carried out on the effects of soil condition, namely, soil conductivity, on lightning field propagation. In the studies, the soil conductivity was varied using water content [14, 15]. However, the behaviour of EMFs in the existence of frequency dependent soil with varying soil conductivity is yet to be fully explored.

1.3 Problem Statement

A precise understanding of the lightning electromagnetic pulse (LEMP) is critical for determining the precise interaction of the LEMP with any sensitive systems and for selecting the appropriate hazard level, which results in a well-organized design of protective systems. Electromagnetic waves propagating across the flat ground are primarily influenced by the ground's physical and geometric features, such as the soil's electric properties and homogeneity. Several limitations of the methods still exist, for example, in terms of accuracy, applicability, and computational requirements. Because of these limitations, alternative methods were further explored, including solving the field computation in the time domain.

Several previous time-domain based lightning electromagnetic field propagation models can be used to compute the field at a given observation location. However, in these time-domain models, the frequency dependency of soil permittivity and conductivity cannot be incorporated even though it is known that the soil properties change with the propagating wave frequency. The inaccuracy of the estimated electromagnetic fields may lead to an underestimation of the LEMP's interaction with any sensitive devices and the selection of the appropriate hazard level. In addition, the accuracy, applicability, and computing needs of the techniques are still limited. Because of these disadvantages, it was recognized that a practical method was necessary. Therefore, there is a need to mathematically develop a new model for lightning propagation together with a frequency-dependent soil so that more accurate fields can then be computed. Previous attempts on the calculation of lightning EMFs involving a frequency-dependent soil were only carried out using a finite element analysis (FEA), which is a frequency domain solver. Even though the frequency-domain method provides more accurate results than that of the time-domain method, it suffers from many drawbacks in terms of simulation speed, procedure complexity, observation range, consideration for nonlinear effects, and cost. Therefore, there is a need to overcome these drawbacks by using alternative techniques such as the time-domain approach instead of the inferior frequency-domain method.

There is a problem that appears when employing the FDTD approach, the Maxwell equations can't be solved in a lossy propagation medium. There are three methods to represent Maxwell’s equations through the dispersive material: the exact, the simplified, and the approximation models. The exact equation is frequency-dependent for both permittivity and conductivity. Due to the difficulty of needing to do two convolution processes, the FDTD approach cannot be implemented. The simplified equation treats permittivity and conductivity as constant quantities. The approximation equation takes permittivity only as a frequency-dependent parameter into account. These simplifications will impact the precision of the results. So, there is a need for an equation that takes into account that both permittivity and conductivity are frequency dependent and avoids complexity. This is owing to the presence of a convolutional term in the Maxwell update equations, which makes the resulting equations quite complex. Three main approaches previously proposed to solve the convolution term problem, are the Recursive Convolution (RC), the auxiliary differential equation and the Z-Transform techniques. The main drawback of previous studies is that the soil conductivity is actually treated as a constant parameter even though the frequency dependence of soil conductivity significantly affects the lightning electromagnetic fields. Therefore, there is a need to overcome this major drawback by proposing a new technique that considers the frequency dependency of both soil permittivity and conductivity.

The lightning electromagnetic propagation is also known to be affected by soil structure. However, previous work on lightning propagation models over frequency dependent soil assumes the soil to be uniform. Hence, there is also a need to propose a lightning propagation model with soil non-uniformity to be taken into consideration. In addition, the effect of soil conductivity together with frequency dependency, on the lightning electromagnetic field propagation need also be fully understood. The effects of soil structure, lightning return stroke current parameters, and observation distance at which the lightning field is computed, on the computed fields also remain to be fully understood.

1.4 Research Objectives

The main purpose of this study is to improve a more accurate, more efficient, faster, and simpler method to model and compute lightning electromagnetic fields with frequency dependency of soil permittivity and conductivity taken into consideration. To achieve this aim, the following specific objectives are given:

1. To develop an improved model of lightning electromagnetic field propagation incorporating frequency dependent soil based on CRC-FDTD method.
2. To validate the proposed CRC-FDTD method using a direct comparison with the frequency domain method.
3. To determine the effects of soil structure, soil conductivity, observation distance, and lightning return stroke parameters on the lightning electromagnetic fields using the proposed technique.

1.5 Scope of Work

The study focuses on the modelling of a return stroke model that is limited by the following scopes:

(i) The air propagation medium is considered as a homogeneous medium with the following constant properties: Permittivity = 1, conductivity = 0 (mho/m). This means the variation of air property is not considered. This limitation does not adversely affect the computation accuracy, since the air does not have frequency dependency.

(ii) The lightning electromagnetic fields are assumed to propagate without any reflections from any blocking objects or outer atmosphere. Also, the ground is considered as a complete flat surface. For the outer atmosphere, Liao's second-order is applied.

