Evaluation of narrowband frequency domain measurements of electrostatic discharge (ESD) events.

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EVALUATION OF NARROWBAND FREQUENCY
DOMAIN MEASUREMENTS OF ELECTROSTATIC
DISCHARGE (ESD) EVENTS

by

Ling Hsiang (Tony) Lo

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Faculty of Graduate Studies and Research
Through the Department of Electrical Engineering in Partial Fulfilment
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In recent years, the electrostatic discharge (ESD) has become one of the major subjects which often concerns the Electromagnetic Compatibility (EMC) community. Especially, there is a significant increase of discussion for all aspects of ESD issues being developed in the 1997 EOS/ESD Symposium. The introduction of the narrowband frequency-domain method of measurement and the further insight of the Fourier Transform (FT) analysis of the ESD waveforms and events were thoroughly investigated in an attempt to offer a handy tool for exploration of getting faster and faster ESD test sources and to suggest a solution for the increasingly vulnerable equipment and devices.

Traditionally, ESD waveforms have been measured and analyzed in the time domain and various waveform parameters have been related to the severity of the discharge voltage. Distinctively, this thesis describes the examination of electrostatic discharge (ESD) in the frequency domain and relates the ESD waveforms to their spectra. Regardless of the complexity of the ESD waveshape, the spectral contents can be calculated and measured. Therefore, the spectral data can be used to define the severity of the ESD events.

The newly proposed test setup is designed to generate the spectral components to correspond as closely as possible to those of the human ESD event in a given test environment. In this test setup, the variables that affect the test are controlled as much as possible. The human body to equipment under test (EUT) capacitance, $C_d$, is controlled. This is accomplished by the use of a parabolic shield. It reduces variation in $C_d$ due to the human body size, and eliminates some ambiguities in the IEC standard.

Analytical results show that:

(1) ESD waveform rise time equal to or less than that of the oscilloscope cannot be measured accurately.
(2) Significant discrepancies can exist between waveforms which satisfy the description of the IEC 801-2 (1991) standard waveform, now renamed IEC 1000-4-2 (1995), and sample ESD waveforms that the specified time domain parameters allow.

(3) ESD spectral components do not always increase directly with increasing discharge voltage.

(4) Current slew rate is not sufficient to accurately determine likely failure.

Recognizing the weaknesses associated with specifications based on a limited set of time domain parameters, the proposed frequency domain method warrants further investigation and development.
Dedicated to my parents, my wife Yihua, and my son Joshua
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CHAPTER 1

INTRODUCTION

1.1 Electrostatic Discharge

The world is full of electromagnetic interference (EMI) and noise. The EMI and noise can take various forms and manifest themselves in many ways. One of the most common and obvious forms of EMI is an electrostatic discharge (ESD). We all have had the experience of walking across a room and touching another person or object and experiencing an annoying "electric shock". This ESD event of a human body acting as a capacitor, storing charge and discharging itself in close proximity or contact to another object has been studied and characterized. The reason for this is because it is the most common form of ESD event.

Discharges from a metal object such as a key or metal tool held by the hands of charged individuals, are increasingly recognized as reasonable worst-case situations. They generate injection current into victim equipment that often includes high-amplitude spikes. These range from 10 to 30 A peak, with rise time less than 1 nsec and durations of 1 to 4 nsec being reported [1]. Unfortunately, this is bad news for modern microelectronic devices with increasing operational speed, and decreasing power consumption and small size. Therefore, the studies of the ESD issue have become very important for electrical and electronic industries.

1.2 Characteristics of ESD Waveforms

ESD waveforms have traditionally been examined in the time domain. Their shape has been measured and related to the speed of approach of the discharging metal objects,
to the shape and character of these objects, to the ambient humidity and to the bandwidth of the measurement oscilloscope [2-6]. These experiments have been carried out with ESD simulators as well as with actual personnel and furniture discharges.

The parameters of primary concern have been the rise time and peak current of simply shaped pulses. The rise time of a waveform is not readily defined for non-standard shaped pulses such as human ESD waveforms defined by the IEC 801-2 series. Surprisingly, except for rare occasions [7], the frequency domain characteristics of ESD waveforms have not been examined whereas other phenomena of concern in the electromagnetic compatibility (EMC) and EMI areas are traditionally described and specified in the frequency domain [8].

Some distinctive features were found during this research on the frequency domain method of measurement for ESD waveforms. One characteristic is that the spectral components below \( \frac{1}{\pi \times \text{(pulse width)}} \) (Hz) have almost a direct linear relationship to the pulse width and peak current. These low frequency components can be calculated using the Fourier Transform (FT) and measured using the frequency domain method described in this thesis. It appears to be the first time that a FT method has been used to calculate the spectral components of a known ESD waveform. The calculated data can be used to compare with the measured data at any severity level.

1.3 Standardization and ESD Testing

This thesis will discuss an international body of standards concerned with ESD. Specially the International Electrotechnical Commission (IEC) 801-2 series of standards [9-11] will be addressed. The intent is to describe the IEC 801-2 standard with particular emphasis on the different aspects of studies in the frequency domain.

The objective of the IEC 801-2 (Second Edition 1991-04) part 2 [10] is to establish a common reference for evaluating the performance of instrumentation when subjected to electrostatic discharges. The standard also includes ESDs which can occur from personnel to objects near instrumentation. The standard specifies two modes of operation: an air discharge mode and a direct current discharge mode.
Note that the standard changed in April 1991 to the Second Edition. The primary changes were the human body model which was modified from 150 Ω / 150 pF to 330 Ω / 150 pF, the rise time from 5 nanoseconds down to less than 1 nanosecond and the contact discharge was introduced as a more repeatable test method than the previously used air discharge.

In the air discharge mode, a spark from the test probe of the ESD generator is discharged into the air toward the Equipment Under Test (EUT). The generator must be able to provide an adjustable charging voltage up to 15 kV. The discharge level which the EUT must withstand depends on its type and the environment in which it is intended to be used.

In the direct current discharge mode (more commonly known as contact discharge), an impulse is released from the ESD generator. The tip of the generator’s probe should be in actual contact with the EUT when the discharge is released. For this mode the generator should be able to provide an adjustable voltage up to 8 kV. The rise time for the direct current pulse must be between 0.7 - 1.0 nanoseconds.

The air discharge mode is the most realistic method when real world conditions are considered, however, the contact discharge method is more reproducible and overcomes the inconsistencies of air discharges. The air discharge is actually an air-with-contact discharge as defined by the IEC. There is a difference between air only and air-with-contact discharges. In the time domain measurement using an oscilloscope, the difference is not readily detected. In the frequency domain, the difference can readily be seen later in Chapter 4 of this thesis. The details of the experimental setup and the narrowband frequency domain method of measurement will be discussed in Chapters 2 and 3, respectively. The contact discharge is a method in which arcing is produced by a relay switch. The IEC specifies a double-peak waveform in the standard of IEC 801-2 (1991) and now IEC 1000-4-2 [11]. The waveforms and their performances will be discussed in Chapter 4.

In order to help observe the ESD testing results, the statistical approach is introduced to measure the precision and accuracy in Chapter 5. The discussion will be based on examples of experimental facts.
1.4 Research Objectives

(1) To reveal shortcomings of the studies of ESD characteristics in the time domain.

(2) To employ the Fourier Transform analysis exploring the insight of the ESD transients in the frequency domain.

(3) To introduce the method of narrowband frequency-domain measurements of ESD.

(4) To propose a new test setup for ESD measurements.

(5) To study the features and influential factors of human ESD events and ESD generators.
2.1 General Comparison

The oscilloscope used in the time domain is compared to the spectrum analyzer used in the frequency domain.

(1) Amplitude:

The time domain oscilloscope measures time from 0 to a point where current is at a peak using a linear scale. Some amplitude error is always present. For example, a 4 GHz oscilloscope has an error of -3 dB at a 4 GHz analog frequency point. Beyond 4 GHz, the error is unknown but can be estimated based on a slope of -20 dB per decade frequency in the instrument's response characteristic.

