Lightning Transient Study of a Communication Tower

Magnetic Field $H_x$

Scenario 2 (SC2)

Lightning Strike

Observation Point

SC1

SC2

SC3
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Lightning Transient Study of a Communication Tower

2017 Release
# Revision Record

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SPECIAL NOTE

As SES software is constantly evolving, with frequently created updates, minor discrepancies may appear between this How To manual illustrations of the software interface and the present software version interface. These differences are cosmetic in nature and do not impact the validity of the guidance and procedures provided herein. Furthermore, small differences in the reported and plotted numerical values may exist due to continuous enhancements of the computation algorithms.

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CHAPTER 1
INTRODUCTION

1.1 OBJECTIVE

The objective of this example is to demonstrate how to use the combined powers of the HIFREQ and FFTSES modules of the CDEGS software package to study transient electromagnetic fields response near a communication tower subjected to lightning strikes. This booklet describes the modeling of the communication tower and discusses the methods used to obtain its response to a direct lightning strike. The main computation results are discussed and displayed graphically.

Please note that you may press the F1 key at any time to display context-sensitive help pertinent to the topic to which you have given focus with your mouse. You may also access the complete online help file by selecting the Interface Help (F1) option from the Manuals drop down from the Help tab of the CDEGS start-up window.

If you are anxious to start entering data and running CDEGS you may do so by skipping the rest of this chapter, Chapter 2 and Chapter 3. We strongly recommend, however, that you refer to the skipped sections to clarify items related to input files, system configuration and data, and design methodology.

The work is based on a paper published in the Proceedings of the first IEEE International Conference on Electromagnetic Compatibility (Kuala Lumpur, Malaysia, 1995). The paper is also provided in Appendix B. In the paper, a 50 m high communication tower connected to different grounding grids is subjected to a direct lightning strike at various locations of the tower. The transient electromagnetic fields near the base of the tower are computed.
1.2 COMPUTER MODELING TOOL

The computation program modules HIFREQ and FFTSES of the SES’s MultiFields, MultiFieldsPro or CDEGS software package are used for this study. This tutorial also illustrates the use of some of SES input and output processors.

1.3 ORGANIZATION OF THE MANUAL

The organization of this booklet is as follows. Chapter 2 describes the system being modeled. Chapter 3 outlines the computation methodology and briefly describes the three computation steps involved:

1. Frequency Decomposition of the Time Domain Signal
2. Computation of the Frequency Domain Electromagnetic Field Response
3. Computation of the Time Domain Electromagnetic Field Response

The frequency domain decomposition of the lightning pulse with FFTSES is discussed fully in 0. Chapter 5 describes how to model the tower and associated grounding systems. It also illustrates how to use HIFREQ to compute the frequency domain electromagnetic fields around the tower at the frequencies recommended by FFTSES. Chapter 6 shows how to use FFTSES to combine the frequency domain results of Chapter 4 and Chapter 5 to form the time domain electromagnetic fields around the tower. Chapter 7 discusses an iteration of the process of Chapter 5 and Chapter 6, following recommendations by FFTSES.

Finally, Chapter 8 describes how the process described from Chapter 4 to Chapter 7 can be automated by using the AutoTransient tool in CDEGS.

1.4 SOFTWARE NOTE

This tutorial assumes that the reader is using the Windows version of CDEGS.

1.5 FILE NAMING CONVENTIONS

It is important to know which input and output files are created by the CDEGS software. All CDEGS input and output files have the following naming convention:

\[ XY_{JobID}.Fnn \]

where \( XY \) is a two-letter abbreviation corresponding to the name of the program which created the file or which will read the file as input. The JobID consists of string of characters and numbers that is used to label all the files produced during a given CDEGS run. This helps identify the corresponding input, computation, results and plot files. The \( nn \) are two digits used in the extension to indicate the type of file.
The abbreviations used for the various CDEGS modules are as follows:

<table>
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<th>Application</th>
<th>Abbreviation</th>
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<th>Abbreviation</th>
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<td>RESAP</td>
<td>RS</td>
<td>FCDIST</td>
<td>FC</td>
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<tr>
<td>MALT</td>
<td>MT</td>
<td>HIFREQ</td>
<td>HI</td>
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<tr>
<td>MALZ</td>
<td>MZ</td>
<td>FFTSES</td>
<td>FT</td>
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<tr>
<td>TRALIN</td>
<td>TR</td>
<td>SESEnviroPlus</td>
<td>TR</td>
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<tr>
<td>SPLITS</td>
<td>SP</td>
<td>SESShield-3D</td>
<td>SD</td>
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<tr>
<td>SESTLC</td>
<td>TC</td>
<td>ROWCAD</td>
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<tr>
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<tr>
<td>GRSPLITS-3D</td>
<td>SP</td>
<td>CorrCAD</td>
<td>CC</td>
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<tr>
<td>AutoGroundDesign</td>
<td>AD</td>
<td>SESThreshold</td>
<td>TH</td>
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<tr>
<td>SESAmpacity</td>
<td>AP</td>
<td>SESCrossSection</td>
<td>XS</td>
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<tr>
<td>SESImpedance</td>
<td>FM</td>
<td>CSIRPS*</td>
<td>CS</td>
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</table>

* The CSIRPS module is used internally by the graphics and report generating interfaces.

The following four types of files are often used and discussed when a user requests technical support for the software:

- **.F05** Command input file (for computation applications programs). This is a text file that can be opened by any text editor (WordPad or Notepad) and can be modified manually by experienced users.

- **.F09** Computation results file (for computation applications programs). This is a text file that can be opened by any text editor (WordPad or Notepad).

- **.F21** Computation database file (for computation applications programs). This is a binary file that can only be loaded by the CDEGS software for reports and graphics display.

- **.F33** Computation database file (for computation applications programs MALZ and HIFREQ only). This is a binary file that stores the current distribution to recover.

For further details on CDEGS file naming conventions and JobID, consult the CDEGS Help by pressing F1 in the main CDEGS interface and navigating to **Using CDEGS – Working With CDEGS Projects – File Naming Conventions**.
In CDEGS-Legacy, the same help entry is available under the menu Help | Contents | File Naming Conventions.

### 1.6 DEMO EVALUATION

In order to be able to evaluate SES Software without a license, you should install the software as a demo. This will give you access to the computed results without extra effort.

In the demo environment, the input and output files of the case studies in this tutorial are already installed under the SES Software documents subfolder, HowTo; e.g., “C:\Users\Public\Documents\SES Software\<version>\HowTo\CDEGS\Lightn”, where <version> is the version number of SES Software. You must use this default location as the working directory when the software is installed as a demo.

### 1.7 WORKING DIRECTORY

A Working Directory is a folder where all input and output files of case studies are stored and created. If you are doing a demo evaluation, the working directory for this tutorial is already set up by the installation. If you have a valid SES Software license to use the programs that are covered by this tutorial, we recommend using the following working directory to follow the tutorial.
<drive>\CDEGS HowTo\Lightn

e.g., C:\CDEGS HowTo\Lightn

### 1.8 INPUT AND OUTPUT FILES USED IN TUTORIAL

All input and output files used in this tutorial are supplied from the SES Software distribution. When the software is installed as a demo, the full set of distribution files are available under the default SES Software documents subfolder, **Setup.Z**, where “Z” is part of the version number of the software. Note that the package file, SESXY.EXE, may be unpacked at any time (“X” and “Y” are part of the version number of the software) if the tutorial is being followed without a demo installation.

The original files of this tutorial can be found in the distribution under the following subfolders:

- **Input Files:** Examples\Official\HowTo\CDEGS\Lightn\inputs
- **Output Files:** Examples\Official\HowTo\CDEGS\Lightn\outputs

If you prefer to load the input files into the software and simply follow the tutorial, copy all the files from the **inputs** subfolder in the distribution to your working directory. The **outputs** subfolder contains the precomputed results that can be used if you do not have a valid license. The above locations can also be used to refresh files in the working directory if you feel the need to do so. Note that the files found in both the **inputs** and the **outputs** subfolders should be copied directly into the working directory, not into subdirectories.

After the tutorial has been completed, you may wish to explore the other how-to engineering manuals; they can be accessed from the program shortcut, **SES Software X.Y > Documentation > Manuals**. The same manuals can also be retrieved from the SES Software distribution under the subfolder, **PDF\HowTo Manuals**.
CHAPTER 2
DESCRIPTION OF THE PROBLEM BEING MODELED

Figure 2-1 illustrates the problem studied in the Malaysia paper. Three different scenarios are examined in the paper. To reduce the computation time, we have chosen a simplified version of Scenario 1 (SC1) to illustrate how to obtain the temporal evolution of the scalar potential, the electric field and the magnetic field. The resulting configuration is shown in Figure 2-2. It consists of a 50 m high communication tower connected to a simple grounding system. The tower structure is approximated by 10 mm radius steel rods and the grounding system by copper conductors with a 6 mm radius. The grounding system consists of the bottom part of the tower, three vertical ground rods which are driven to a depth of 3 m and a 30 m horizontal conductor which is buried at a depth of 1 m and is used to connect one leg of the tower (Leg A) to the three vertical ground rods. To simplify Scenario 1, the horizontal loop conductors on the communication tower and a 40 × 65 m rectangular conductor loop buried at a depth of 0.5 m are removed. Such simplification will not change the main features of the transient electromagnetic fields near the tower. A uniform soil with a 100 Ω-m resistivity, a relative permittivity of 1 and relative permeability of 1 is assumed.
The lightning surge current considered in this study is defined by the following double exponential type function:

\[ I(t) = I_m \left( e^{-\alpha t} - e^{-\beta t} \right) \]  \hspace{1cm} (1)

where \( I_m = 30 \text{ kA}, \alpha = 1.4 \times 10^4 \text{ s}^{-1} \) and \( \beta = 6 \times 10^6 \text{ s}^{-1} \). The waveform, as shown in Figure 2-1, is characterized by a rise time of 1 μs and a half-value time of 50 μs, which are typical values for lightning strokes.
The method used to obtain the electromagnetic fields in the time domain is described as follows. By means of the Fourier Transform, the scalar potential and electromagnetic field in the time domain are given by

\[ V(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} V(\omega)e^{i\omega t} d\omega = \frac{1}{2\pi} \int_{-\infty}^{+\infty} V_o(\omega)I(\omega)e^{i\omega t} d\omega \]  

\[ E(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} E(\omega)e^{i\omega t} d\omega = \frac{1}{2\pi} \int_{-\infty}^{+\infty} E_o(\omega)I(\omega)e^{i\omega t} d\omega \]  

\[ H(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} H(\omega)e^{i\omega t} d\omega = \frac{1}{2\pi} \int_{-\infty}^{+\infty} H_o(\omega)I(\omega)e^{i\omega t} d\omega \]  

where

\[ I(\omega) = \int_{-\infty}^{+\infty} I(t)e^{-i\omega t} dt \]  

is the frequency spectrum of the lightning surge current and \( V_o(\omega), E_o(\omega), H_o(\omega) \) are the unmodulated scalar potential, electric field and magnetic field in the frequency domain, respectively.

The unmodulated electromagnetic fields are generated by a unit current energization of the conductor network. The computation of the frequency domain response \( V_o(\omega), E_o(\omega), H_o(\omega) \) is done by HIFREQ, while both the forward and inverse Fourier Transform are carried out by FFTSES.

The program outlined above requires, in principle, the computation of the electromagnetic field frequency domain response for a very large number of frequencies. This can be highly time consuming and can render such studies impracticable.

One of the most attractive features of the FFTSES program is its ability to compute the time domain electromagnetic fields from the corresponding frequency domain response at a relatively small number of frequencies. The program actually recommends a set of computation frequencies, based on the shape of the input signal and, eventually, on that of the frequency domain response.

This leads to an iterative procedure as outlined in the following.

1. **Frequency Decomposition of the Time Domain Signal:** Using FFTSES, select a time domain lightning signal (using built-in functions) and express it in the frequency domain. The program recommends some computation frequencies for the electromagnetic fields response.

2. **Computation of the Frequency Domain System Response:** Build a conductor model for the tower and associated grounding structure. Using HIFREQ, compute the unmodulated
frequency domain system response $V_\omega(\omega), E_\omega(\omega), H_\omega(\omega)$ at the recommended frequencies.