(iii) The typical cloud-to-ground lightning flash consists of an electrical conductor channel that is over 6.4 kilometres (4 miles) in height, extending from inside the cloud to the surface of the earth. In this research, the recommended height for the lightning channel is 7 km [24].

(iv) The soil moisture is selected as a percentage of soil water content and is limited to a range from 0.5% to 100%. The frequency-dependency is limited to the range of 0 Hz (DC) to 5 MHz since the proportional relation of permittivity and conductivity to frequency can be neglected.

(v) In the frequency independent soil (FIS) model, the conductivity and permittivity are considered as a mean value (constant value) of frequency-dependent soil for the same frequency range at each water content.

(vi) In soil structure, the scenarios are limited to two layers, and each layer has different water content percentages. This research is limited to five soil structures.

(vii) Only four typical cases of return stroke currents are carried out in this research. The study of return stroke effects is limited to main parameters, namely; peak values, front times, and decay time.

(viii) The comparison between soil models is limited to which model the conductivity can be governed through the initial value conductivity. Because the conductivity and the permittivity can be calculated for various percentages of water content. The soil models are utilised in this research; Scott (S) Expressions, Smith and Longmire (SL) Expressions, Visacro and Portela (VP) Expressions, Messier (M) Expressions, and Alipio and Visacro (AV) Expressions.

1.6 Research Contributions

The following are the primary contributions of this thesis work:

i. Proposed CRC-FDTD algorithm for EMF computation in time domain

Electromagnetic field modelling and computation in the time domain poses a challenge to mathematical expressions. This study has successfully developed a time domain analysis taking consideration of the frequency dependency of the soil medium through a combination of the CRC and FDTD techniques. The proposed algorithm considers the dispersive or lossy properties of the soil propagation medium without resorting to approximations for soil permittivity and conductivity as were done in previous research.

ii. Lightning electromagnetic field propagation model

There are several limitations faced when carrying out simulation studies in the frequency domain, such as the problem of speed and ease of use. It is desired to have an alternative lightning EMF propagation model in the time domain where the simulation process is faster and easier. Based on the developed Constant Recursive Convolution Finite-Difference Time-Domain (CRC-FDTD) algorithm, the return stroke lightning electromagnetic field propagation and determination at any observation location are possible to be materialized. The propagation and computation of the electromagnetic fields were implemented in the time domain using C++ and the soil is modelled as having frequency dependent permittivity and conductivity. The lightning electromagnetic field propagation model was successfully implemented with the measured electromagnetic fields that can be determined at any observation distance and for both in the air as well as within the soil. This has helped to improve the accuracy and efficiency of lightning electromagnetic field modelling and computation, and hence eventually may solve the problem of underestimating their effects on man-made systems.

iii. Effects of key factors on lightning EMF

The effects of several key factors, such as observation distance, soil moisture, soil structure, and parameters of lightning current, on the behaviour of the return stroke lightning electromagnetic fields when propagating over lossy soil remain are yet to be fully understood. The electromagnetic field propagation model developed in this work has enabled these effects to be studied and analysed. The effects of these key factors on the lightning electromagnetic fields are listed below:

a. Observation Distance

Compared to the propagation model using frequency independent soil, the propagation model using the frequency dependent soil gives a more accurate result. This is true for all electromagnetic field components studied and measured in air as well as within the soil. The frequency-dependency of the soil has some impacts on the generated lightning EMFs above and within the soil. For various observation distances, the frequency dependency of soil affects both the computed vertical and radial electric fields. To a lesser extent, it also affects the azimuthal magnetic field (within soil). The waveshape, peak values, and polarities of EMFs may all be affected by the distance from the lightning channel. These variations give a new insight into the behaviour of lightning EMF.

b. Soil Moisture

The impacts of variable soil water content on the lightning EMFs using a frequency dependent soil (FDS) model were also studied. The research has shown that water presence in the soil gives different effects on the lightning electromagnetic field propagation when, together with the water presence, the soil is also modelled either as frequency dependent or as frequency independent. Also, water presence affects the lightning electromagnetic fields within the soil more than it affects the fields above the soil.

c. Soil Homogeneity

The soil structure has a direct impact on the lightning electromagnetic field propagation. The structure and uniformity of soil give significant effects on the above ground lightning electric field, and these effects increase with the propagation distance. However, they have an unnoticeable effect on the above ground azimuthal magnetic field. On the other hand, the propagation of the three electromagnetic field components within the soil is significantly affected by the soil structure and uniformity, and these effects reduce with the propagation distance. The presence of water in the non-uniform soil also affects the EMF propagation for all fields.