The frequency axis often uses a log scale where each frequency component always occupies the same spacing determined by the bandwidth of the receiver.

(2) Rise time:

The latest and fastest non-repetitive (real time) oscilloscopes from two main stream companies are:

HP 54722A [12]: Bandwidth (-3 dB) = 2 GHz; Digitizing rate (Sample rate) = 8 GSa/s;

Time interval accuracy (best case) = ± 50 ps

Tektronix SCD 5000 [13]: Bandwidth (-3 dB) ≥ 4.5 GHz; Single-shot sample rate = 200 GS/s; Horizontal time per point = 5 ps/pt

(5 ns time window with 1024 point record length)

The fastest oscilloscope (the Tektronix SCD 5000) with the rise time of 10 ps for the ESD waveform will be used as an example for calculation of the studies to demonstrate how the
ESD events may not be measured "accurately". (Further illustration of very fast ESD pulses will be discussed in Case Study (1) of Section 4.3.1)

The rise time of the image on the screen of the oscilloscope can be calculated [14]

\[ T_n = \sqrt{T_{ro}^2 + T_{rw}^2} \]  

(2.1)

where \( T_n \) = rise time of the image
\( T_{ro} \) = rise time of the oscilloscope
\( T_{rw} \) = rise time of the waveform

It is assumed that the rise time (\( T_r \)) of the oscilloscope from the calculation of

**Case 1:** If \( T_{ro} = 0.35/BW \) [13-14]

(from Tektronix's transient event digitizer)

\[ T_{ro} = 0.35/(4.5 \text{ GHz}) = 77.78 \text{ ps} \]

Hence, following Eq. (2.1)

\[ T_n = \sqrt{77.78^2 + 10^2} = 78.42 \text{ ps} \]

In this case, the ESD rise time of 10 ps cannot be seen correctly. The observed rise time is very close to that of the oscilloscope.

**Case 2:** If \( T_{ro} = 0.8/BW \) [15]

(from F. E. Terman's definition: 0.7 to 0.9/BW for the reasons of overshooting and undershooting of the waveform)

\[ T_{ro} = 0.8/(4.5 \text{ GHz}) = 177.78 \text{ ps} \]

Then

\[ T_n = \sqrt{177.78^2 + 10^2} = 178.06 \text{ ps} = \text{rise time of the oscilloscope} \]

In this case, the conclusion is the same as Case 1.

**Case 3:** If \( T_{ro} = 1/BW = 1/(4.5 \text{ GHz}) = 222.22 \text{ ps} \)

Then

\[ T_n = \sqrt{222.22^2 + 10^2} = 222.44 \text{ ps} = \text{rise time of the oscilloscope} \]
In this case, the conclusion is also the same as Case 1.

In most of the cases, measurement results of the very fast ESD transients are influenced by the oscilloscope's rise time. It is noted that even a 6 GHz bandwidth oscilloscope does not model the ESD current well. When the oscilloscope's bandwidth is less than that of the transient event, the rise time of the event's image will be greater than that of the event, and the event display's amplitude will be less than that of the event [16].

According to Oliver's approximation [14], for the rise time measurement error to be less than 2 percent of the input waveform, therefore

\[ T_r = \sqrt{T_{ro}^2 + T_{rw}^2} \leq 1.02 \ T_{rw} \]  \hspace{1cm} (2.2)

The input waveform's rise time must be

\[ T_{rw} \geq 5 \ T_{ro} \]  \hspace{1cm} (2.3)

For \( T_{rw} = 10 \) ps, \( T_{ro} \) must be less than or equal to 2 ps which is not available so far.

Also, if one considers the "time per point" of 5 ps/pt of the Tektronix SCD 5000, during the 10 ps of the waveform's rise time, there are only two sampling points taken. The record lacks the information necessary to describe this transient. Usually, the sampling rate of one tenth of the rise time is considered to be adequate (At least 10 points are taken for this case).

(3) Waveshape

From the waveshape point of view, if the waveform contains 10 to 20 percent harmonics, it is hard to detect and quantify by using visual inspection in the time domain using an oscilloscope. An example waveform of 20 percent distortion using the addition of two sine-wave current sources and a 1 Ω load is shown in Figure 2.1. One component has an amplitude of 10V, frequency of 10 MHz; the other has an amplitude of 2V and frequency of 20 MHz without time delay or voltage offset. The resultant waveform is shown in Figure 2.2. From this waveshape there is no clear indication of the percentage of distortion being added. However, from Figure 2.3, the frequency response is shown and the second harmonic at 20 MHz leads us to recognize the 20 percent distortion. This exercise illustrates the value of examining waveshape properties in the frequency domain.
In the ESD waveforms, other than single-peak waveform, it is hard to decide the rise time and peak current in the time domain based on the traditional definitions if the waveshapes of ESD transients are "irregular" which means the waveshapes look different from that of IEC Standard and have many ripples, peaks and valleys. The multi-peak waveform shown in Fig. 3 of Wallace's paper "6 GHz Time Domain Measurement of Fast Transient Events" [17] is one such example.

Therefore, using the oscilloscope to measure the very fast ESD transients will encounter problems and using the spectrum analyzer is a possible solution based on the preceding analysis.

2.2 Test Setup for Frequency-Domain Measurement

In most ESD test setups, the ESD simulator, the ground return wire, the test environment, the distributed capacitor $C_d$ and the equipment under test (EUT) contribute to the results of the measurement. This is true regardless of whether the instrument generates a time domain or frequency domain display. The objective of the test setup for the suggested narrowband frequency domain method of measurement is to retain the spectral components as closely as possible to correspond to that of the human discharge event in a given test environment. In this test setup, the variables that affect the test are controlled as much as possible. The human body to EUT capacitance, $C_d$, is controlled to 74 pF. This is accomplished by the use of a parabolic shield [18]. It reduces variations in $C_d$ which are due to differences in the human body size and proximity. The $C_d$ is virtually identical in both the human and generator test situation. It is noted that the $C_d$ can vary between 74 to 120 pF in most measurement situations. In the field, $C_d$ can be as low as 10 pF with small hand-held digital products. The $C_d$ is an unknown in the IEC 801-2 standard.

Frequency-domain measurement may be defined as the study of energy distribution across the frequency spectrum for a given electrical signal. The narrowband frequency-domain method is a test process in which the ESD spectral content is measured. The schematic diagram of the test setup used in this study is shown in Figure 2.4. It consists of one Hewlett-Packard model 8591E spectrum analyzer, one 50 Ω 318 kHz high-pass filter
and 14 dB pi attenuator, one 60 cm RF co-axial cable with N connectors, one 2 Ω test
target (mounted on a parabolic shield of 19 cm diameter), and one Spellman High Voltage
DC power supply (Model RHR 15PN30 with one 100 MΩ resistor).

2.3 Description of the Instrumentation

2.3.1 Choosing a Proper Instrument

The spectrum analyzer is an excellent solution for EMI and ESD related testing,
providing stand-alone capability for diagnostic tests and complete receiver capability for
final compliance testing. The spectrum analyzer has long been recognized as a versatile,
general purpose test instrument useful in a wide range of measurement applications. One
application of major concern to manufacturers of electronic products is electrostatic
discharge (ESD) design and measurement.

Since the ESD transients produce broadband spectral energy from DC up to
several gigahertz, this test method requires the use of a spectrum analyzer or receiver,
which is capable of measuring the spectral components, instead of using an oscilloscope.
A spectrum analyzer is an instrument designed to graphically present amplitude as a
function of frequency in a portion of the spectrum.