3. **Computation of the time domain system response:** Extract the results from the HIFREQ database and create the FFTSES database with SIRPS. Compute the time domain system response $V(t), E(t)$ and $H(t)$ with FFTSES. The program recommends more computation frequencies, based on the shape of the frequency domain response.

Steps 2 and 3 are then repeated until FFTSES stops recommending frequencies or until sufficient accuracy is achieved.

**Note:**

By its very nature, such a study involves repeated runs of HIFREQ, SIRPS and FFTSES. All those runs could be done under a common “JobID”. However, this would mean that ulterior HIFREQ runs would overwrite the database created in the prior ones. Since all of the HIFREQ databases might be needed for further analysis, it is recommended to execute each HIFREQ run under a different JobID. This will avoid repeating some HIFREQ runs (which can be time consuming). In this example, the common JobID will be chosen as TRANSI (for transient) and we will use RUN1, RUN2 and RUN3 as JobIDs for the three different HIFREQ runs.

In the following Chapters, the computations outlined above are described in detail. Within each chapter, step-by-step instructions about how to carry out the computations are given: These instructions include:

- How to setup the input file.
- How to submit the HIFREQ or FFTSES run.
- How to extract results from the output files.
CHAPTER 4
FREQUENCY DECOMPOSITION OF THE TIME DOMAIN SIGNAL

In this Chapter, we will describe how to decompose the time domain signal $I(t)$ into the frequency spectrum $I(\omega)$ by using the forward FFT in FFTSES.

4.1 PREPARATION OF THE FORWARD FOURIER TRANSFORM INPUT FILE

The Fourier transform input file can be prepared using the FFTSES module interface or with a standard text editor such as the one provided with CDEGS.

The following section describes the Windows compatible input session, which is used to generate the SICL (SES Input Command Language) Command mode compatible input file, (F05 file extension) described in Appendix A both of which can be reloaded during subsequent sessions.

4.1.1 Windows Input Mode

This section describes in detail how to prepare the FFTSES input data using the Windows Input Mode. The most important features in preparing the data are explained in section 4.1.1.2.

4.1.1.1 Start-Up Procedures
In the SES Software <Version#> group folder, where <Version#> is the version number of the software, you should see the icons representing Autogrid Pro, AutoGroundDesign, CDEGS, Right-of-Way, SESEnviroPlus, SESShield-3D and SESTLC software packages, as well as four folders. The Documentation folder contains help documents for various utilities and software packages. The Program Folders provides shortcuts to programs, installation and projects folders. The System folder allows you to conveniently set up security keys. Various utilities can be found in the Tools folder. The main function of each software package and utility is described hereafter.

SOFTWARE PACKAGES

- **Autogrid Pro** provides a simple, integrated environment for carrying out detailed grounding studies. This package combines the computational powers of the computation modules RESAP, MALT and FCDIST with a simple, largely automated interface.

- **AutoGroundDesign** offers powerful and intelligent functions that help electrical engineers design safe grounding installations quickly and efficiently. The time devoted to design a safe and also cost-effective grounding grid is minimized by the use of automation techniques and appropriate databases. This module can help reduce considerably the time needed to complete a grounding design.

- **Right-of-Way** is a powerful integrated software package for the analysis of electromagnetic interference between electric power lines and adjacent installations such as pipelines and communication lines. It is especially designed to simplify and to automate the modeling of...
complex right-of-way configurations. The Right-of-Way interface runs the TRALIN and SPLITS computation modules and several other related components in the background.

- **SESEnviroPlus** is a sophisticated program that evaluates the environmental impact (radio interference, audible-noise, corona losses, and electromagnetic fields) of AC, DC or mixed transmission line systems.

- **SESShield-3D** is a powerful graphical program for the design and analysis of protective measures against lightning for substations and electrical networks. Its 3D graphical environment can be used to model accurately systems with complex geometries.

- **SESTLC** is a simplified analysis tool useful to quickly estimate the inductive and conductive electromagnetic interference levels on metallic utility paths such as pipelines and railways located close to electric lines (and not necessary parallel to them), as well as the magnetic and electric fields of arbitrary configurations of parallel transmission and distribution lines. It can also compute line parameters.

- **CorrCAD** tackles a large variety of cathodic protection design tasks and related issues, onshore and offshore, and can also predict the degree of corrosion control provided by a system. A typical application for corrosion control includes Impressed Cathodic Current Protection systems (ICCP) and use of sacrificial anodes in anodic protection systems, where anodic current is impressed on corroding material to enforce passivation. Another application is to estimate the effect of stray currents such as those produced by HVDC electrodes or dc rail traction systems on the corrosion of buried metallic structures. CorrCAD can evaluate the corrosion status of the structure and help optimize the location and characteristics of the corrosion protective system (such as ICCP) to minimize stray current interference effects on protected structures such as pipelines.

- **CDEGS** is a powerful set of integrated software tools designed to accurately analyze problems involving grounding, electromagnetic fields, electromagnetic interference including AC/DC interference mitigation studies and various aspects of cathodic protection and anode bed analysis with a global perspective, starting literally from the ground up. It consists of eight computation modules: RESAP, MALT, MALZ, SPLITS, TRALIN, HIFREQ, FCDIST and FFTSES. This is the primary interface used to enter data, run computations, and examine results for all software packages other than Right-of-Way, Autogrid Pro, AutoGroundDesign, SESTLC, SESShield-3D and SESEnviroPlus. This interface also provides access to the utilities listed below.

CDEGS is accessible via a modern, user-friendly and flexible main interface. A legacy interface, called CDEGS-Legacy, is also available.

**TOOLS**

- **AutoTransient** automates the process required to carry out a transient analysis with the HIFREQ and FFTSES modules

- **CETU** simplifies the transfer of Right-of-Way and SPLITS output data to MALZ or HIFREQ. A typical application is the calculation of conductive interference levels in an AC interference study.
Chapter 4. Frequency Decomposition of the Time Domain Signal

- **F05TextEditor** is an enhanced text editor that recognizes the command structure of the module indicated by the file prefix. The program provides syntax highlighting and a command parameter identification tooltip to greatly simplify manual editing of an .f05 file.

- **FFT21Data** extracts data directly from FFTSES’ output database files (file 21) in a spreadsheet-compatible format or in a format recognized by the SESPLOT utility.

- **GraRep** is a program that displays and prints graphics or text files. For more information on GraRep see Chapter 6 of the **Utilities Manual** or invoke the Windows Help item from the menu bar.

- **GRServer** is an advanced output processor which displays, plots, prints, and modifies configuration and computation results obtained during previous and current CDEGS sessions.

- **GRSplits** plots the circuit models entered in SPLITS or FCDIST input files. This program greatly simplifies the task of manipulating, visualizing and checking the components of a SPLITS or FCDIST circuit.

- **GRSplits-3D** is a powerful interactive 3D graphical environment that allows you to view and edit the circuit data contained in SPLITS input files and to simultaneously visualize the computation results.

- **RowCAD** is a graphical user interface for the visualization and specification of the geometrical data of Right-of-Way projects. Its 3D graphical environment can be used to visualize, specify and edit the path data of Right-of-Way, and to define the electrical properties of those paths.

- **SESAmpacity** computes the ampacity, the temperature rise or the minimum size of a bare buried conductor during a fault. It also computes the temperature of bare overhead conductors for a given current or the current corresponding to a given temperature, accounting for environmental conditions.

- **SESBat** is a utility that allows you to submit several CDEGS computation module runs at once. The programs can be run with different JobIDs and from different Working Directories.

- **SESCAD** is a CAD program which allows you to create, modify, and view complex grounding networks and aboveground metallic structures, in these dimensions. It is a graphical utility for the development of conductor networks in MALT, MALZ and HIFREQ.

- **SESConductorDatabase** gives access to the SES Conductor Database. It allows you to view the electrical properties of conductors in the database, and to add new conductors to the database or modify their properties.

- **SESConverter** is a DXF-DWG Converter tool that can be used to import CAD based files to various SES software package compatible input files or export various SES software package input command files to CAD files compatible with the DXF or DWG format. The program allows filtering of data to be imported aided by a 2D viewer of selected data, to avoid excessive conductor creation in the SES software package compatible files.
Chapter 4. Frequency Decomposition of the Time Domain Signal

- **SESCrossSection** provides an interactive interface with direct visual system representation for the specification of conductor characteristics and locations within a conductor path cross-section. The program allows data specification for eventual use in CorrCAD, Right-of-Way, Cable and Conductor modes of SESLibrary, SESeBundle, and Circuit, Group and Single modes of the TRALIN module.

- **SESCurveFit** is a general curve fitting tool with a special focus on "Polarization curves" used in CorrCAD. It incorporates a curve digitizer utility as well.

- **SESeBundle** finds the characteristics of an equivalent single conductor accurately representing a bundle of conductors, as far as their series impedance is concerned. This utility is particularly useful to simplify models in modules, such as HIFREQ, where reducing the number of conductors is important to keep the computational time low.

- **SESEnviroPlot** is an intuitive Windows application that dynamically displays computation data produced by the **SESEnviroPlus** software module.

- **SESFcdist** is an interactive and flexible interface to prepare and run input files, and view results from, the FCDIST computation module.

- **SESFFT** is a **Fast Fourier Transform** computation module designed to help you automate time domain (lightning and switching surges) analyses based on frequency domain results obtained from CDEGS computation modules such as SPLITs, MALZ, and HIFREQ. The forward and inverse **Fast Fourier** transformations, the sample selection of the frequency spectrum, and related reporting and plotting functions have been automated in SESFFT.

- **SESGSE** rapidly computes the ground resistances of simple grounding systems, such as ground rods, horizontal wires, plates, rings, etc., in uniform soils. SESGSE also estimates the required size of such grounding systems to achieve a given ground resistance.

- **SESImpedance** computes the internal impedance per unit length of long conductors of arbitrary geometry and composition, and whose cross-section does not vary over the length of the conductor. The program uses the Finite Element Method (FEM) for calculating the electrical characteristics of conductors and is capable of handling conductors of arbitrary shapes and realistic material properties. The calculations fully account for skin effect, and can be carried out at low or high frequency.

- **SESLibrary** allows you to inspect the properties of a large number of **components** that can be part of models for many SES Software computation modules. It currently includes a comprehensive database of conductors as well as several power cables.

- **SESPlot** provides simple plots from data read from a text file.

- **SESPlotViewer** is a tool used by SESEnviroPlus for plot rendering.

- **SESResap** is an interactive and flexible interface to prepare and run input files and view results from the RESAP computation module.
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- **SESResultsViewer** processes the computation data and results of all computation modules in CDEGS, offering a complete solution for displaying the plots and reports in an integrated viewer. It presents a light layout with intuitive organization of its settings that use sensible defaults that, in turn, allow for a fast configuration of the settings in order to achieve the desired output results.

- **SESScript** is a script interpreter that adds programming capabilities to SES input files. SESScript can systematically generate hundreds of files from a single input file containing a mixture of the SICL command language and scripting code and user-defined parameter ranges and increments.

- **SESShield** provides optimum solutions for the protection of transmission lines and substations against direct lightning strikes and optimizes the location and configuration of shield wires and masts in order to prevent the exposure of energized conductors, busses and equipment. It can also perform risk assessment calculations associated with lightning strikes on various structures.

- **SESSystemViewer** is a powerful 3D graphics rendition software that allows you to visualize the complete system including the entire network and surrounding soil structure. Furthermore, computation results are displayed right on the system components.

- **SESThreshold** is an application for computing threshold limits, as recommended by industry standards, for touch and step voltages. It is coupled with the Zone Editor application, allowing zones where different threshold limits are applicable to be defined.

- **SESTralin** is an interactive and flexible interface to prepare and run input files, and view results from, the TRALIN computation module.

- **SoilModelEditor** is a standalone module with an interactive graphical interface that assists in the creation of soils models for all relevant target SES modules.

- **SoilModelManager** is a software tool that automates the selection of soil model structures that apply during various seasons.

- **SoilTransfer** utility allows you to transfer the soil model found in several SES files into several MALT, MALZ or HIFREQ input (F05) files.

- **TransposIT** is a tool for the analysis of line transpositions on coupled electric power line circuits. To ensure that voltage unbalance is kept within predefined limits, it allows the user to determine the optimal number of power line transpositions and their required locations.

- **WMFPrint** displays and prints WMF files (Windows Metafiles) generated by CDEGS or any other software.

During this tutorial, for simplicity, we will be using the Windows **CDEGS** icon to carry out most of the input and output tasks. We will refer to the other utility modules when appropriate.