d. Lightning Current

Beside the effects of soil water content, the return stroke current parameters effects, namely, the decay time, rise time, and peak value, on EMF propagation are yet to be fully discovered. The soil response on the lightning electromagnetic field propagation was found to be dependent on these parameters. The shape and magnitude of above and below ground electromagnetic fields were directly influenced by the current waveform. The measurement of the lightning electromagnetic field waveforms enables us to determine the magnitudes and shape of a lightning currents source.

iv. Comparative Performance of Frequency Domain Soil Models

Because of its attractive attributes, frequency domain electromagnetic field simulation using frequency domain soil models still remains popular for certain applications. Researchers have previously developed a number of soil models that include frequency dependence. However, an analysis on their relative performance is yet to be made available. In this work, five soil models were assessed in a frequency domain simulation. By comparing the computed electromagnetic fields in the air as well in the soil, it is found that two frequency domain soil models, namely, the Scott mode (S) and the Alipio and Visacro (AV) models are more suitable to be adopted in frequency domain electromagnetic field propagation studies.

1.7 Research Significance

This research has made several contributions as listed above. The research also has several significance as listed below.

i. The use of frequency domain solvers to study lightning EMF poses many challenges such as a very long simulation duration due to thousands of frequencies needed to be simulated so as to accurately represent the fast rising lightning return stroke current. A quicker method is provided by a time domain solver, such as the FDTD method. However, the challenge when using the FDTD method is the difficulty to solve the Maxwell equations in a lossy propagation medium. This is mainly due to the complexity of the algorithm or resultant equations, primarily due to the presence of a recursive convolution term when deriving the so-called Maxwell update equations. This research has solved the said difficulty by introducing the CRC-FDTD method which is more accurate than previously reported FDTD methods. The introduction of this new method has enabled us to carry out lightning EMF studies in an easier and faster manner compared to that provided by the frequency domain method.

ii. The use of the proposed CRC-FDTD method has enabled us to carry out many studies on the lightning EMF including the effects of many key factors such as soil moisture, soil homogeneity, propagation distance and return stroke parameters. Such studies were not so easily carried out previously because of the limitations faced when using the frequency domain method.

iii. Despite the frequency domain method having a better simulation result accuracy than that of the time domain method, the currently available frequency domain methods are not capable of simulating the non-linear properties of the propagation medium, such as the soil ionization phenomenon. The proposed CRC-FDTD method however is able to model such nonlinear properties. Under such a situation, this may narrow the difference in accuracy between the CRC-FDTD method and the frequency domain method.

1.8 Thesis Outline

This thesis is organized into five chapters that contain in-depth information of the study and provide a comprehensive description of the work. The first chapter discusses the research background, the reasons for carrying out this thesis, the goals to achieve to complete this work, research objectives, research scopes, research contributions, and research significance.

Chapter 2 covers the literature review on lightning return-stroke, lightning channel models, lightning current waveform, lightning electromagnetic pulse (LEMP) models, the propagation media, the effects of frequency-dependent soil, and soil uniformity on lightning electromagnetic propagation, and an overview of numerical solvers used to determine electromagnetic fields in time and frequency domain.

Chapter 3 outlines the research methodology, which starts with the general differential form for Maxwell's equations and the shortcomings in previous electromagnetic radiation models and the need to adjust the finite-difference time-domain approach for lightning propagation models, followed by a comparison between non-dispersive medium and dispersive medium. The lightning return stroke model consists of four parts, namely, determination of the lightning return stroke current parameters, modelling of the return stroke, the soil, and electromagnetic field propagation. The numerical solvers were described that have been used in this research to determine the electromagnetic field. The method and model parameters of the lightning electromagnetic pulse over soil frequency-dependent, the effect of FDS on LEMP, effects of soil uniformity on LEMP, the return stroke parameters effects on LEMP, and distance effect on LEMP was described. Five soil models and their expressions and equations are given in detail to be assessed based on their eligibility to model lightning electromagnetic propagation.

Chapter 4 reports and discusses the results obtained from simulations. At the beginning of this chapter, the CRC-FDTD mathematical derivation and the linear relationship between the soil total current density, J_T, and the soil electric field, E, are explained. The results of the CRC-FDTD method have been validated with the FEA method through the examination for the lightning EMF propagation over and within a FDS. Also, the chapter reports the results of the FDS effect, soil uniformity effects, return stroke parameters effects, and distance effects, on LEMP by using the improved CRC-FDTD method. In addition, soil models assessments are also presented. All the results are given in form of graphical plots namely; the radial electric field (E_r), the vertical electric field (E_z), and the azimuthal magnetic field (H_ϕ).

The findings of this study are summarized in Chapter 5. This chapter also includes recommendations and plans for future research.

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