In the case of the broadband time-domain oscilloscope, all the signals as well as the
environmental EMI which may be present within the bandpass will be processed. Since
most broadband amplifiers are not perfectly linear in amplitude and in phase, they can
produce intermodulation products and harmonic distortions. These undesirable products
will be added to the waveform and will complicate the ESD measurement process. In the
case of a narrowband spectrum analyzer, particularly those with a preselector built in, the
input signal is preselected. Only the spectral components selected at a certain frequency
will be processed, therefore, reducing the effects of intermodulation and harmonics.
Figure 2.1  Input of two sine-wave current sources

Figure 2.2  Resultant waveform of the addition of two sine-waves
Figure 2.3  Frequency response of 20% distorted sine-wave for Figure 2.2

Figure 2.4  Test setup for frequency-domain measurement
2.3.2 Spectrum Analyzer

The main component of the spectrum analyzer/EMI receiver is the spectrum analyzer itself. It provides the main control functions including centre frequency, frequency span, and reference level. The spectrum analyzer offers several advantages over a conventional EMI receiver. First of all, the spectrum analyzer can sweep over a wide frequency range to quickly spot EMI trouble spots. Secondly, the spectrum analyzer uses a frequency and amplitude CRT display to allow visual discrimination of signal types. Thirdly, the spectrum analyzer can be used for general purpose measurements including EMI design diagnostic tests, outdoor open site ambient monitoring, and standard spectrum analysis lab measurements (e.g. harmonic and intermodulation distortion tests).

In the spectrum analyzer, the superheterodyne approach is used because it provides wide input frequency coverage while permitting the signal processing to be done at the single intermediate frequency (IF). Figure 2.5 shows the superheterodyne analyzer in its simplest form. An incoming signal mixes with the local oscillator (LO), and when a mixing product equals the IF, this signal passes through to the peak detector. The detector output is amplified to cause a vertical deflection on the CRT display. The synchronism between the horizontal frequency axis of the CRT display and the tuning of the local oscillator is provided by the sweep generator which both drives the horizontal CRT deflection and tunes the LO. The fundamental front panel control functions such as centre frequency, frequency span, sweep time, resolution bandwidth, reference level are labeled in the appropriate sections of the block diagram.

Using the spectrum analyzer (HP 8591E), the results are presented in terms of peak values of dBm per megahertz. A pulse entering a circuit must be treated by considering the response at each sampling frequency and integrating the results. The spectrum analyzer is set up as follow:

Log reference level: 0 dBm (or 107 dBμV/MHz)
with 10 dB input attenuator

Centre frequency: 1 MHz to 1 GHz
in 1, 1.3, 1.8, 2.4, 3.2, 4.2, 5.6, 7.5, 10 sequence*

*Zoom in for peaks and valleys
Frequency span: 0 Hz
Resolution BW: 100 kHz (measuring range from 1 MHz to 75 MHz) and 1 MHz (measuring range from 100 MHz to 1 GHz)
Video BW: the same as resolution bandwidth
Scan-rate: 20 seconds
Display: Maximum hold
Calibration: Internal and external calibration sources

To ensure that the spectrum analyzer is calibrated, the internal self-calibration is run. The calibration can also be verified by testing an external, known source at different frequency points.

2.3.3 Attenuator and Filter

A pi attenuator and a 10 nF capacitor with characteristics of high-pass filter were used to reduce most of the potentially damaging energy from DC to 1 MHz. If the network is tested at the voltage less than 6 kV, a 14 dB attenuator is used.

![Figure 2.5](image)

Figure 2.5 Block diagram of the spectrum analyzer
Figure 2.6  Frequency response of the 14 dB attenuator and filter

Figure 2.7  Frequency response of the 24 dB attenuator and filter
If the test voltage is greater than 6 kV but less than 16 kV, then a 24 dB attenuator is chosen. Its frequency response is from 1 MHz to 1 GHz shown in Figure 2.6 and Figure 2.7.

2.3.4 Test Target

The 2 Ω test target used as the current-sensing transducer is in accordance with the IEC 1000-4-2 standard specifications [11].

According to the IEC 1000-4-2 standard, the test network contains a 2.04 Ω (25 pieces of 51 Ω in parallel) test target with a 48 Ω (5 pieces of 240 Ω in parallel) impedance matching network. The structure is shown in Figure 2.8.

2.3.5 Parabolic Shield

During the test procedure, the human discharge is applied to the test target, which is mounted in the middle of the parabolic shield [18]. The constructional details are shown in Figure 2.8. Unlike the usual IEC 801-2 specified method in which a ground plane is used to minimize radiation, a parabolic shield is used to control the distributed capacitance C_d more consistently. The C_d is an unknown in the IEC 801-2 (1991) standard [10].

2.3.6 Impedance Matching (50Ω) and the Test Circuit

According to the description of the IEC 801-2 standard, the test network is a 50 Ω impedance matching system.

How is the test network designed? In order to correlate the measured data and the ESD discharge current, the network is intentionally designed to indicate that the value of discharge voltage at the output end is equal to that of discharge current at the input. The 2.04 Ω test target with the 48 Ω resistor transfer the maximum power of ESD signal to the output of 50 Ω spectrum analyzer. The circuit diagram and the schematic diagram are shown in Figure 2.9 and Figure 2.10, respectively. The output voltage can be calculated as follow:

\[
V_D = \frac{50}{48 + 50} \times 50 \times \left(\frac{98}{2.04 + 98} \times I_{ESD} \times 2.04\right) = I_{ESD} \times 1 \text{ (volts)} \quad (2.4)
\]
2.3.7 Commercial ESD Generators

In order to simulate the human ESD effects, three commercial ESD generators are employed to perform the discharge tests incorporated with the human finger (body) model, and the human-with-metal model. One is non-IEC specified and using piezoelectric technology and spark-gap arcing principle, specified as generator #1 [19]. Two of them are IEC compliant generators; specified as generator #2 [20], and generator #3 [21].

It is noted that the non-IEC type generator (#1) operates to reproduce the process of real world human ESD; a capacitively coupled human model rather than the directly connected model as specified by IEC 801-2 (1991) is used. At a given test site, the human-with-metal spectral data were first obtained. Generator #1 was then tailored (adjusted) to match that of the human situation. This test setup is radically different from that specified by the IEC but closer to the real world ESD conditions. It should be pointed out that the IEC 801-2 measurement circuit is a capacitor-resistor discharged circuit with a 2-3 meter ground return cable in series, whereas generator #1 uses a capacitive coupling for the return path. Further, the ground return wire affects the current differently depending upon how and where it is connected. It creates a current path in the product under test that is not exactly the same as in the actual human ESD situation.

In the IEC 801-2 standard, the test circuit is configured to a directly connected circuit with a 2-3 meter ground return wire in series and the $C_d$ is an unknown. The schematic diagram is shown in Figure 2.11. In the capacitive coupling model, the discharge loop is constructed by linking the metallic case of generator #1 with the human hand through the discharge tip to the test target (or the EUT). The schematic diagram is shown in Figure 2.12. The $C_d$ is controlled by the use of a parabolic shield.

The controlled spark-gap arcing employed in the non-IEC specified generator (#1) is to generate broadband spectral energy which is similar to the human ESD transients. In the experiment of the next chapter, the generator will be tested to explore the features and differences between the real human ESD and the test generators.
Figure 2.8  Constructional details of the test target (dimensions not to scale)
Figure 2.9  Circuit diagram for the IEC test network, attenuation network, and the HP 8591E spectrum analyzer

Figure 2.10  Schematic diagram of the IEC specified measurement network
Figure 2.11  Schematic diagram of the IEC 801-2 specified generator

* 150 Ω for the IEC 801-2 (1984) standard
330 Ω for the IEC 801-2 (1991) standard

** C_d is an unknown which exists between the generator and the EUT, ground return path, and coupling planes [10].

Figure 2.12  Schematic diagram of the non-IEC specified ESD generator

* the piezoelectric ceramic slugs provide a total charging capacitance of 100 pF and a charge voltage of up to 21 kV at 3 kV per 1000 psi.
** the impedance and internal spark gap are selected for different human models
*** C_d is controlled in the range of 74 to 120 pF
3.1 Introduction

A broadband signal may be dispersed across tens or hundreds of megahertz or more and is often composed of narrow pulses having relatively short rise and fall times. Its spectral distribution results from the individual characteristics of the pulses. The faster the rise and fall of the pulses, the broader is the overall spectrum. The ESD signal is such a kind.