In the **SES Software** group folder, double-click the **CDEGS** icon to start the CDEGS program. You will get the CDEGS start-up window shown in the following figure. Enter the complete path of your working directory in the **Working Directory** field (or use the … button to browse to the directory). Any character string can be used for the **Current Job ID**.
In the following session, we recommend the following Working Directory and Current Job ID:

**Working Directory:** `<drive>\CDEGS HowTo \Lightn`

**Current Job ID:** `TRANSI`

Before launching FFTSES, note the following about the CDEGS user interface:

- If the model has not been created for the selected module, the two status indicators under the module icon are red, as shown below. You can click **Specify** to build a new model.

- If the model of the selected module is created but has not been run yet (i.e., a valid F05 file exists, but no output files), the color of the left indicator changes to green (the right one remains red). You can click **Specify** to modify the model or **Compute** to launch the computations, as shown in the following figure. Note that for the modules not included in your license, this **Compute** option is locked.
Once the model for the selected module is computed (i.e., a valid F21 file exists), the second status indicator turns to green. You can click Specify to modify the model, Compute to relaunch the computations or Examine to view/plot the results. For the example shown below, the MALZ model is created (F05 file), it has been run (F21 file), and therefore, the results can be viewed. Note that if for any reason, only the F21 file is present in the project folder, only the second indicator is turned to green.

### 4.1.1.2 Data Entry

Click the FFTSES button located in the CDEGS ribbon under the Modules tab and select Specify. The FFTSES screen will appear and you are now able to input your data.

In the following section, it is assumed that the reader is entering the data as indicated in the instructions. Note that it is advisable to save your work regularly with the use of the Project | Save menu item. The entered data will be saved in an editable (text) files called FT_TRANSI.F05. Each file can be retrieved at any time with the use of the Project | Open menu item. The same method can be used if an input session has to be interrupted (close all active windows to exit the program after saving your data).

If you intend to enter the data manually, proceed with this section, otherwise, you can directly open the file “FT_TRANSI.F05” copied to the working directory as described in Section 1.8.
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As shown in Figure A.1 in Appendix A, the FFTSES commands are grouped into modules, reflecting the hierarchical nature of the SES Input Command Language. Each module of Figure A.1 (with the exception of the OPTION module) is associated to a button in the FFTSES screen. The OPTION module is actually part of the FFTSES main screen.

The Help Key (F1) can be used to obtain relevant context-sensitive information when any CDEGS input or output text field is selected.

The data entry fields in the Module Description tab (accessible through Project | Project Info) allow you to type comment lines that are used to describe the case to be analyzed. They are echoed in the FFTSES output.

A Run-ID EX3: LIGHTNING is entered in the Run-Identification data entry field (select Specify to define this value) and the Metric System of Units is chosen. The Run-ID is useful in identifying all the plots which will be made later in Section 4.3.

Now, getting back to the main screen of the project through Open | Recent Files | TRANSI, you can choose the FFT type on the top of the screen. It determines whether the forward FFT or inverse FFT will be performed and what physical quantities will be subjected to the Fourier Transformation.

The Forward-FFT option, which invokes the Fast Fourier Transform (FFT) is selected by default. The option button Lightning Surge is chosen to invoke a built-in transient function generator. The parameter 12 entered in data entry field for Sampling Exponent specifies $N = 2^{12} = 4096$ points to be used for digitizing the time domain signal. In the case of built-in functions, $N$ specifies the number of points to be generated. The Time-Duration box specifies the time window $T$ of the surge signal. 0-300 μs is considered in this case. The surge coefficients in Eq. (1) are entered under Surge Parameters. Note the Sampling Frequency and Sampling Time that are updated.
The FFTSES program analyses the input signal by discretizing it in the time domain. The result of the analysis is the (discrete) frequency spectrum of the signal. The number of samples used when discretizing the signal determines the time resolution, i.e. the shortest event in time that can be modelled with the program. As mentioned earlier, in FFTSES, this number must be a power of 2, and is expressed as the **Sampling Exponent**.

In principle, this number should be made as large as possible. However, the resulting database size grows very fast as a function of the **Sampling Exponent**.

Two criteria govern the selection of the **Time Duration** parameter:

- **The Time Duration** determines the frequency resolution (i.e., the difference in frequency between two successive points in the frequency spectrum). The precise relationship is $\Delta f = 1/T$.

- **The Time Duration** should be selected so that the input signal is very small at the end of the time window.

To improve the frequency resolution, the time duration of this signal should be increased. Note that this automatically reduces the time-domain resolution ($T/N$, where $N$ is the number of samples). Therefore, the number of samples should be increased at the same time, to compensate.

In this example, $T = 300 \, \mu s$, which corresponds to $\Delta f = 3333.3 \, Hz$, is chosen. The rise time of the voltage surge is $1 \, \mu s$. To be on the safe side, a time step of $0.1 \, \mu s$ was chosen. This corresponds to $300/0.1 = 3000$ sampling points. Since FFTSES can take only a power of 2 for the number of sampling points, the value $2^{12} = 4096$ was chosen. The Nyquist frequency is therefore
$f = \frac{4096}{2 \times 300} \times 10^6 = 6.827 \text{MHz}$

This frequency is the highest one you can find in the first HIFREQ input file (the Nyquist frequency actually corresponds to half of the Sampling Frequency).

At this point, you have completed the preparation of the data: it is ready to be submitted to the FFTSES computation module in the next section.

If you are a licensee of the CDEGS software you will now be able to proceed to Section 4.2. Users of the demo software are not able to process the input file, but are able to peruse all output files which are already available. Therefore read Section 4.2 for reference only. Any attempt to start a computation module will result in a message stating that it is not active.

### 4.2 SUBMISSION OF THE FFTSES RUN

From the FFTSES screen, click the **Compute Forward FFT** to submit and run the model. This does two things:

- It saves input file under the name FT_TRANSFO5. Each input file can be reread from the FFTSES main screen using **Project | Open | Recent Files**. The *.F05 files are ASCII files you can edit and view at any time.

- It starts the FFTSES computation program.

The FFTSES program will start and will carry out all requested computations. At completion the program will produce four important files: an output file (FT_TRANSFO9), a database file (FT_TRANSF21), a storage file (FT_TRANSF07) and an ASCII file (FT_TRANSF27). These files are already in your working directory.

The output file is an ASCII file, while the storage and database files are binary files. Any ERROR or WARNING messages generated during the FFTSES run will appear in the output file. The output file contains all the information from your FFTSES run. It contains the double-exponential type function generated data for the surge signal as well as the lightning surge current spectrum data for $I(\omega)$. You can view the output file by clicking **View Report (F09)** at the bottom of the Computation Trace panel of the main FFTSES window. You can also use the GraRep utility (See Section 4.1.1.1) to view and edit any ASCII output files.

The storage file FT_TRANSFO7 stores the lightning current spectrum $I(\omega)$. This file will be used later for the inverse Fourier Transformation. The ASCII file FT_TRANSF27 contains the computation frequencies recommended by FFTSES.

**WARNING:**

If you use a different “JobID” (such as "newid") for the inverse Fourier operation, you must then rename FT_TRANSFO7 to FT_newid.F07 in order to carry out successfully the inverse...
operation using FFTSES. The following running error message will appear during the inverse FFT run if you fail to carry out this file renaming.

* ERROR * The storage file is empty, make sure that you have run the appropriate forward FFT using the current JOBID to create storage files (on unit 7) or rename the corresponding storage file created with different JOBID to the one with the current JOBID.

The next section looks at the computation results.

### 4.3 EXTRACTION OF FFTSES COMPUTATION RESULTS

The DATABASE file FT_TRANSI.F21 is normally used to display the computation results and reports. In the following sections, we will show you how to use the FFTSES interface to produce the corresponding graphs.

#### 4.3.1 Windows Mode Output Processor

If you have followed the instructions up to this point, the active JobID should be "TRANSI". We will therefore extract the results and display the plots on screen. To do so, select the **Results** tab at the bottom left of the FFTSES window.

Enter a **Plot Title** in order to identify the plot. Select **Both Real-Imaginary** under **Unmodulated Spectrum** and **Real Part** under **Time domain** to request that both the real and imaginary parts of the frequency spectrum \( I(\omega) \) and the real part of the lightning surge current \( I(t) \) be plotted. (Note that only the real part of the time domain signal exists). Click **Plot** to load the GraRep utility module and obtain a screen plot of the computed results.

You can cut and paste this plot to any other software supporting WMF files such as WordPad, Word, Excel, Corel, etc. Simply hit “Control C” or select the **Edit** menu from the menu bar then pick the **Copy Current Plot** item to store the plot in the paste buffer. You can visualize, shift, scale and add comments then print the plot by clicking the print preview button 📄. You can print plots and reports displayed by the GraRep utility module directly to any Windows compatible printers simply by clicking on the print button 📣, or by selecting the **Print** item from the **File** menu. You can also send the plot and report to a file for processing as explained in Appendix B.

There are three graphs displayed on screen. The first graph (displayed in Figure 4-1) shows the lightning surge signal you have defined. The second and third graphs are shown in Figure 4-2 and Figure 4-3 which display the real and imaginary parts of the lightning surge current spectrum \( I(\omega) \), respectively.
Figure 4-1  Input Signal in the Time Domain
Figure 4-2  Real Part of Frequency Spectrum of Input Signal

Figure 4-3  Imaginary Part of Frequency Spectrum of Input Signal
The program recommends 17 frequencies for running HIFREQ. They are the essential frequencies that are required in order to recover the original lightning surge signal. Therefore all of those frequencies will have to be used for the coming HIFREQ run. They can be found at the end of the output file FT_TRANSI.F09 and in the file FT_TRANSI.F27. In FT_TRANSI.F27, they are written in a format that can be directly imported into the HIFREQ input file.

Once you are done examining the results, click **Data Input** at the left bottom of the FFTSES window to go back to the main screen.
CHAPTER 5
COMPUTATION OF THE FREQUENCY
DOMAIN SYSTEM RESPONSE

In this chapter, we will describe how to compute the unmodulated electromagnetic response, \( V_o(\omega) \), \( E_o(\omega) \), and \( H_o(\omega) \) by using HIFREQ.

5.1 PREPARATION OF THE HIFREQ INPUT FILE

You can prepare the HIFREQ input file using SESCAD or your favorite text editor (or the one provided with CDEGS).

The following section describes how to use the SESCAD program to generate the input file (.F05 extension). SESCAD is a CAD program which allows you to create, modify, and view complex grounding networks and aboveground metallic structures in three dimensions. The input file is shown in Printout A.2 in Appendix A. It can be reloaded during subsequent sessions.

5.1.1 SESCAD Input Mode

The most important features in preparing the data are explained in Section 5.1.1.2.

5.1.1.1 Start-Up Procedures

This step is identical to the one already described in Section 4.1.1.1. In the SES Software group folder, double-click the CDEGS icon to start the CDEGS program interface (if not already started). You will be prompted for a Working Directory and a Current JobID. Make sure that the proposed working directory is the same as the one used in the preceding chapter and enter RUN1 as the JobID. We choose RUN1 as our JobID for this HIFREQ run. This is the first HIFREQ run among, usually, a number of HIFREQ runs in order to complete a transient study.

From the main CDEGS window, click HIFREQ and select Specify from the drop-down list. Then, at the bottom of the CDEGS – Specify – HIFREQ dialog, click SESCAD. You are now ready to input data. The file HI_RUN1.F05 is created without any data. Note that the abbreviation "HI" means that this is a HIFREQ input file and the Job ID is "EXAMPLE 3 - RUN1".
Chapter 5. Computation of the Frequency Domain System Response

![Diagram of CDEGS software interface showing computation modules and job identification.

- Working Directory: C:\CDEGS\HowToLightn
- Current JobID: RUN1
  - Date Modified: 2017-03-06 12:58 PM
  - Path: C:\CDEGS\HowToLightn
- RLC, RLC1, TRANSI
  - Date Modified: 2017-03-06 12:58 PM
  - Path: C:\CDEGS\HowToLightn

![Diagram of CDEGS - Specify - HIFREQ window.

- Case Description
- Module Description
- Project Description

Run Identification:
- Use JobID
- Specify
- EXAMPLE 3 - RUN1

System of Units:
- Metric
- Imperial

Define:
- SESCAD...
In the following section, it is assumed that the reader is entering the data as indicated in the instructions. Note that it is advisable to save your work regularly. This file can be retrieved at any time by clicking Open Document… under the File menu, if a data entry session has to be interrupted.

If you intend to enter the data manually, proceed with Section 5.1.1.2, otherwise, you can directly open the file “FT_RUN1.F05” copied to the working directory as described in Section 1.8.

5.1.1.2 Data Entry
As shown in Figure A.2 in Appendix A, the HIFREQ commands are grouped into modules, reflecting the hierarchical nature of the SES Input Command Language.

We will first define Run ID and System of Units by selecting Define | Units and Other Settings… in the SESCAD. Under the Module Level | Grid | Case Description block of this window, you can enter comment lines that are used to describe the case. They are echoed in the HIFREQ output (.F09 file). In this tutorial, “EXAMPLE 3 - RUN1” is entered under the Specify option, and the Metric Systems of Units is chosen. Note that a Run ID is different from the Job ID. The run-id is useful in identifying all the plots which will be made later in Section 5.3.

The soil structure is defined by selecting the Define | Soil Model… menu item. The following screen will appear.
HIFREQ supports horizontally layered soils, with any number of layers (Uniform or Horizontal): It also supports an Infinite Medium soil model. Select a Uniform soil. The data entry fields under Soil Characteristics allow you to define the properties of the air and earth. In this example, the default properties for both the air and the earth (a soil with resistivity of 100 Ω-m, relative permeability and relative permittivity of 1) are used. You can therefore simply click OK to return to the SESCAD screen.

We will now model the communication tower and its grounding system, simulate a lightning strike at the top of tower, and also define observation points for computing scalar potentials and electromagnetic fields. The data entered below in the SESCAD are shown in Figure 2-2 which is reproduced here for convenience in Figure 5-1.
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Figure 5-1   Reproduction of Figure 2-2 which is a simplified Version of Scenario 1

HIFREQ can model different types of conductors (other than copper) and various coating types of the conductors. We will therefore first define conductor types and coating types which are needed in the study. One type of conductor encountered in this study is a steel conductor for the communication tower. This conductor type is specified by selecting the Define | Conductor Types… menu and entering the data, which includes resistivity, permeability, internal radius, load of the conductor and identification.

Conductor type No. 1 is defined as steel. Conductor Type No. 0 is a default conductor, which is pure copper, unless it has been redefined.

The coating type for the conductors is specified in the Define | Coating Types… Coating Type No. 0 is a default coating, which is no coating, unless it has been redefined.
The lightning strike on the communication tower is simulated by means of a Lead ENERGIZATION, which injects current at the top of communication tower, as shown in Figure 2-2. The Lead energization is defined by selecting the **Define | Energization Types...** menu. Bus No. 1 is a Lead energization with a Unit Current of 1 A. As explained in Chapter 3, the unit current of 1 A must be used in order to compute the unmodulated responses (see Eqs (2) to (4)).
Click **OK** to return to the SESCAD screen.

With the conductor type, coating type and energization type defined, the conductor network in Figure 2-2 can now be defined and energized in SESCAD. The following describes the steps.

**Step (1).** Create Conductor #1 which simulates the lightning strike at the top of the tower. Select **Edit | Create Object** and enter the XYZ coordinates for **Start** and **End**, as indicated in Point D in Figure 2-2 and the screen below. Click on the **Characteristics…** button and select Unit **Current** from the drop-down list of the **Energization** to energize the conductor. Click on the **Apply** button to create Conductor #1. *The energization current in HIFREQ is always assumed to flow from the origin of a conductor towards the end.* Therefore, you must specify Zstart = -50.5 m (positive Z axis going towards ground) so that 1 A is injected into the tower. Note that a completely different situation occurs if the Z coordinates of the origin and end of this conductor are interchanged. In this case, the program would force the current to be zero at Z = -50.5 m since this point is not connected to any other conductors and the result would be that the entire 1.0 A would have to leak between Z = -50 m and Z = -50.5 m, generating huge potentials and electric fields.

**Step (2).** Create Conductor #2, #3 and #4 which correspond to the three legs of the tower, at Points A, B, and C, respectively. The three rods are driven 3 m into the ground from Zstart = 0 and Zend = 3 m. They are done similarly by select **Edit | Create Object**. We first create Conductor #2 at Point A by using the following screens. Click on the **Characteristics…** button to select **Steel** from the list of the **Conductor Type** and enter the radius of 0.006 m. Click on the **Apply** button to create Conductor #2 and click on the **Close** button to close the screen. Conductors #3 can be created quickly by using **Tools | Shift Objects…** Select **Apply to Duplicate**, enter 10 m under **Quick Distance (m)** and click on the move down arrow. Similarly, Conductor #4 is created by moving and copying Conductor #3, 8.6 m to the right and 5 m up, to X = 63.6 m, Y = 25 m.
Step (3). Create Conductors #5, #6 and #7 which correspond to the three legs of the tower, from Point D at the top of the tower to Points A, B, and C, respectively. First, change the view to XZ, Orthogonal Projection View; then click on the Draw Conductors button on the left to draw a conductor. Draw a conductor from the end of Conductor #1 to start of Conductor #2. Right click on the conductor and select Characteristics… Select Steel from the list of the Conductor Type, enter the radius of 0.01 m and enter 25 for subdivision. The number of subdivision will be discussed in detail next. You can click on the Quick Info button and rest the mouse on top of this conductor (it becomes pink) to view its coordinates. Similarly, you can create Conductor #6 and #7 by repeating the same steps.
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Step (4). Create Conductors #8, #9 and #10 which correspond to the loop at the base of the tower at 1 m below grade, from Points A to B, B to C, and C to A (see Figure 2-2). First, draw three conductors by using **Draw Conductors** to interconnect the bottom of the tower. Select the three conductors by clicking on one and holding down the **Shift** key to select the next one or by drawing a square around them. Select **Tools | Shift Objects...** and shift them 2 m up in z direction to $Z = 1$ m. Right click on them and choose **Characteristics** to assign a radius of 6 mm and enter 5 in **Subdivision**. Note that by default, conductor type is set to 0 which is copper.

Step (5). Create the remaining conductors which correspond to the 3 m rods at Points E, F and G, and the horizontal conductor from Point A to G. The three 3 m rods at Points E, F and G can be created by shifting the rod at Point A with appropriate distances (see Figure 2-2). After the three rods are created, the horizontal conductor at 1 m below grade can be created by using **Draw Conductors**. Click on the node where the 3 m rod at Point A intersects with the
Chapter 5. Computation of the Frequency Domain System Response

loop. Hold down the Ctrl Key to draw a conductor from this node to Point G. Holding down the Ctrl Key will force the line to be drawn horizontally in this case. SESCAD detects any nearby conductors and will snap to them automatically. Select the three rods and the horizontal conductor. Right click on them and assign a radius of 6 mm and enter 15 in Subdivision. SESCAD also assigns a default conductor type (copper).

Conductor segmentation has an important effect on computations, especially at high frequencies. A condition that should be satisfied is that the longest conductor segment should be no longer than about \( \lambda/6 \), where \( \lambda \) is the wavelength in the medium where the segment is located. Simple approximations for \( \lambda \) (in meters) are

\[
\lambda = \frac{3 \times 10^8}{f} \quad \text{in the air}
\]
\[
\lambda = \frac{3160}{f} \quad \text{in the soil}
\]

where \( f \) is the frequency in Hz and \( \rho \) the resistivity of the soil in \( \Omega \)-m. These formula can be accessed from the Tools | Electromagnetics Calculator menu item in the AutoTransient tool (see Chapter 8).

The largest frequency recommended by FFTSES in this study is 6.827 MHz. The most stringent conditions are obtained for this frequency. Conductor segments should therefore be no longer than 12.09/6 = 2.02 meters in the soil and 43.94/6 = 7.32 meters in the air. The same segmentation was used for all frequencies since otherwise FFTSES would not be able to compute the time domain currents and GPR of conductors.

In this example, the electric, magnetic fields and the scalar potential are computed for a total of 17 frequencies that were recommended by the forward FFTSES. There are 75 observation points, all located at the earth’s surface (i.e., at \( Z = 0.0 \) m). The points start at \( X = 0 \) m, \( Y = 30.5 \) m with increments of 1 m in the X direction. The observation points are defined by clicking on the Edit | Create Objects… and select Profiles | Single Profile, enter the Profile Start and Profile Step. Click on the Apply button to generate the profile.
Please note that HIFREQ uses a Cartesian coordinates system with the Z-axis directed downwards. When the height of the observation point is precisely zero (i.e., the observation point lies at the air-soil interface), HIFREQ assumes that the point is in the *ground* for the purpose of calculating the electric and magnetic fields. If the fields in the air but close to the air-soil interface are desired, an observation profile must be specified at a small height (for instance, Z = -0.01 m) above the ground.

The computation frequencies for the first round of HIFREQ run contains the entire set of frequencies recommended by FFTSES in the previous step. These are written in the file FT_TRANSI.F27. These frequencies could be entered by hand but it is simpler to import them by clicking on Define | Computation Settings under Computation Frequencies. (Note that Multiple Frequencies must be selected.) The following screen will appear (with an empty grid).

Click on Import and use the File Name FT_TRANSI.F27. This will import the 17 frequencies recommended in FT_TRANSI.F27 (if you have directly loaded the HI_RUN1.F05 input file, you do not have to import the frequencies from FT_TRANSI.F27 as they have already been entered into the file). Click OK to return to the SESCAD screen.

Step (6). At this stage, we have one last step to finalize the HIFREQ input file. The Advanced Options, which are invoked by clicking Define | Advanced Options from the SESCAD top menu, is usually not required. It is only used to override the default setup for the computation
algorithms which decide the method for current computation and for the Sommerfeld integration. Depending on the computation frequency and on the source and observation locations, the Sommerfeld integral can be computed by the Low-Frequency or the In-Soil approximation, or carried out by Double-Integration with increasing computation time from the first method to the last. By default, the selection among the three algorithms is done automatically by HIFREQ (See the on-line help of HIFREQ for a detailed discussion).

In this example, because the size of the conductor network is comparable with the wavelength corresponding to the Nyquist frequency, it is found that the default parameters for the Sommerfeld integration are not high enough. From the left menu of the HIFREQ – Advanced Options dialog, change the default Integration Variables $M = 4$ and $N = 3$ for the Sommerfeld integration to $M = 32$ and $N = 15$. This will force the Sommerfeld integration to be carried out with higher accuracy, i.e., 32 points for the Gaussian integration and 15 points for the Laguerre integration.

Select the Source-Observer Location and Algorithm option from the left menu and force HIFREQ to choose the DOUBLE-INTEGRATION algorithm for all the frequencies. Please note that as a result of this higher accuracy, the computation time will be significantly increased. Click OK to return to HIFREQ main screen and we are ready for submission of the HIFREQ run.
If you are a licensee of the CDEGS software you will now be able to proceed to Section 5.2. Users of the demo software are not able to process the input file, but are able to peruse all output files which are already available. Therefore read Section 5.2 for reference only. Any attempt to start a computation module will result in a message stating that it is not active.

5.2 SUBMISSION OF THE HIFREQ RUN

There are two ways to submit the HIFREQ runs:

5.2.1 Submit Computation Program Using SESCAD

You can submit the run directly from SESCAD, by selecting the Run/Reports | Save & Run menu item. This will start the SESBatch program and automatically run the computation module. Note that for illustration purposes, the generic grounding grid shown in the following screen shot has been used instead of the specific case discussed in this How To manual.
Chapter 5. Computation of the Frequency Domain System Response

Once the run is complete, a window will pop up to inform you that a log file has been generated. Click the OK button to close the message window. SESBatch allows you to conveniently access some of the important files that it generates. For example, from the Tools | View Run Log File… menu item you can view the log file generated during the computations. From the Tools | View Output File… menu item you can view the output file, which may contain ERROR or WARNING messages requiring your attention. Finally, you can launch Output Toolbox directly from the Tools | View Results with Output Toolbox… menu item.

5.2.2 Submit Computation Program Using CDEGS

In the CDEGS Start Up screen, make sure the Working Directory is \CDEGS HowTo\Lightn and the JobID is RUN1. The Compute option should be available under the HIFREQ button to submit the HIFREQ Computation run.