3.1.1 Determination of the Signal Bandwidth

Determining whether the signal is narrowband or broadband is important for the following two reasons: (1) for knowing which limit to compare the source to during tests and (2) for determining the proper method of measuring the pulse spectra.

Classification of a signal as narrowband or broadband depends on the frequency spectrum occupied by the signal relative to the bandwidth of the receiver. Signals occupying a narrower frequency spectrum relative to the resolution bandwidth are defined as narrowband. Signals occupying a broader frequency spectrum relative to the resolution bandwidth are characterized as broadband. Sources of broadband signals can be impulsive emissions from automobile ignition systems, digital circuits, switching power supplies and random noises. It is important to note that most of these emissions could be displayed as either narrowband or broadband signals, depending on the receiver bandwidth chosen.
3.1.2 Design Principle of the Test Method

The test method is designed to measure broadband ESD signal level by using a narrowband frequency-domain method.

At narrow bandwidth settings spectral lines are displayed. The amplitude level of each component is a function of the receiver bandwidth. As the receiver bandwidth increases, more of the signal spectrum is captured with a resulting increase in amplitude reading. The reference bandwidth used for MIL-STD 461 [22] tests is a 1 MHz impulse bandwidth. The measurements are "normalized" in per megahertz so that the amplitude levels are those which result from using a "standardized" 1 MHz resolution bandwidth.

Common measurement units for narrowband signals are dBµV (conducted emissions) and dBµV/m (field strength of radiated emissions). Common broadband signal measurement units are dBµV/MHz and dBµV/m/MHz.

In the measurement of ESD using the spectrum analyzer (HP 8591E), the original data were taken directly from the spectrum analyzer digital reading in dBm/MHz. For reasons of (1) the maximum power transmission (from 50 to 50 ohm system) resulting in voltage drop of 6 dB (2) the attenuation (a 14 dB attenuator was used) and (3) the usage of 100 kHz resolution bandwidth (RB) for factor of 20 dB compensation (the 100 kHz RB was used to measure the signals from 1 MHz to 75 MHz), the originally discharged signals existing at the test target are calibrated by adding the correction factor of (6+14+20) dB for measurements from 1 MHz to 75 MHz, or adding (6+14) dB for measurements from 100 MHz to 1 GHz. Therefore, the unit of "dBm" is recalculated to "dBµV" in order to do the logarithmic adjustment.

Decibels are the ratio of two quantities. Absolute power, voltage, or current levels can be expressed in dB by giving their value above or reference to some base quantity. For example, voltages are commonly expressed relative to 1 µV as dBµV. The very common dB above one milliwatt is usually denoted as dBm [23]. Note that "dBm" is a power measurement. The definition of 0 dBm is assuming that 1 mW is measured across a constant 50 Ω impedance. The voltage value can be obtained by

\[ 1 \times 10^3 = \frac{V^2}{50}, \quad V = 0.2236 \text{ (volts)}. \]

21
On the other hand, "dBμV" represents the voltage value referring to 1 μV in logarithm. Hence,

\[ V (\text{dBμV}) = 20 \log_{10}\left(\frac{0.2236}{10^{-6}}\right) = 107 \text{ (dB)} \]

Therefore, "dBm" can be converted to "dBμV" as follows:

\[ V (\text{dBμV}) = P (\text{dBm}) + 107 \text{ dB} \quad (3.1) \]

For example, the measured value of -32.80 dBm at 1 MHz is equal to 
(-32.80+107+6+14+20) = 114.20 dBμV. The measured value of -43.61 dBm at 560 MHz is equal to (-43.61+107+6+14) = 83.39 dBμV. In Chapter 4, dBm/MHz is converted to V/MHz and dBμV/MHz for the graphs and the comparison. In Chapter 5, for the statistical analysis purpose, the dBμV/MHz values are listed and recalculated to values in V/MHz.

In this proposed method, the spectral components above 1 MHz are measured. The spectral components below 1 MHz are eliminated by a 318 kHz high-pass filter, since most of the spectral energy is below 1 MHz. This prevents the potential overloading of the spectrum analyzer receiver. The spectrum analyzer receiver is tuned to a test frequency above 1 MHz. The output from the current sensor is coupled to the input network of a bandpass attenuator through a 60 cm coaxial cable. The output from the network is fed to the spectrum analyzer. Currently there are many EMI spectrum analyzers with a tracking preselector built in. These are more suitable for ESD measurement. However, a low cost spectrum analyzer without a tracking preselector can be used, but a high-pass filter and an external attenuator must be used to prevent spurious signal intermodulation generation due to overloading.

3.2 ESD Parameters

A natural ESD is a very complicated single event transient. The high voltage difference between two bodies creates arcing that contains a range of spectral components. Using the Fourier Transform analysis for a known ESD waveform one can determine the frequency domain characteristics.
Usually, workers are accustomed to observing electrical waveforms with respect to time on an oscilloscope. Pulse information is read directly on the calibrated screen. Time-domain parameters are described as follows:

1. Amplitude (A, ampere): the contact discharge current is recorded
2. Time interval (t_p, second): the technique of the proposed FFT method in this thesis is referred to 2 μs.
3. Rise-time (t_r): the time for the amplitude to go from 10% to 90% of the peak value
4. Pulse width (P_w): the time for the discharge current from the 50% point of the peak value on the leading edge to the 50% point on the trailing edge

It is noted that a linear scale is used in time-domain measurements.

On the other hand, a signal amplitude can be presented in terms of its frequency-domain content and displayed along the X-axis of the CRT which is calibrated with respect to the frequency. Frequency-domain characteristics for a trapezoidal waveform are:

1. Duty cycle (δ): a ratio of the pulse width to the referenced time period
2. Amplitude (2Aδ): unit can be A/MHz, V/MHz or dBμV/MHz in this application
3. First corner frequency (f_1 = 1/πP_w): starting frequency point of -20 dB/decade slope
4. Second corner frequency (f_2 = 1/πt_r): starting frequency point of -40 dB/decade slope

A log scale is often used in the plot of the frequency response. The ESD parameter and its spectrum is shown in Figure 3.1.

3.3 Test Procedures

Frequency-domain measurements are used to investigate the human-finger and human-with-metal ESD at each of a number of ESD voltages.

Initially, the human body is charged by touching the open-end of a 100 MΩ resistor connected to a high voltage source. The body is isolated by a piece of 5 cm (2 inches) thick, 80×80 cm² plywood. The human discharge is then applied through finger contact to the test target, which is mounted in the middle of the parabolic shield (see Figure 2.8). At each frequency setting, 10 or more discharges were performed.
In the second measurement using a human-with-metal source, the procedures are almost identical to those using the human finger. The metal objects are a screw driver (with a plastic handle, length = 20 cm), a thin and sharp metal file (entirely metallic, length = 14 cm), a key (entirely metallic, length = 5.5 cm), an identical generator-size (non-IEC type, generator #1) metal wand, which is a 15 cm by 2.5 cm diameter aluminum rod. The human hand with metal objects are discharged through the contact pin to the test target. It is noted that in the situation using the screw driver with a plastic handle, the human hand must maintain contact with the metallic part during charging from the power supply and discharging to the test target.

In the third measurement, three commercial ESD generators are tested.

**Figure 3.1** Parameters for an example of a periodic trapezoidal pulse and its spectrum
3.4 Considerations of the Experiment

3.4.1 Broadband Normalization (Correction Factor)

The corrected peak value (dBμV/MHz) is equal to the measured value (dBm/MHz) + 107 dB + 6 dB (impedance matching factor) + 14 dB (attenuation).