The program will produce four important files: an OUTPUT file (HI_RUN1.F09), a REPORT file (HI_RUN1.F17), a DATABASE file (HI_RUN1.F21) and a CURRENT RECOVERY file (HI_RUN1.F33). These files are already in your working directory.
Chapter 5. Computation of the Frequency Domain System Response

The OUTPUT and REPORT files are ASCII files, while the DATABASE and the CURRENT RECOVERY files are binary files. Any ERROR or WARNING messages generated during the HIFREQ run will appear in the OUTPUT file. You can view the OUTPUT file by clicking File Viewer under the Tools tab.

### 5.3 EXTRACTION OF HIFREQ COMPUTATION RESULTS

The OUTPUT file (HI_RUN1.F09) contains all the information from your HIFREQ run. It contains the current distribution and the ground potential rise (GPR) for each conductor segment, as well as the requested scalar potentials and electromagnetic fields computed at the specified observation points. With the SES Text viewer or any other text editor, searching for the string "Leaking" will get you to the location of current distributions of segments quickly, searching for the string "Scalar" will get you to the location of the GPR or scalar potential quickly, and so on. The CURRENT RECOVERY file (HI_RUN1.F33) is used for a second round of computations where the current computation will be bypassed. The REPORT file (HI_RUN1.F17) lists the conductor segment information and the current distribution for each conductor segment.

The DATABASE file (HI_RUN1.F21) is normally used by the SES Interactive Report & Plot Software (SIRPS) to display the computation results. The computation results can be classified into two categories: CONFIGURATION plots and COMPUTATION plots. The CONFIGURATION plots allow you to view the conductor network, to label the conductor segments with their GPR, longitudinal and leakage currents, and so on. The COMPUTATION plots allow you to examine the scalar potential and the electromagnetic fields computed at selected observation points.

Since we are interested in studying the frequency and time dependence of the network currents and potentials, we will not extract any HIFREQ results in this section: the time and frequency dependence of the results will instead be collected by FFTSES in the next section.
CHAPTER 6

COMPUTATION OF THE TIME DOMAIN SYSTEM RESPONSE

With the frequency spectrum $I(\omega)$ obtained in Chapter 4 and the unmodulated system responses computed in Chapter 5, we will now describe how to obtain the time domain system response $V(t)$, $E(t)$ and $H(t)$ by using Eq. (2) to (4) in Chapter 3.

6.1 PREPARATION OF INVERSE FOURIER TRANSFORM INPUT FILE

Similar to the procedures described in Section 4.1, the inverse Fourier transform input file can be prepared.

6.1.1 Windows Input Mode

The Windows Input Mode is described in this section. The most important features in preparing the data are explained in Section 6.1.1.1.

6.1.1.1 Start-Up Procedures

This step is identical to the one already described in Section 4.1.1.1. Assume that the CDEGS program interface has already started. Select TRANSI from the Job ID list (click Date Modified to sort the Job IDs according to their usage history).

Click the FFTSES button located in the CDEGS ribbon under the Modules tab and select Specify. The FFTSES screen will appear and the input data from the previous FT_TRANSI.F05 is automatically loaded into the screen. Note that this is the data file used for the forward FFT operation.

In the FFTSES screen, select Inverse from the FFT drop down menu, which invokes the inverse FFT operation. From the Conductors and Profiles Selection table, select the Profiles tab, click Add, and select Scalar Potentials for the Fourier Transform.

The two options under the Response drop down menu indicate that the system response in the frequency domain can be User Defined for user-specified data or Computed, which acts directly on the FFTSES database files established next by clicking HIFREQ/MALZ Response Files. In this study, select Computed to use the data from the FFTSES database files.
The data entered in the **Conductors and Profiles Selection** table in the above screen selects all recommended frequencies and the observation point No. 56 in PROFILE 1, which is at \( X = 55.0 \) m, \( Y = 30.5 \) m, \( Z = 0.0 \) m (see the input file HI_RUN1.F05).

Click **HIFREQ/MALZ Response Files** to invoke the **FFTSES Database Management** screen to construct the FFTSES databases.

There are four FFTSES database files, FT\_JobID.F81, FT\_JobID.F82, FT\_JobID.F83 and FT\_JobID.F84, where JobID=TRANSI in this case. The following table shows the correspondence between the database files and the physical quantities stored in these files. Note that by default, the program generates the four database files, unless no profile points are defined in the HIFREQ model. In this latter case, only JobID.F84 is generated.

<table>
<thead>
<tr>
<th>Database File</th>
<th>Physical Quantities</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT_JobID.F81</td>
<td>Scalar Potential</td>
</tr>
<tr>
<td>FT_JobID.F82</td>
<td>Electric Field</td>
</tr>
<tr>
<td>FT_JobID.F83</td>
<td>Magnetic Field</td>
</tr>
<tr>
<td>FT_JobID.F84</td>
<td>Currents and GPR of Conductor Segments</td>
</tr>
</tbody>
</table>

**Table 6.1 FFTSES Database Files**
Click the Add button to select the HIFREQ database files from the following screen (use CTRL or SHIFT keys if a number of files are need to be selected). Select HI_RUN1.F21 and click Open.

Click the Create button to start constructing the FFTSES databases. Five database files FT_TRANSI.F80, FT_TRANSI.F81, FT_TRANSI.F82, FT_TRANSI.F83 and FT_TRANSI.F84 are generated as a result of this extraction. FT_TRANSI.F80 is a control file for the database files. When the database construction is complete, click OK to return to the FFTSES screen.

### 6.2 SUBMISSION OF THE FFTSES RUN

At this point, you have completed the preparation of the data.

If you are using the DEMO version of the software, proceed directly to Section 6.3. Otherwise, click the Compute Inverse FFT button. Responding Yes will proceed to save the case, the FFTSES computation module will automatically start and will carry out all requested computations. At completion the program will produce three important files: an output file (FT_TRANSI.F09), a database file (FT_TRANSI.F21), and an ASCII file (FT_TRANSI.F27). These files are already in your working directory. The contents of file have been described in Section 4.2.

### 6.3 EXTRACTION OF FFTSES COMPUTATION RESULTS

In the following section, we will show you how to use the FFTSES interface to produce the corresponding graphs.

#### 6.3.1 Windows Mode Output Processor

If you have followed the instructions up to this point, the active JobID should be "TRANSI". Select the Results tab at the bottom left of the FFTSES screen.

Enter a Plot Title in order to identify the plot. Select Both Real-Imaginary under Unmodulated Spectrum, Modulated Spectrum and Time Domain to request both the real and imaginary part of the plot made for each of these quantities. Click the Plot button to load the GraRep utility module and obtain a screen plot of the computed results.

Six graphs are generated. The first and second graphs (displayed in Figure 6-1 and Figure 6-2) show the real and imaginary parts of the unmodulated scalar potential \( V_0(\omega) \) for a unit current as computed by HIFREQ, respectively. The curves are obviously only roughly defined. The third and fourth graphs
displayed in Figure 6-3 and Figure 6-4 show the real and imaginary parts of the modulated scalar potential, \( i.e., \) the product of \( V_\omega(\omega) \) and \( I(\omega) \), respectively. These curves go to zero for very large frequencies, as they should.

![Figure 6-1](image_url)  
**Figure 6-1**  
Real Part of Unmodulated Scalar Potential
Chapter 6. Computation of the Time Domain System Response

Figure 6-2 Imaginary Part of Unmodulated Scalar Potential

Figure 6-3 Real Part of Modulated Scalar Potential
Figure 6-4  Imaginary Part of Modulated Scalar Potential

Figure 6-5  Real Part of Time Domain Scalar Potential
Chapter 6. Computation of the Time Domain System Response

The fifth and sixth graphs (displayed in Figure 6-5 and Figure 6-6) show the real and imaginary parts of the time domain scalar potential \( V(t) \), respectively. The imaginary part of \( V(t) \) in Figure 6-6 is negligible, as expected. The effect of the lack of smoothness of the frequency domain response curve is apparent in the peak that occurs at \( t = 300 \mu s \) in Figure 6-5. This is usually an indication that the frequency domain response has not been determined sufficiently accurately. As a matter of fact, FFTSES recommends that the frequency domain response be computed at 35 additional frequencies.

The output file contains all the information from your FFTSES run for the inverse FFT Transformation. It contains the unmodulated scalar potential at the observation point No. 56 (data for Figure 6-1 and Figure 6-2). The 35 additional frequencies recommended for running HIFREQ are, again, written at the end of the output file FT_TRANSI.F09 and in the file FT_TRANSI.F27. The recommendation of these frequencies is based on the unmodulated system response (Figure 6-1 and Figure 6-2). Normally all of those frequencies should be used for the next HIFREQ runs.

To clearly view the voltage surge in Figure 6-5 over the time window between 0 to 40 μs, choose User-Defined by clicking in the Options field in the FFTSES Graphics screen. The data entered force the scale of time axis to be \( X_{\text{min}} = 0 \), \( X_{\text{max}} = 40 \mu s \) and the scale of the scalar potential axis to be \( Y_{\text{min}} = 0 \) and \( Y_{\text{max}} = 300000 \).

Figure 6-7 shows the time domain response of the scalar potential between 0 and 40 μs.
Chapter 6. Computation of the Time Domain System Response

Figure 6-7 Close-Up on the Time Domain Scalar Potential
CHAPTER 7
ADDITIONAL HIFREQ AND FFTSES COMPUTATIONS

In 0 to 6, we have described in detail how to obtain the time domain transient scalar potential (Figure 6-5) at the observation point $X = 55.0\ m$, $Y = 30.5\ m$, $Z = 0.0\ m$ after the first round of HIFREQ and FFTSES computations. As shown in Figure 6-1 and Figure 6-2, the unmodulated scalar potential $V_o(\omega)$ is not well defined after this run. As a result, FFTSES recommends 35 additional frequencies at which the scalar potential should be computed. In the following, we will describe how to complete the additional HIFREQ and FFTSES computations.

The computation steps in the second round of HIFREQ and FFTSES computation are identical to those in the first round of the computations. Only the computation steps in 0 and 6 need to be repeated.

7.1 WINDOWS INPUT MODE

Change the JobID to RUN2 in order to prepare the HIFREQ input and proceed as in Section 5.1.1 (5.1.1.1) to load the HIFREQ input file into SESCAD.

The only change that has to be made to the HIFREQ input is to replace the 17 computation frequencies used in the first run by the 35 newly recommended frequencies. This is very easy to do using the Import feature, as will be explained shortly. If you do not want to import the frequencies in this way, you can simply load the file HI_RUN2.F05 where these frequencies have already been entered.

Once the HI_RUN2.F05 file is open in SESCAD, click Define | Computation Settings. Then, under Computation Frequencies, click Import and browse to the FT_TRANSI.F27 file to import the 35 new frequencies. Click OK to close the dialog and from the SESCAD top menu, select Run/Reports | Save & Run, to start the run using SESBatch.

This is a long HIFREQ run. For those who wish to bypass this HIFREQ run, the results of this run (RUN2) can be found in the following subdirectory (if you selected the option to load the output files during the installation of the program):

```
Examples\Official\HowTo\CDEGS\Lightn\outputs
```

Copy the resulting HIFREQ database (filename HI_RUN2.F21) to your working directory, change the JobID to TRANSI and proceed as in Chapter 6 to rebuild the FFTSES databases and to carry out the inverse FFT operation. At this stage, the computation results for 52 frequencies are stored in the FFTSES databases. The results can be extracted as in Section 6.3.
Figure 7-1 to Figure 7-5 show the new results. Figure 7-1 and Figure 7-2 show the real and imaginary parts of the new unmodulated scalar potential. Figure 7-3 and Figure 7-4 show the real and imaginary parts of the new modulated scalar potential. The curves are now very smooth. They exhibit a resonance behavior, with the first peak located at 1.5 MHz. The wavelength in the air at that frequency is about 200 m, which is 4 times the height of the tower. The width of the peak is about 100 kHz, which can be very well resolved with a frequency step of 3.33 kHz (Section 4.1.1).

The smoothness of the curves is reflected in Figure 7-5, which displays the new time domain response: the large peak at \( t = 300 \mu s \) has all but disappeared. Figure 7-6 shows the time domain response of the scalar potential between 0 and 40 \( \mu s \).

![Figure 7-1](image1.png)

**Figure 7-1**  Real Part of Unmodulated Scalar Potential after a Second Round of Computations
Chapter 7. Additional HIFREQ and FFTSES Computations

Figure 7-2  Imaginary Part of Unmodulated Scalar Potential after a Second Round of Computations

Figure 7-3  Real Part of Modulated Scalar Potential after a Second Round of Computations
Chapter 7. Additional HIFREQ and FFTSES Computations

Figure 7-4  Imaginary Part of Modulated Scalar Potential after a Second Round of Computations

Figure 7-5  Time Domain Scalar Potential after a Second Round of Computations
Additional HIFREQ and FFTSES Computations

FFTSES again recommends 28 additional computation frequencies. The above steps were repeated for these 28 additional frequencies (HIFREQ input file HI_RUN3.F05). The only changes in these runs are, again, the computation frequencies in the HIFREQ run. Figure 7-7 shows the time domain response between 0 to 40 µs, which is essentially identical to Figure 7-6.
Now that the accuracy of the computations is known to be sufficient, it is a simple matter to use FFTSES to obtain the time domain electromagnetic fields at any profile point initially specified in the HIFREQ input. For example, Figure 7-8 and Figure 7-9 show the Y-component of electric field and X-component of magnetic fields at the same location as the scalar potential, respectively. These were obtained by choosing Y-Component of Electric Field (for Figure 7-8) and X-Component of Magnetic Field (for Figure 7-9) as for the Quantity in the Conductors and Profiles Selection table under the Profiles tab in the Inverse FFTSES screen, and then by re-submitting the FFTSES run.

![Figure 7-8 Time Evolution of Y Component of Electric Field](image)
Chapter 7. Additional HIFREQ and FFTSES Computations

Figure 7-9  Time Evolution of X Component of Magnetic Field

As you probably have already noticed, most of the computation time in the HIFREQ/FFTSES process is spent in the HIFREQ computation part. One thing which is worth pointing out is how to select the computation frequencies for HIFREQ based on the frequencies recommended by FFTSES. FFTSES sometimes recommends more frequencies than is strictly required. If the HIFREQ computation time is short, you can just take all the recommended frequencies and submit them to HIFREQ. When the computation time becomes a major concern to you, some of the frequencies can be dropped. The true criteria for such “iterative” HIFREQ and FFTSES computation is the time domain response or the modulated electromagnetic field response. In this example, because there is a resonance at 1.5 MHz, more frequencies with finer steps are required around 1.5 MHz. From Figure 7-3 and Figure 7-4, the modulated scalar potential becomes negligible at frequencies higher than 2 MHz. Therefore, dropping some of those frequencies would not affect the results significantly.

Please note that the frequencies in the first set of frequencies should never be dropped.
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CHAPTER 8
USING AUTOTRANSIENT TO CARRY OUT STUDY

In this chapter, we will describe how to use the AutoTransient tool to complete the process that is described in Chapter 4 to 7. It is assumed that the reader is entering the data by following the instructions in this chapter.

Note that the input and output files created at the end of in this chapter can be found in the following directory in the SES Software distribution media:

```
Examples\Official\HowTo\CDEGS\Lightn\AutoTransient
```

### 8.1 OVERVIEW OF THE STEPS IN THE ANALYSIS

The steps required to carry out the study are as follows:

1. **Prepare the FFTSES template file.** This file should contain information regarding the input signal (i.e., the lightning surge or transient signal) as well as data defining which quantities are to be computed (in this case, the scalar potential, electric field and magnetic field).

2. **Prepare the HIFREQ template file.** This file should define the conductors making up the system under study, define the energization point and observation points for computing scalar potentials, electric fields and magnetic fields. It is not necessary to specify the computation frequencies, as AutoTransient automatically substitutes the proper frequencies into the template as part of the processing.

3. **Create the AutoTransient project.** This consists mainly in defining the name and location of the project files, and in importing the template files.

4. **Run AutoTransient.** This creates all necessary output files.

5. **Examine the Results.** Use SESResultsViewer or FFT21Data to look at the computation results.

Steps 1 and 2 have been described in Chapter 4 to 6. In the remaining sections, Steps 3 to 5 are described in greater detail.

### 8.2 PREPARE THE FFTSES TEMPLATE FILE

The FFTSES template file is `FT_TRANSIF05`. This file is described in Chapter 4. It computes the scalar potential at \( X = 55 \) m and \( Y = 30.5 \) m. If other quantities (for example, **Y-Component of Electric Field** and **X-Component of Magnetic Field**) at this location are to be computed, you should create different FFTSES template files: one for each quantity under a different scenario (see next).
Chapter 8. Using AutoTransient to Carry Out Study

The two most important points to remember in preparing the template file are:

- Make sure to only request quantities that were also requested in the HIFREQ template.
- It is recommended to process a single point or segment at a time. This is because requesting data from several points or segments simultaneously complicates the analysis of the response curves and may cause FFTSES to recommend an excessively large number of computation frequencies.

AutoTransient monitors Item 1, and will warn you (or forbid running the case) if there is a mismatch between the computation quantities requested in HIFREQ and FFTSES. The program also issues a warning if Item 2 is not respected, although running is allowed in this case.

8.3 PREPARE THE HIFREQ TEMPLATE FILE

The HIFREQ template file is HI_RUN1.F05. Chapter 5 provides details.

As mentioned in Chapter 5, an important aspect of a transient study is to determine an appropriate length for the segments. A good rule of thumb is to make sure that the length of the segments doesn’t exceed 1/6 of the wavelength of electromagnetic propagation in the medium of interest, at the maximum frequency contributing significantly to the results.

AutoTransient offers a simple tool that computes various electromagnetic propagation constants of an electrical medium of given characteristics. This tool can be accessed from the Tools | Electromagnetics Calculator menu item in AutoTransient.

8.4 CREATE THE AUTOTRANSIENT PROJECT

The data used by AutoTransient is organized into scenarios and project. An AutoTransient scenario contains all the data required to carry out a complete transient study with HIFREQ and FFTSES, including the template files for those programs. An AutoTransient project is simply a collection of related scenarios.

8.4.1 Start-Up Procedures

Before anything can be done with AutoTransient, a new project must be created, or an existing one must be open. The HIFREQ and FFTSES template files for the transient study should be ready before creating the new project (or more generally a new scenario), since you are prompted for the location of those files as part of the creation of the scenario.

To create a new AutoTransient project:

1. Start AutoTransient by clicking on Tools | AutoTransient in CDEGS Start-up window (or by clicking on Start | All Programs | SES Software <Version> | Tools | AutoTransient, where <Version> is the version of you SES Software).
2. In AutoTransient, select File | New Project.
3. In the New Project dialog, enter (or browse to) a folder for the Project File Location. In this example, this is set to “C:\CDEGS Howto\Lightn”.
4. Enter ‘AutoTransient’ under **Project Name**. Note that the **Project File Location** automatically updates to “C:\CDEGS Howto\Lightn\AutoTransient”.

5. Enter ‘Potential’ under **Scenario Name**. This is to create a scenario to compute scalar potential. Note that the **Scenario File Location** automatically updates to “C:\CDEGS Howto\Lightn\AutoTransient\Potential”.

6. Click **Create**.

7. In the **Define Template Files** dialog, enter or browse to the filename of the FFTSES and the HIFREQ template files created in Chapter 4 and 5, then click **OK**.

The **Repairable Import Error** shown here could be prompted if the input FFTSES file (ft_TRANSI.f05) does not have a specified import database. This can be repaired by selecting **Repair this defect** and checking the corresponding database, as shown in the following screen.

Note that if you want to choose your FT_TRANSI.F05 as the template, you have to recover it to its original settings; this is because the FT_TRANSI.F05 we have at the end of last chapter (Chapter 7) is different from that of Chapter 4. For example, in Chapter 4 the **Computation Type** is **Forward-FFT** while it is **Inverse-FFT** in Chapter 7; moreover, the **Quantity** is **Scalar Potentials** in Chapter 4 but it is **Y-component of Electric Field** in Chapter 7.

The AutoTransient project is now ready to use.

---

1 This can occur if the FFTSES file has been prepared with the previous version of the program.
8.5 EDIT SCENARIO DATA

Most of the data required in a transient analysis is defined in the FFTSES and HIFREQ template files. Very little data needs to be defined in AutoTransient, and in most cases, it is unnecessary to enter any data in the program other than the paths to the template files.

The following data can be edited in AutoTransient:

- Description of the project and scenarios, and other comments. (Use Project | Properties).
- Options controlling how the automated process is carried out. (Use Project | Edit Scenario Processing Options).
- Selection of the database files, output files and plot files that should be kept at the end of a run. (Use Project | Edit Scenario File Management Options).

Consult the program’s on-line help for more details.

8.6 RUN THE ANALYSIS

Running AutoTransient

Before running the AutoTransient, please close any computation CDEGS programs, as these programs could interfere with AutoTransient and cause serious malfunctions.

To run the scenario, select Project | Start Processing.

Messages are issued on a regular basis in the Program Output and Messages sections of the main screen to keep you posted on the progress of the computations.

The processing of this example should take about half an hour on most computers. For larger cases, the processing could take several hours, even days. AutoTransient can allow you to stop and restart the processing with minimal loss of data by saving the state of the computations to disk when stopping. Consult the on-line help for the Stop Processing feature for more details.

During the processing, the program copies selected output and database files to the following various subfolders under the scenario folder C:\CDEGS Howto\Lightn\AutoTransient\Potential:
History: This folder stores all HIFREQ .F21 database files which takes most of time to generate and are essential to create FFTSES databases. These files are used when the scenario needs to be restarted, and can also be used to continue the analysis manually, if desired.

Results: This folder stores all HIFREQ .F05 input files. The files in this folder are used to visualize the results.

Template: This folder stores the two HIFREQ and FFTSES template files.

Work: This folder stores temporary working files during the AutoTransient analysis. If AutoTransient process completes successfully, this folder is empty.

The processing is complete after six runs.

8.7 EXAMINING THE RESULTS

Once the scenario has finished running, you can examine the computation results stored in the Results and History folders using the FFTSES interface itself. You can also display animation-style plots of the time-domain results with FFT21Data. These programs can be launched directly from AutoTransient using the functions of the Tools menu.

There are three main types of results that you can examine:

- **Forward FFTSES Results** (with the FFTSES interface): Shows the characteristics of the input surge and of its frequency spectrum.

- **HIFREQ Results** (with SESResultsViewer): Displays the response of the conductor network at a given frequency.

- **Inverse FFTSES** (with the FFTSES interface): Displays the frequency spectrum of selected parts of the network (or observation points) as well as its time-domain response.

To examine the Forward FFTSES Results:

1. In AutoTransient, select Tools | View/Plot FFTSES Forward Results | With FFTSES. This will start the FFTSES program and load the computation database for the Forward FFTSES operation of the scenario.

2. In FFTSES under the Results tab, click Plot. This generates 3 plots (displayed in GraRep) which are shown in Figure 4-1, Figure 4-2 and Figure 4-3 and redisplayed below:

---

2 You also have the option to use the legacy tools Output Toolbox and GRServer.
the time-domain surge and the real and imaginary part of the frequency spectrum of the surge.

Figure 8-1 Input Signal in the Time Domain

Figure 8-2 Real Part of Frequency Spectrum of Input Signal
Figure 8-3  Imaginary Part of Frequency Spectrum of Input Signal

3. Close FFTSES.

To examine the Inverse FFTSES Results:

1. In AutoTransient, select Tools | View/Plot FFTSES Inverse Results | With FFTSES. This will start the FFTSES program and load the computation database for the last Inverse FFTSES operation of the scenario.

2. In FFTSES, make sure Modulated is enabled and click Plot. Again, this generates 5 plots in GraRep shown below: the real and imaginary parts of the unmodulated, modulated frequency spectrum of the potential at X = 55 m, Y = 30.5 m, and its time-domain response.
Figure 8-4  Real Part of Unmodulated Scalar Potential Computed by AutoTransient
Chapter 8. Using AutoTransient to Carry Out Study

Figure 8-5  Imaginary Part of Unmodulated Scalar Potential Computed by AutoTransient

Figure 8-6  Real Part of Modulated Scalar Potential Computed by AutoTransient
Chapter 8. Using AutoTransient to Carry Out Study

To get a better view of the early time-domain response:

1. Under Plot Options, set Unmodulated and Modulated to None since we only want the time-domain response of the network.
2. Enter User-Defined for Time, Xmin = 0, Xmax = 40, for the Type of Axes Scaling.
3. Click Plot.
4. Close FFTSES.