If the resolution bandwidth of 100 kHz is used, rather than 1 MHz, the correction factor of $20 \log_{10}(1 \text{ MHz}/100 \text{ kHz}) = 20 \text{ dB}$ should be added for the bandwidth normalization.

3.4.2 VSWR

Voltage standing wave ratio (VSWR) is an indicator of the impedance matching of the test network. The IEC test target and the 14 dB attenuator verified and calibrated to the VSWR at 1 GHz is less than 1:1.22. The network analyzer (HP 8714B) is used for this purpose.

For 50 Ω impedance network, it is denoted that $R_L = Z_c = 50 \Omega$, where $R_L$ is the impedance of the load. Since $\text{VSWR} = 1:1.22$, at higher frequency range the load impedance should be $39 < R_L < 61$.

Considering the IEC test network shown in Figure 2.10,

\[ V_D = \frac{50}{48 + 50} V_A \]  \hspace{1cm} (3.2)

If error occurred, the range of the output voltage would be

\[ \frac{39}{48 + 39} V_A < V_D < \frac{61}{48 + 61} V_A \]  \hspace{1cm} (3.3)

The maximum of tolerance is $\frac{50 - 39}{98} = 12.14\%$  \hspace{1cm} (3.4)

The minimum of tolerance is $\frac{50 - 61}{98} = -9.69\%$  \hspace{1cm} (3.5)

For return coefficient = -9.69%, the return loss = $-20 \log_{10}(1/0.0969) = -20.27 \text{ (dB)}$. 

25
In this experiment, the test result for the return loss of the IEC specified test target at 1 GHz is -23.46 dB. The result is shown in Figure 3.2.

3.4.3 Dynamic Range and Spurious Signal Response

As the input signal amplitude approaches the local oscillator voltage level, vigorous harmonics are generated which can combine with the local oscillator harmonics to produce the IF frequency. This is then passed through the IF amplifier to the detector and subsequently appears on the analyzer display. Such responses are termed "spurious" since they do not represent true input signals of the indicated frequency. The amplitude of spurious responses is non-linearly related to input signal level and can seriously clutter the display of a spectrum analyzer making it impossible to distinguish true inputs from the false signals produced by the mixer. No spurious responses would be visible on the analyzer display if the input signal were kept extremely small. Doing this, however, would severely limit the amplitude range of the instrument. On the other hand, stronger input signals cause larger spurious responses. It is recommended that the analyzer input attenuator be used to keep signal input to the mixer at -30 dBm or less for minimum spurious generation and full 60 dB dynamic range.

The test data of the ESD signal levels are in the ranges shown in Table 3.1.

Most of them satisfied the condition of the input signals to the mixer being equal to or less than -30 dBm except ESD at 8 kV (but it is still in the safe range).

Regarding the dynamic range, in the specification of HP 8591E spectrum analyzer, there is a limit of the spectrum analyzer of maximum +30 dBm input signal level. Comparing to the noise level which is -74 dBm for 100 kHz bandwidth (or -64 dBm for 1 MHz bandwidth), therefore there is a 104 dBm dynamic range for the instrument at 100 kHz bandwidth (or a 94 dBm dynamic range at 1 MHz bandwidth). It is also critical to consider the ESD maximum signal level operating below the overloading level of the instrument to ensure the test data are accurate. From the calculation of the 100 kHz bandwidth case, an input signal of maximum value 0 dBm is set. A 14 dB attenuator is chosen to further reduce the input signal level. At the same time, an acceptable minimum signal level is set to 10 dB higher than the noise level which is -64 dBm. Thus a 50 dBm
signal operating range is expected to be safe and reliable within the instrument dynamic range.

![Graph showing test results of return loss of the IEC test target.]

**Figure 3.2** Test result of return loss of the IEC test target

<table>
<thead>
<tr>
<th>Human-with-metal ESD voltage</th>
<th>Operating frequency 1 MHz ~ 1 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 kV</td>
<td>max (dBm) -40 ~ -60</td>
</tr>
<tr>
<td></td>
<td>min (dBm) -48 ~ -64</td>
</tr>
<tr>
<td>4 kV</td>
<td>max (dBm) -30 ~ -53</td>
</tr>
<tr>
<td></td>
<td>min (dBm) -36 ~ -64</td>
</tr>
<tr>
<td>8 kV</td>
<td>max (dBm) -23 ~ -48</td>
</tr>
<tr>
<td></td>
<td>min (dBm) -31 ~ -64</td>
</tr>
</tbody>
</table>

**Table 3.1** Summary of the test data measured from 2 to 8 kV
3.4.4 Overloading of the Double-Balanced Mixer

Overload is a condition wherein high-level signals saturate the input mixer, causing the true signal level to be compressed in amplitude. What is the solution to the overload problem? RF preselector filters, step attenuators, or fixed filters were used to limit the number and level of input signals.

Preselector filters allow only a small portion of the frequency spectrum to be incident on the input mixer of the spectrum analyzer at one time, thereby virtually eliminating overload. As with other preselected receivers, there is still a limit to the total power which the preselector can withstand and remain linear. For this reason, RF attenuators generally precede the preselector filters in a typical RF block diagram.

In the specification of the HP 8591E spectrum analyzer, it is learned that the maximum input signal is limited to +30 dBm, 1 watt. If the signal is lower than that, the measured result can be sure that it will not saturate the input double-balanced mixer. Mathematically, +30 dBm can be calculated to 137 dBμV (0 dBm = 107 dBμV). Since there is a 14 dB attenuator connected before the IEC test network which is a 50 Ω impedance matching network giving a 6 dB voltage division, an extra 20 dB protection is expected. Therefore, if an input ESD signal is less than 157 dBμV, it is safe and accurate to use the spectrum analyzer as the measuring equipment in the frequency domain.

From the measured data, the value of 2 kV ESD signal level is 112 dBμV/MHz. It is also expected that 4 kV ESD will be 118 dBμV (two times means adding 6 dB), 8 kV be 124 dBμV, 16 kV be 130 dBμV. All of them will be in the safe range of testing.

On the other hand, a high-pass filter of a 10 nF capacitor associated with the 14 dB attenuator can cut off most of the energy level from DC all the way to 1 MHz to prevent the overloading problem. It is also a protection to the spectrum analyzer. For discharge over 8 kV, a 24 dB attenuator is recommended.

3.4.5 Concerns of the Experimental Safety

The testing voltage levels and methods for human discharges specified by the IEC 801-2 Standards are used to simulate the condition of a transfer of the electric charge between the personnel and objects of the different electrostatic potential in proximity or
through the direct contact. The generation of electrostatic charge of the proposed test method is controlled by a DC power supply which is connected to a 100 MΩ resistor for the current limitation. The charged human body is well-isolated by a wooden platform with four rubber bottoms to prevent electric hazards and energy loss. This approach was employed by some authors in the technical papers, such as Saini [24] and King [25]. If the test procedures are strictly followed, there will be no danger to the human body. Such tests are usually performed by the personnel knowledgeable of ESD testing hazards.

According to the literature reviews in Internet web sites of the National Institute of Health (http://www.nih.gov) and the National Institute of Environmental Health Science (http://www.niehs.nih.gov) and the National Library of Medicine (http://www.ncbi.nlm.nih.gov), some epidemiological studies have suggested that a link may exist between exposure to power-frequency (50/60 Hz) electric and magnetic fields (EMFs) and certain types of cancers, primarily leukemia and brain cancer. Other studies have found no such link. The result is inconclusive. However, laboratory researches are continuing.

One paper "Electrostatic therapy (EST) of lung cancer and pulmonary metastasis: report of 15 cases" described fifteen patients who were treated with electrostatic therapy and concluded that no marked effect of EST for treatment of cancer could be observed. The research of electrostatic discharge effects for human health has not been found yet at this moment.
CHAPTER 4

COMPARATIVE PERFORMANCES OF THE IEC STANDARDS AND ESD EVENTS

4.1 Introduction

The electrostatic discharge (ESD) standard 1000-4-2 developed by the International Electrotechnical Commission (IEC) has been the principal standard upon which almost all current simulators are based. One serious problem [26] encountered by the industry was that two compliant simulators produced inconsistent results when tested on a given product. The old IEC 801-2 standard set in 1984 and established by the European Union in their Electromagnetic Compatibility Directives [27] indicated the seriousness of the new 1000-4-2 standard.

The objective of this chapter is to evaluate the ESD events in the frequency domain. The measurement results of spectral components of the narrowband frequency domain method of measurement of ESD events produced by a human, and three commercial ESD generators, two using an IEC design and another one using spark-gap arcing are analyzed in the frequency domain from 1 MHz to 1 GHz. The experimental results will be compared with the Fourier Transform results of the two IEC published waveforms [9] [10]. Investigation of influential factors of human ESD phenomena at different discharge voltages with conditions of four different kinds of metal objects, two ESD generators, different human weights (60 - 80 kg), clothes on and off, and different humidities are assessed.
4.2 The Fourier Transform Analysis

An ESD is a very common natural single event transient. The high voltage
difference between two bodies creates arcing that has characteristic spectral components.
Using the Fourier Transform for a known ESD waveform one can obtain the frequency-
domain spectrum. The MATLAB program [28] for the "exact" Fourier Transform (FT) or
the PSPICE program [29] for the Fast Fourier Transform (FFT) may be used for this
analysis.

It is noted that all the information of the IEC specified waveforms and measured
transient data were entered into the computer using a piece-wise linear ESD current
source model. For consistency with electromagnetic interference (EMI) practice, the X
and Y axis were plotted on a logarithmic scale. The goal of this analysis is to use the
convenient and readily available methods with reasonable accuracy to make comparative
evaluation of ESD events.

Possibly, sharp corners and slightly different straight-line segments may affect the
approximation. However, the effects of a more abrupt change in the rising edge of the
waveshape contribute very small portions of the influence on the higher frequency range of
the corresponding spectrum. This influence can be neglected. An example is shown in
4.3.2 Case Study (2).

4.2.1 The "exact" Fourier Transform

Using the Fourier Transform theorems, a piece-wise linear model of the non-
recurring ESD pulse waveform can be converted exactly to its frequency-domain
response. The calculation of the "exact" Fourier Transform which do not require defining
the period is compared to that of the Fast Fourier Transform which is a computing
technique of reasonably accurate approximation.

A given set of n+1 coordinates (t_1,y_1), (t_2,y_2), ... (t_{n+1},y_{n+1}) is used to define the
piece-wise linear model of an ESD pulse discharge current waveform. The desired Fourier
Transform (FT) \( F(\omega) \) of this model can be obtained by summing up the FT of the
integration of the first derivatives, \( F(\omega) = \Im \{ f(t) \} = \Im \{ \int (f'_1 + f'_2 + ... + f'_n) \} \) of the
original linear function, \( y = f(t) \), at different time segments. The values, \( v_1, v_2, ..., v_n \), of the derivatives are the slopes for the linear equations, \( f_1, f_2, ..., f_n \). The waveforms of the first derivatives are rectangular pulses with durations of \( T_1, T_2, ..., T_n \), shifted some time constants, \( \tau_1, \tau_2, ..., \tau_n \), from that of the standard rectangular pulse, of amplitude \( v_0 \) and duration \( \tau_0 \). The standard rectangular pulse is centred at \( t = 0 \) and is symmetric with respect to \( Y \)-axis.

For a standard rectangular pulse (please see Figure 4.1):

\[
f(t) = \begin{cases} 
0 & \text{for } -\infty < t < -\frac{\tau_0}{2} \\
v_i & \text{for } -\frac{\tau_0}{2} < t < \frac{\tau_0}{2}, \quad (\tau_0: \text{pulse width of the rectangular pulse}) \\
0 & \text{for } \frac{\tau_0}{2} < t < \infty
\end{cases}
\]

\[
\frac{df(t)}{dt} = v_i \left[ \delta\left(t + \frac{\tau_0}{2}\right) - \delta\left(t - \frac{\tau_0}{2}\right) \right]
\]

\[
\mathcal{Z}\left\{ \frac{df(t)}{dt} \right\} = v_i \left[ e^{-\frac{j\omega \tau_0}{2}} - e^{\frac{j\omega \tau_0}{2}} \right] = v_i \left[ e^{-\frac{j\omega \tau_0}{2}} - e^{\frac{j\omega \tau_0}{2}} \right]
\]

\[
\mathcal{Z}\{f(t)\} = \mathcal{Z}\left\{ \int_{-\infty}^{\infty} \frac{df(t)}{dt} \right\} = v_i \left[ \frac{e^{\frac{j\omega \tau_0}{2}} - e^{-\frac{j\omega \tau_0}{2}}}{j\omega} \right] = v_i \tau_0 \left[ \frac{e^{\frac{j\omega \tau_0}{2}} - e^{-\frac{j\omega \tau_0}{2}}}{2j} \right] \left[ \frac{1}{\omega \tau_0 / 2} \right]
\]

\[
= v_i \tau_0 \cdot \frac{\sin\left(\frac{\omega \tau_0}{2}\right)}{\left(\frac{\omega \tau_0}{2}\right)}
\]

Noted that the negative slope results in the same conclusion.
Figure 4.1 A standard rectangular pulse with amplitude $v_0$, duration $\tau_0$

For a piece-wise linear model of an ESD waveform (please see Figure 4.2):

The slopes for $f(t)$:

$$v_1 = \frac{y_2 - y_1}{t_2 - t_1}, \quad v_2 = \frac{y_3 - y_2}{t_3 - t_2}, \ldots, \quad v_n = \frac{y_{n+1} - y_n}{t_{n+1} - t_n}$$  \quad (4.5)

The durations (pulse widths) for $f'(t)$:

$$T_1 = t_2 - t_1, \quad T_2 = t_3 - t_2, \ldots, \quad T_n = t_{n+1} - t_n$$  \quad (4.6)

The central points of the rectangular pulses, $f'(t)$, at $t$-axis

$$\tau_1 = \frac{t_1 + t_2}{2}, \quad \tau_2 = \frac{t_3 + t_2}{2}, \ldots, \quad \tau_n = \frac{t_{n+1} + t_n}{2}$$  \quad (4.7)
Figure 4.2  The first and second derivatives of a piece-wise linear model

Therefore.

\[ t_1 = \tau_1 - T_i/2, \quad t_2 = \tau_1 + T_i/2, \ldots \]  \hspace{1cm} (4.8)

The second derivatives of these slope, \( v_1, \ v_2, \ldots, \ v_n \), are a series of impulses representing the change of the slopes. The FT of summation of the integration of the second derivatives are equal to the FT of the first derivatives. The expressions are described as follows:
\[
\frac{d^2 f(t)}{dt^2} = v_1 \left[ \delta \left( t - \left( \tau_1 - \frac{T_1}{2} \right) \right) - \delta \left( t - \left( \tau_1 - \frac{T_1}{2} \right) \right) \right] + \ldots \\
+ v_n \left[ \delta \left( t - \left( \tau_n - \frac{T_n}{2} \right) \right) - \delta \left( t - \left( \tau_n + \frac{T_n}{2} \right) \right) \right]
\] (4.9)

\[
\mathcal{F}\left\{ \frac{d^2 f(t)}{dt^2} \right\} = v_1 \left[ e^{-j \omega \left( \tau_1 - \frac{T_1}{2} \right)} - e^{-j \omega \left( \tau_1 + \frac{T_1}{2} \right)} \right] + \ldots + v_n \left[ e^{-j \omega \left( \tau_n - \frac{T_n}{2} \right)} - e^{-j \omega \left( \tau_n + \frac{T_n}{2} \right)} \right]
\] (4.10)