![Time Domain Scalar Potential Computed by AutoTransient](image)

**Figure 8-9** Time Domain Scalar Potential Computed by AutoTransient

### 8.8 CONTINUING THE ANALYSIS

The files in the **History** sub-folder of the scenario folder can be used to restart the analysis to examine other physical quantities, either manually or with AutoTransient. As an example, this section walks you through the steps needed to compute the **Y-Component of Electric Field** and **X-Component of Magnetic Field** in AutoTransient.

The procedure is in three main steps:

1. Create a new AutoTransient Scenario. To reduce the computation time, the results that were already computed in the previous scenario are used as a starting point.

2. Modify the FFTSES template to request **Y-Component of Electric Field** and **X-Component of Magnetic Field**.

3. Process the scenario, and examine the results.
8.8.1 Creating a Second Scenario

To create a second scenario in the project:

1. In AutoTransient, select **Project | New Scenario**.
2. In the **New Scenario** dialog, enter ‘Y-Electric’ under **Scenario Name**. Note that the **Scenario File Location** automatically updates to “C:\CDEGS Howto\Lightn\AutoTransient\Y-Electric”. Note also that the **Reference Scenario** is set to the “Potential” scenario by default. This is important in the next step. Click **Create**.
3. In the **Define Template Files** dialog, select **Copy template file from Scenario “Potential”** under **FFTSES Template File**, and select **Share template file from Scenario “Potential”**. Click **OK**.

A second scenario is created in file “Y-Electric”. Initially, this scenario uses the same FFTSES template file as the first scenario. Also, this new scenario shares the HIFREQ template (and HIFREQ databases) with the first scenario.

8.8.2 Modifying the FFTSES Template

This section shows how to modify the FFTSES template file to request **Y-Component of Electric Field** at X = 55 m, Y = 30.5 m (Profile 1, Point 56).

To modify the FFTSES template file:

1. In AutoTransient, select **Tools | Edit FFTSES Template File | With FFTSES…** This loads the FFTSES template file and allows you to edit it.
2. In the FFTSES main screen, select **Inverse** from the **FFT** drop down menu.
3. In the **Inverse** screen, from the **Conductors and Profiles Selection** table, select the **Profiles** tab, click **Add**, select select **Y-Component of Electric Field**, and define Point No. 56 in Profile 1 to define the observation point at X = 55 m and Y = 30.5 m. Click **OK**.
4. Click Save in the FFTSES main screen to save the changes and close the program.

8.8.3 Processing the “Y-Electric” Scenario

To process the scenario:

1. In AutoTransient, click Project | Start Processing;
2. In the Restart Options dialog, leave Do not run any additional frequencies unchecked and click OK.

The program re-computes the FFTSES databases for the new quantity, based on the existing HIFREQ results. It then proceeds as usual, namely it detects if any more computation frequencies are required, and if so, runs HIFREQ at those frequencies.

In this example, one extra HIFREQ run is required (for a total of 6 frequencies).

The results can be examined as before. The following plot shows the time domain Y-component of electric field at X = 55 m, Y = 30.5 m. This curve is almost identical to Figure 7-8.
8.8.4 Creating a Third Scenario

A scenario called “X-Magnetic” is created to examine the **X-Component of Magnetic Field** at $X = 55\, \text{m}$, $Y = 30.5\, \text{m}$ (Point No. 56 in Profile 1). The steps are the same as those described in the second scenario\(^3\). AutoTransient carried out two extra runs for a total of 11 frequencies. Figure 8-11 shows the results which is virtually the same as Figure 7-9.

\[^3\] The reference scenario can be either Potential or Y-Electric as they both share the same HIFREQ template file.
8.8.5 Save Project

To save the project, select File | Save Project.

This example used only some of the features of the program. More powerful features are available, particularly as regards the specification of frequency-dependent parameters in the conductor network. Consult the program’s on-line help for more details.
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CHAPTER 9
CONCLUSION

This concludes our step-by-step instructions on how to conduct a transient analysis using the HIFREQ Electromagnetic Field Analysis Computation module and the Fast Fourier Transform package FFTSES.

Only a few of the many features of the software have been used in this tutorial. You should try the many other options available to familiarize yourself with the CDEGS software package. Your SES Software distribution media also contains a wealth of information stored under the PDF directory. There you will find the Getting Started with SES Software Packages manual (PDF\getstart.pdf) which contains useful information on the CDEGS environment. You will also find other How To…Engineering Guides, Annual Users’ Group Meeting Proceedings and much more. All Help documents are also available online.
APPENDIX A
COMMAND INPUT MODE

In this section, the Command Mode compatible input files are described in detail.

Printout A.1 is the resulting FFTSES Command Mode compatible input file which obtains the frequency domain components $I(\omega)$ using forward FFT. This FFTSES file can be edited directly by an experienced user or is automatically produced when using one of the above-listed input interface modules. Similar files can be prepared quite easily by following the information contained in the template shown below.

```
FFTSES

TEXT,MODULE, FORWARD FFT: Frequency decomposition of a double
TEXT,MODULE, exponential-type lightning surge signal.
TEXT,MODULE, INVERSE FFT: Obtain transient scalar potentials and
TEXT,MODULE, electromagnetic fields.

OPTIONS
PRINTOUT

UNITS, METRIC
RUN-IDENTIFICATION, EX3: LIGHTNING
COMPUTATIONS, ON
DIRECTION, Forward
FORWARD-FFT, 30
   SAMPLING-EXPONENT, 12
   LIGHTNING-SURGE, DOUBLE-EXPONENTIAL
      SURGE-COEFFICIENTS, 30000., 14000., 6000000., 0., 0., 0.
      TIME-DURATION, MICROSECOND, 0., 300.
INVERSE-FFT
DATABASE
   IMPORT
      POTENTIAL, NONE
      ELECTRIC, OFF
      MAGNETIC, OFF
      CONDUCTOR-DATA, OFF
MODULATION, ON
SPECIFIED-SURGE, INTERPOLATION
   ANIMATION-SA, NO
   EXTRACT, POTENTIAL, ,, 56, 56, 1, 1
GRAPHICS, ON
   PLOT-IDENTIF, LIGHTNING
   REPRESENTAT
      FONT, DEVICE-SPECI
SELECT
   UNMODULATED, BOTH-REAL-IMAGINARY
   TIME-DOMAIN, BOTH-REAL-IMAGINARY
WHERE, POSTSCRIPT

ENDPROGRAM
```

Printout A.1 FFTSES Input File FT_TRANSI.F05
Figure A.1  FFTSES Command Mode Compatible Input File Template
Appendix A. Command Input Mode

Printout A.2 is the HIFREQ input file used to compute the unmodulated electromagnetic response. This file can be edited directly by an experienced user or is automatically produced when using one of the input interface modules listed at the beginning of this appendix.

Similar files can be prepared quite easily by following the template shown in Figure A.2.
Appendix A. Command Input Mode

INDIVIDUAL,6666.667
INDIVIDUAL,10000.001
INDIVIDUAL,13333.334
INDIVIDUAL,16666.668
INDIVIDUAL,20000.002
INDIVIDUAL,23333.334
INDIVIDUAL,26666.668
INDIVIDUAL,30000.003
INDIVIDUAL,33333.334
INDIVIDUAL,36666.668
INDIVIDUAL,40000.004
INDIVIDUAL,43333.334
INDIVIDUAL,46666.668
INDIVIDUAL,50000.005
INDIVIDUAL,53333.334
INDIVIDUAL,56666.668
INDIVIDUAL,60000.006
INDIVIDUAL,63333.334
INDIVIDUAL,66666.668
INDIVIDUAL,70000.007
INDIVIDUAL,73333.334
INDIVIDUAL,76666.668
INDIVIDUAL,80000.008
INDIVIDUAL,83333.334
INDIVIDUAL,86666.668
INDIVIDUAL,90000.009
INDIVIDUAL,93333.334
INDIVIDUAL,96666.668
INDIVIDUAL,100000.01

METHODOLOGY
INTEGRATION
SOMMERFELD,AUTOMATIC,0,0.005,32,15
SOURCE-LOCAT,AIR
OBSERVER-LOC,AIR
ALGORITHM,DOUBLE-INTEG
SOURCE-LOCAT,AIR
OBSERVER-LOC,SOIL
ALGORITHM,DOUBLE-INTEG
SOURCE-LOCAT,SOIL
OBSERVER-LOC,AIR
ALGORITHM,DOUBLE-INTEG
SOURCE-LOCAT,SOIL
OBSERVER-LOC,SOIL
ALGORITHM,DOUBLE-INTEG

ENDPROGRAM

Printout A.2 HIFREQ Input File HI_RUN1.F05
Figure A.2  HIFREQ Command Mode Compatible Input File Template
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APPENDIX B
THE MALAYSIA PAPER

In this Appendix, the paper “Lightning Response of Communication Towers and Associated Grounding Networks” that appeared in the Proceedings of the International Conference on Electromagnetic Compatibility (ICEMC ‘95 KUL) is reprinted.
LIGHTNING TRANSIENT RESPONSE OF COMMUNICATION TOWERS
AND ASSOCIATED GROUNDING NETWORKS

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Abstract: The transient behaviour of a communication tower subjected to a lightning strike is investigated using the field theory approach. A 50 m communication tower connected to two different grounding grids is studied. The lightning strike is simulated by injecting a 30 kA current surge having a double exponential. To obtain the temporal electromagnetic field response, the lightning surge current is decomposed into its frequency domain spectrum using the forward Fast Fourier Transform. The current distribution in the tower and grounding conductors, the scalar potentials and the electromagnetic fields are first computed at selected frequencies. The time domain scalar potentials and electromagnetic fields are then obtained using the inverse Fast Fourier Transform. Three different lightning strike scenarios are examined: (i) tower with a simple grounding grid, (ii) tower with an enhanced grounding grid and (iii) enhanced grounding grid without tower. The frequency domain and time domain results indicate that the tower with an enhanced grounding grid has considerably lower scalar potentials and electric fields during the lightning surge. When lightning strikes the tower, the transient electromagnetic fields at the earth surface initially oscillate at the tower resonance frequency with significant amplitude. When lightning strikes the enhanced grid only, the transient fields show no oscillation and are much smaller.

1. Introduction

Tall structures such as transmission lines and communication towers are more susceptible to lightning strikes than other types of structures. A lightning strike to an elevated structure is a common cause of transients on overhead lines, power and communication cables and terminal electronic equipment near the strike site. With increasing use of semiconductors in modern electronic equipment which are inherently more sensitive to voltage or current surges, analysis of the transient electromagnetic response near the strike site has become essential in designing protection of communication systems. Circuit models and field theory methods have been used to examine the transient behaviour of lightning protection systems. In the circuit approach, the protection conductor network and the "victim" device are simulated by equivalent impedances and the induced currents and voltages are then calculated using conventional circuit theory [1]. In the field theory approach, the electromagnetic field equations are solved for the protection conductor network energized by a lightning strike. The energization is simulated by injecting the required current surge at the point where lightning has struck. In the past, most of the work on transient electromagnetic response was carried out using the circuit model. In this paper, we present a field theory approach. A 50 m high communication tower connected to different grounding grids is subjected to a direct lightning strike at the top of the tower. The transient electromagnetic fields near the tower base are computed. Both the spatial and temporal distributions of electromagnetic fields at the strike site are presented.

2. Computation Methods

The computation of the current distribution of an aboveground conductor network energized by a single frequency current or voltage excitation is well described and organized in antenna theory. The techniques employed are usually based on the electric field point-matching approach using the Moment Method [2-5] and have focused on the high frequency range (megahertz or more). Using similar techniques, the authors have developed software, known as CDEGS/HIFREQ [6-8], which computes the current distribution for a network consisting of both aboveground and buried conductors excited at arbitrary frequencies. The details of this method are given in [7] and [8]. This paper is based on a method which represents an improvement over the electric field point-matching technique described in [7] and [8]. This method is briefly summarized as follows.

The conductor network is subdivided into small segments so that the thin-wire approximation can be applied. Consider conductor node \( n \) shared by \( N_n \) segments. The segments impinging on node \( n \) are numbered \( i_n = 1, \ldots, N_n \). The electric field boundary condition \( E_{tan} \cdot Z_{in} I = 0 \) is integrated along the surface of two consecutive conductor segments to obtain
Appendix C. The Malaysia Paper

\[ g(n,i) = \int_{l/2}^{l} (E_{\text{tan}} - Z_{\text{int}}I) dl \quad (1) \]

where \( E_{\text{tan}} \) is the tangential component of \( \mathbf{E} \) at the conductor surface, \( I \) the longitudinal current flowing in the conductor, and \( Z_{\text{int}} \) the internal impedance of the conductor. The integration path is from the midpoint of one segment \( \frac{l_i}{2} \) to the midpoint of the next segment \( \frac{l_{i+1}}{2} \). An objective function is constructed and minimized subject to the following linear constraints on the current flowing in the conductors and leaving conductor nodes.