\[
\mathcal{F}\left\{ \frac{df(t)}{dt} \right\} = \mathcal{F}\left\{ \int_{-\infty}^{\infty} \frac{df(t)}{dt} \right\} = \frac{1}{j \omega} \left[ v_1 \left[ e^{-j \omega \left( \tau_1 - \frac{T_1}{2} \right)} - e^{-j \omega \left( \tau_1 + \frac{T_1}{2} \right)} \right] + \ldots + v_n \left[ e^{-j \omega \left( \tau_n - \frac{T_n}{2} \right)} - e^{-j \omega \left( \tau_n + \frac{T_n}{2} \right)} \right] \right]
\] (4.11)

\[
\mathcal{F}\{f(t)\} = \mathcal{F}\left\{ \int_{-\infty}^{\infty} \frac{df(t)}{dt} \right\} = \frac{1}{(j \omega)^2} \left[ v_1 \left[ e^{-j \omega \left( \tau_1 - \frac{T_1}{2} \right)} - e^{-j \omega \left( \tau_1 + \frac{T_1}{2} \right)} \right] - \ldots + v_n \left[ e^{-j \omega \left( \tau_n - \frac{T_n}{2} \right)} - e^{-j \omega \left( \tau_n + \frac{T_n}{2} \right)} \right] \right]
\] (4.12)

Let \( \theta = \omega \tau, \phi = \frac{\omega T}{2} \).

\[
e^{-j \omega \left( \tau_1 - \frac{T_1}{2} \right)} = \cos \left( \omega \tau + \frac{\omega T}{2} \right) - j \sin \left( \omega \tau + \frac{\omega T}{2} \right) = \cos (\theta + \phi) - j \sin (\theta + \phi)
\]

\[
e^{-j \omega \left( \tau_1 + \frac{T_1}{2} \right)} = - \cos \left( \omega \tau - \frac{\omega T}{2} \right) + j \sin \left( \omega \tau - \frac{\omega T}{2} \right) = - \cos (\theta - \phi) + j \sin (\theta - \phi)
\]

where \( \cos (\theta + \phi) = \cos \theta \cos \phi - \sin \theta \sin \phi \), \( \cos (\theta - \phi) = \cos \theta \cos \phi + \sin \theta \sin \phi \), \( \sin (\theta + \phi) = \sin \theta \cos \phi + \cos \theta \sin \phi \), \( \sin (\theta - \phi) = \sin \theta \cos \phi - \cos \theta \sin \phi \)

so

\[
e^{-j \omega \tau} - e^{-j \omega \left( \tau + \frac{T}{2} \right)} = -2 \left( \sin \theta \sin \phi + j \cos \theta \sin \phi \right) = -2 \sin \phi \left( \sin \theta + j \cos \theta \right)
\]
Finally,
\[ F(\omega) = \Im \{f(t)\} \]
\[ = -\frac{2}{\omega} \left( v_1 \sin \left( \frac{\omega T_1}{2} \right) \left( \sin \omega \tau_1 + j \cos \omega \tau_1 \right) + \cdots + v_n \sin \left( \frac{\omega T_n}{2} \right) \left( \sin \omega \tau_n + j \cos \omega \tau_n \right) \right) \] (4.13)

where \( \omega = 2 \pi f \).

As an example, writing a MATLAB program (please see Appendix C, (1) and (2)) based on the IEC 801-2 (1984) model in Figure 4.3, its Fourier Transform of Eq. (4.13) can be plotted as Figure 4.4.

### 4.2.2 The Fast Fourier Transform

The Fourier Transform in the PSPICE program is a discrete Fourier Transform (DFT), where the Fourier integral has been replaced by a nearly equivalent summation formula applied to evenly spaced samples of the signal. Furthermore, the transform is accomplished by a special technique credited to Cooley and Tukey, which is commonly called a Fast Fourier Transform (FFT). This is a numerical trick if the size of the data sequence is a power of two (such as 256, or 4096), a much shorter sequence of calculations can be used to get the same results as the discrete Fourier Transform [30].

The computational technique of FFT can be employed to analyze the non-periodic ESD transients as long as the reference time interval is selected properly.

For instance, the spectral amplitude at 1 MHz in Figure 4.4 from the "exact" Fourier Transform is 0.294 A. As Section 3.2 mentioned, the spectral amplitude of a periodic signal is equal to \( 2 I_p \delta \), where \( I_p \) is the peak current and \( \delta \) is the ratio of the pulse width (\( P_w \)) to the period (\( T_p \)). From Figure 4.3, it is known that \( I_p = 9 \) A, and \( P_w = 30 \) ns. Hence

\[ 0.294 = 2 \times 9 \times (30 \times 10^{-9} / T_p) \]

\[ T_p = 2 \mu\text{sec} \]

Using a reference time interval of 2 \( \mu\text{sec} \), the plot of the FFT result is shown in Figure 4.5 which is identical to that of Figure 4.4. The example FFT calculation in PSPICE source code is illustrated in Appendix C, (3).
Figure 4.3 The discharge current waveform is defined by the IEC 801-2 (1984) standard.

Figure 4.4 The "exact" Fourier Transform of the IEC 801-2 (1984) waveform.
4.3 Case Studies

4.3.1 Case Study (1): Two Exponential ESD Pulses with the Same Peak Current and Rise Time but with Different Pulse Widths

With the advance of wide bandwidth oscilloscopes, the records of ESD waveforms will become more complicated. The rise time and peak current have been overemphasized while other features of the waveform are virtually ignored. It will be shown in the following case study that the rise time and peak current are not the only important parameters [31].

To illustrate this point, the FFT of two exponential ESD pulses with the same peak current and rise time but with different pulse widths are analyzed. The two waveforms are shown in Figure 4.6 and Figure 4.7. Their spectra are shown in Figure 4.8 and Figure 4.9. It is noted that for calculation purpose, the unit of Volt/MHz in the frequency spectrum is used to represent the quantitative spectral distribution of discharge current density, usually expressed in A/MHz.
In terms of the current slew rate (di/dt) and the second corner frequency (f₂), both pulses are identical (2000 A/ns and 31.8 GHz, respectively). However, the amplitude of the spectral components of pulse 1 is 17 dB higher than that of pulse 2 at 1 MHz. The first corner frequency of pulse 1 is 159 MHz, and for pulse 2 is 1590 MHz. At the lower end of the spectrum, therefore, it is obvious that a given product sensitive below 1000 MHz would fail in pulse 1 while passing in pulse 2. The difference in spectral response is shown in Figure 4.10. These two pulses also illustrate the fact that no oscilloscope can accurately measure the time domain parameter. The rise time value (Tᵣ = 10 ps) is beyond the bandwidth of the modern oscilloscope.

4.3.2 Case Study (2): Parameters of the IEC 801-2 1984 and 1991 Specified Waveforms

The IEC 801-2 1984 and 1991 published waveforms are shown in Figure 4.11 and Figure 4.12, respectively.

The spectrum of IEC 801-2 1984 current waveform is shown in Figure 4.13.

The IEC 801-2 1991 standard specified both contact and air discharges. The most significant addition was the contact discharge method, which was thought to have overcome the inconsistencies of air discharges. Air discharge is actually air-with-contact discharge as defined by IEC. There is a difference between air only and air-with-contact discharges. In the time domain using an oscilloscope, the difference is not easily detected. In the frequency domain, the difference can readily be seen in a graph shown later in this chapter.

Contact discharge is a method in which arcing is produced by a relay switch. The IEC specifies a double-peak waveform, shown in Figure 4.12.

IEC 801-2 (1991) [10] (now IEC 1000-4-2) specified that the waveform of the output current of the ESD generator during the verification procedure shall conform to Figure 4.12. The waveform parameters are listed in Appendix B. Any kind of ESD generator complying with these parameters, i.e. discharge voltage, first peak of discharge current, rise time, current at 30 ns, and current at 60 ns, then is considered to be an IEC compliant ESD generator. We will study the two possible extreme cases of the IEC 801-2
1991 waveform parameters specified at 2 kV. One is the single-peak waveform (defined as 1991A) illustrated as dotted line in Figure 4.12. The other is the typically published double-peak waveform (defined as 1991B). Current waveforms between these two arbitrary limits are still meeting the requirements of the IEC standard. The variation is mainly due to the variations in components and manufacturers. The spectra are shown as Figure 4.14 and 4.15.