(i) zero out-flow currents at all nodes terminating in the dissipative medium (pseudo nodes) which are not energized.

(ii) fixed longitudinal currents at pseudo nodes where specified currents are injected into the network.

(iii) Kirchoff’s law for the conservation of current flow at conductor nodes.

(iv) any other excitation conditions such as voltages, scalar potentials, incident electric fields which restrict or clamp the longitudinal current flow along one or more conductor segments.

For a node with \( N \) segments, there are \( N-1 \) independent equations from the electric field boundary condition Eq. (1). Since the segment currents must also satisfy Kirchoff’s law, we have \( N \) equations to determine the \( N \) unknown segment currents at the node. The current distribution in the conductor network is obtained by solving the equation set. The scalar potentials and the electromagnetic fields at arbitrary observation points can then be calculated using the formula given in [8]. The network can be energized by different types of excitations, such as current injections, delta-gap voltage generators or incident electric fields.

![Figure 1](image.png)

**Figure 1** A double exponential lightning surge current.

3. Description of the Problem Being Modelled

Figure 2 illustrates the problem being studied. Three scenarios are studied. Scenario 1 (SC1) consists of a 50 m high communication tower connected to a simple grounding system. The tower structure is approximated by 6 mm radius steel rods and the grounding system by copper conductors with a 6 mm radius as well. The grounding system consists of the bottom part of the tower, three vertical ground rods which are driven to a depth of 3 m and a 30 m horizontal conductor which is buried at a depth of 1 m and is used to connect one leg of the tower (Leg A) to the three vertical ground rods. A 40 \( \times \) 65 m rectangular loop buried at a depth of 0.5 m
represents the outer loop connected to a fence surrounding the tower (the metallic fence is not modeled in this study).

Scenario 2 (SC2) examines the effects of an enhanced grounding system resulting from the addition of several horizontal conductor connections from the base of the tower to the outer fence loop. The additional conductors are at a depth of 0.5 m. By removing the steel tower from Scenario 2, we then get Scenario 3 (SC3), which is used to examine the lightning response of the enhanced grounding grid only. In Scenarios 1 and 2, lightning strikes the top of the tower, while in Scenario 3, lightning strikes Leg A of the tower. In all three scenarios, a uniform soil with a 100 \( \Omega \cdot m \) resistivity, a relative permittivity of 1 and relative permeability of 1 is assumed.

![Figure 2](image)

Figure 2 A communication tower with two different grounding systems is subjected to lightning strikes.

4 Computation Results

4.1. Frequency Domain Results

The spatial distributions of the scalar potentials and electromagnetic fields at large number of observation points located on the earth surface over the grounding system are computed for the three scenarios (SC1, SC2 and SC3). The computations were carried out at 50 Hz, 100 kHz, 500 kHz and 1 MHz by injecting \((1000.0 + j 0.0) \) A into the conductor network. A mesh of observation points is defined by 50 parallel profiles covering the grounding grid from \( Y = 0 \) to \( Y = 49 \) m in 1 m steps. Each profile consists of 75 observation points starting at \( x = 0 \) and spaced in 1 m increment. 3-D perspective plots of the scalar potentials and the electromagnetic fields are shown hereafter. The results corresponding to the 50 Hz and 100 kHz are both reported in this paper.

Figures 3, 4, 5 and 6 show 3D perspectives of the earth surface scalar potential. Figures 3 and 4 correspond to the current injection at 50 Hz for scenarios SC1 and SC2 respectively. Figures 5 and 6 correspond to the current injection at 100 kHz for scenarios SC2 and SC3 respectively. Figure 4 clearly indicates that connecting the tower to the fence loop greatly reduces the scalar potential and also equalizes the potential over the grounding grid, at 50 Hz. Therefore, step and touch voltages are reduced with the enhanced grid. The potential plot reflects the configuration of the grounding grid (see Figure 2). Note that the peak due to Leg C of the tower \((x = 63.6, y = 25.0)\) is not as pronounced as the other two because the closest observation point to Leg C is at \( x = 64.0, y = 25.0 \), while there are observation points directly on the surface of the other two legs. The scalar potential for scenario SC3 is almost identical to the one corresponding to scenario SC2. In other words, the earth surface potential at low frequency is mainly determined by the buried structures.

At higher frequencies, the impedance of the grounding grid is no longer negligible and most of the earth current dissipates close to the injection point. Such behaviour is illustrated in Figures 5 and 6. A direct injection of current to the enhanced grid without the tower (SC3) results in a very sharp peak near the injection point. In all three scenarios, the scalar potentials near the injection point have much higher values than those elsewhere. The potential increases with increasing frequency. The scalar potentials at 500 kHz and 1 MHz are similar in shape to the 100 kHz results but with sharper attenuation as one moves away from the point of current injection.

Figures 7, 8 and 9 display the total (resultant) electric field at 50 Hz. Figures 7 and 9 correspond to the simple grid (SC1) and the enhanced grid (SC2) respectively. Figure 8 is the same as Figure 7, except that the vertical scale has been expanded 20 times. Again, the electric fields at the earth surface for the case of the
tower with the enhanced grid are about 10 times smaller than those produced by the tower with the simple grid. The arrows in these figures indicate that the total electric fields actually reach much higher values. ($E_{\text{max}} = 40$ kV/m for SC1 and $E_{\text{max}} = 4$ kV/m for SC2). As in the case of the scalar potentials, the total electric fields increases with increasing frequency. The electric fields at 500 kHz and 1 MHz are similar in shape to those at 100 kHz.

Unlike the total electric field, the total magnetic field $H$ is about the same for Scenarios 1 and 2. Its peak value reaches about 6 kA/m near the three legs of the tower, at 50 Hz, 100 kHz and 500 kHz. The total magnetic field $H$ shows a weak frequency dependence. Similar behaviour is observed for Scenario 3, but with a higher peak value of 16 kA/m near the injection location (Leg A).
4.2. Time Domain Results

In order to select an appropriate number of representative frequencies from the lightning current frequency spectrum, we compute the unmodulated field response (such as scalar potential) at an observation point by energizing the network using a unit current \((1.0 + j 0.0) \, \text{A}\). Figure 10 shows both the real and imaginary parts of the unmodulated scalar potential as a function of frequency at an observation point located at the surface of the soil at \(x = 55.0, y = 30.5\) (Scenario 2). A total of 96 frequencies from 2 Hz to 13.65 Mhz were chosen in order to adequately define the frequency response curve. Most of the frequencies are below 4 MHz, since the modulated scalar potential is found to approach zero above 4 MHz. A sharp peak is observed at about 1.5 MHz (1.4 MHz for the real part and 1.47 MHz for the imaginary part) which corresponds to the resonance frequency of the 50 m tower (50 m is \(1/4\) times the wavelength in air at 1.5 MHz). At each selected frequency, the scalar potentials, electric fields and magnetic fields were computed at various earth surface observation points near the fence and tower legs. In the following, we examine the temporal variation of the
scalar potential and the electromagnetic field at a point located at \( x = 55.0, y = 30.5, z = 0.0 \) near Leg A.

Figures 11, 12, 13 and 14 show the temporal evolutions of the scalar potential \( \phi \), step voltage \( \Delta \phi \), Y-component of the electric field \( E_y \) and X-component of the magnetic field \( H_x \), respectively. The step voltage is computed as the voltage difference between the two earth surface points located at \((55.0, 30.5, 0.0)\) and \((56.0, 30.5, 0.0)\). Note that \( E_y \) and \( H_x \) are the dominant components of \( E \) and \( H \) respectively, at the observation point located at \((55.0, 30.5, 0.0)\). For clarity, only the time variation up to 40 \( \mu \)s is shown.

A salient feature in these figures is the oscillation of these quantities during the first 10 \( \mu \)s after lightning strikes the top of the tower (SC1 and SC2). The frequency of the oscillations, which is about 1.44 MHz, corresponds to the resonance frequency of the tower. The magnitudes of the scalar potentials, electric fields and magnetic fields are very large in these curves. When the lightning strikes the enhanced grid (SC3) directly, the oscillations disappear and the magnitudes of \( \phi \), \( \Delta \phi \), \( E_y \) and \( H_x \) become much smaller. Similar observations hold for the other components of \( E \) and \( H \). A comparison between Scenarios SC1 and SC2 (Figures 11-14) shows that the enhanced grounding grid performs better than the simple grid by reducing the transient electromagnetic field response. As shown in Figures 11-13, \( \phi \), \( \Delta \phi \) and \( E_y \) (SC2) rapidly decay towards zero. However, Figure 14 indicates that the transient magnetic fields increase when the enhanced grid is used. This may be due to the increased number of grounding conductors in Scenario 2.

Figure 11 Transient scalar potential at \( x = 55.0, y = 30.5, z = 0.0 \) for the three scenarios.

Figure 12 Transient step voltage between two earth surface points for the three scenarios.

Figure 13 Transient electric field \( E_y \) at \( x = 55.0, y = 30.5, z = 0.0 \) for the three scenarios.

5. Conclusions

A detailed frequency and time domain analysis of the electromagnetic fields generated by a communication tower subjected to a lightning strike for the three scenarios was carried out. At low frequencies, the earth surface scalar potential over the area of the grounding grid is reduced and equalized by connecting the tower legs to a nearby fence loop surrounding the tower. The electric field is also reduced by these
connections. The scalar potential and electric field are significantly dependent on frequency, while the magnetic field shows rather a weak dependence on the frequency. The scalar potential and electric field increase with increasing frequency and exhibit higher values near the current injection sites.

When lightning strikes the communication tower, the transient scalar potential, step voltage, electric field and magnetic field at the earth surface near the tower oscillate at the resonance frequency of the tower. Such oscillations result in very large transient electromagnetic fields in the initial period after lightning strikes. The oscillations no longer exist in the absence of the tower and the transient field magnitudes are much lower.

6. Acknowledgments

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7. References


Biographies

Dr. Farid P. Dawalibi (M'72, SM'82) was born in Lebanon in November 1947. He received a Bachelor of Engineering degree from St. Joseph's University, affiliated with the University of Lyon, and the M.Sc. and Ph.D. degrees from Ecole Polytechnique of the University of Montreal. From 1971 to 1976, he worked as a consulting engineer with the Shawinigan Engineering Company, in Montreal. He worked on numerous projects involving power system analysis and design, railway electrification studies and specialized computer software code development. In 1976, he joined
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In 1979, he founded Safe Engineering Services & technologies, a company which specializes in soil effects on power networks. Since then he has been responsible for the engineering activities of the company including the development of computer software related to power system applications.

He is the author of more than seventy papers on power system grounding and safety, inductive interference and electromagnetic field analysis. He has written several research reports for CEA and EPRI.

Dr. Dawalibi is a corresponding member of various IEEE Committee Working Groups, and a senior member of the IEEE Power Engineering Society and the Canadian Society for Electrical Engineering. He is a registered Engineer in the Province of Quebec.

Dr. Wenxin Ruan was born in P. R. China in 1964. He received the B.Sc. degree in physics from Lanzhou University, P. R. China in 1985. He received the Ph.D. degree in experimental physics from the University of Manitoba, Winnipeg, Canada in 1993. From 1987 to 1992, he was a research associate with the Department of Physics at the University of Manitoba, where he worked on constructing a SQUID AC susceptometer/magnetometer and studying magnetic phase transitions in reentrant magnetic alloys with quenched structural disorder.

In 1993, he worked as a postdoctoral fellow in the Institute of Biomedical Engineering at Ecole Polytechnique, University of Montreal. He worked on the Electrical Impedance Tomography using induced current methods.

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Dr. Simon Fortin was born in 1962. He received a B. Sc. degree (1985) in Physics from Laval University, Quebec and a Ph. D. degree (1991) in Physics from the University of British Columbia, Vancouver. His area of specialization was in the theoretical aspects of high-energy particle physics. In 1992-1993, he was a research assistant with the Nuclear Physics Department at the University of Montreal, again specializing in particle physics.

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