Figure 4.6 Discharge current of exponential ESD pulse 1

Figure 4.7 Discharge current of exponential ESD pulse 2
Figure 4.8  Spectrum of pulse 1 (Pw = 2 ns)

Figure 4.9  Spectrum of pulse 2 (Pw = 200 ps)
Figure 4.10 Spectra of two ESD pulses with the same peak current (20 A) and rise time (10 ps) but with different pulse widths (pulse 1: 2 ns and pulse 2: 200 ps)

Figure 4.11 The IEC 801-2 (1984) waveform, current values at 2 kV discharges are used for FFT analysis
Figure 4.12  The IEC 801-2 (1991) double-peak waveform with the initial spike, and the current values at 2 kV are used in FFT analysis. The dotted IEC 801-2 single-peak (1991A) waveform is acceptable by the standard.

Figure 4.13  Spectrum of the IEC 801-2 (1984) specified single-peak waveform
**Figure 4.14** Spectrum of IEC 801-2 (1991) specified single-peak waveform (1991A)

**Figure 4.15** The spectrum of IEC 801-2 (1991) specified double-peak waveform (1991B)
4.3.3 Comparison of the IEC 801-2 Standards

The superimposed spectra are plotted in Figure 4.16.

The waveform of 1991B has higher current slew rate (7.5 A/ns) than that of 1984 (1.8 A/ns). At frequency range below 56 MHz, the 1991B has lower spectral level than the other two. Also, beginning from the frequency point of 100 MHz, the spectral level of 1991A and 1991B is higher than that of the 1984. The worse case can be found at 21 MHz, the curve of 1991B indicating a 29.8 dB difference from that of 1991A and 32.8 dB from that of 1984. It is possible for a product to pass a test waveform having spectrum B while at the same time, fail a test waveform having spectrum A. Below 56 MHz, the 1984 spectrum is more severe than that of 1991B

The FFT results show that the IEC waveform specification could produce a discrepancy of up to 29.8 dB at some frequencies. To eliminate this discrepancy the complete waveform to 5 RC (250 ns) must be specified.
4.3.4 Closeness of Approximation of Piece-Wise Linear Current Source

In Section 4.2, it is mentioned that there is the possibility of sharp corners and slightly different straight-line segments which may affect the approximation. As an example, Figure 4.11 with a sharp corner at the origin in the beginning of the rising edge is zoomed into Figure 4.17. On the other hand, Figure 4.18 with entirely the same parameters as Figure 4.11 has a more gradual or rounded corner near the origin. Figure 4.18 is zoomed into Figure 4.19 which can be compared to Figure 4.17. The spectrum of Figure 4.18 is plotted in Figure 4.20. Figure 4.21 is the comparison of spectra between Figure 4.13 (spectrum of the rising slope with a sharp corner in the waveshape) and Figure 4.20 (spectrum of the rising slope with a rounded corner in the waveshape). In Figure 4.21, it is noted that the Y axis is starting from 60 dBμV/MHz which is very close to the noise level in the spectrum receiver.

From the comparison, therefore, it can be concluded that the approximation with or without a small corner will not significantly influence the spectrum below about 200 MHz, but appears to produce discrepancies of up to 3 dB at higher frequencies.

Figure 4.17  Zoom in for Figure 4.11 (IEC 801-2 1984 with a sharp corner at the origin)
Figure 4.18  The IEC 801-2 (1984) waveform, with a rounded corner at the origin

Figure 4.19  Zoom in for Figure 4.18 (IEC 801-2 1984 with a rounded corner at the origin)
Figure 4.20  The spectrum of Figure 4.18 (IEC 801-2 1984 with a rounded corner at the origin)

Figure 4.21  Comparison for the spectrum of Figure 4.13 and Figure 4.20
4.4 Performances of the IEC Standards and ESD Events

The experimental results measured at a 2 kV discharge voltage using human-finger, human-with-metal, and the commercial spark-gap (non-IEC specified) generator are shown in Figure 4.22. The spectral components of this ESD generator are also compared to the human-with-metal model and those of the IEC 801-2 standards specified in the previous section, shown as Figure 4.23. The spectral response of air only and air-with-contact discharges from a IEC 801-2 (1984) standard generator are shown in Figure 4.24. Physically the human hand cannot control the small gap width for 2 kV air arcing without making any contact; the comparison of 4 kV air discharges is shown. The difference between air only and air-with-contact discharges in the current waveform was undetectable and not specified in the IEC standard.

Examining both cases from Figure 4.22 and Figure 4.23, one can see that the human-with-metal discharges generate higher spectral contents than those of human-finger discharges, and than those of the IEC specified models at higher frequencies. The spectrum of the commercial (non-IEC specified) ESD generator using a spark-gap arcing process [19] matches closer to the human-with-metal model.

In Figure 4.25, a person of 70 kg is charged up to 2, 4 and 8 kV. The results show that spectral components of the discharges are more directly related to the charged voltages. This data can be used to calibrate generators to simulate the human finger discharge situation. Figure 4.26 shows the results of human-with-metal discharges at 2, 4 and 8 kV. The spectral components beyond 100 MHz are about the same with the 2 kV curve slightly higher whereas the IEC specified a constant rise time and 2, 4, 6, 8 kV discharge voltages which generate monotonically increasing spectral contents. In Figure 4.27 the spectrum of the commercial IEC specified simulator is compared to the IEC 801-2 (1991) standard and human-with-metal model at 2 kV. This simulator shows a characteristic dip at about 21 MHz. Its spectral components at 1 MHz are about 6 dB higher than that of the human-with-metal model and 7 dB higher than that of the IEC 801-2 (1991) standard. Beyond the 10 MHz range, the IEC type ESD simulator does not match the human-with-metal model.
Figure 4.22 Spectra for the comparison among the measured results of human-finger (hf2k), human-with-metal (hm2k), non-IEC specified commercial generator calibrated to human-with-metal model (non-IEC 2k) at 2 kV discharges.

Figure 4.23 Comparison among spectra of the IEC 801-2 Standards (1991A and 1991B), human-with-metal model and spark gap generator at 2 kV discharges.
Figure 4.24  Difference between air-with-contact and air only discharges using IEC 801-2 (1984) ESD simulator at 4 kV

Figure 4.25  Spectra of the human-finger ESD at 2, 4 and 8 kV
Figure 4.26  Spectra of human-with-metal at 2, 4, and 8 kV compared to those of IEC 801-2 (1991) at 2 and 8 kV

Figure 4.27  Comparison among spectra of the IEC 801-2 (1991) standard, human-with-metal model and an IEC ESD simulator at 2 kV discharges
4.5 Influential Factors of ESD Events

In developing a method of measurement, great attention is laid on determining the best possibly consistent environmental conditions during the use of the test method. This requires a study of the factors that may influence the precision and the accuracy of the method. The study of factors of accuracy and precision includes that of the dependence of these measures on the type of metal object that is measured, on the magnitude of the measured value, on environmental conditions (temperature, relative humidity, etc.), as well as matters of calibration of the measuring equipment.

An investigation was made on influential factors of human ESD phenomena at different discharge voltages with conditions of four different kinds of metal objects, two ESD generators, different human weights (60 - 80 kg), clothes on and off, and different levels of relative humidity. The test data were plotted by using the average of amplitudes at each frequency setting.

Conditions will be described sequentially.

(1) Human-with-metal model using a screw driver (L = 20 cm). The human hand touches the metallic part directly. The measured results are shown in Figure 4.28.

It can be concluded that

1. At frequencies $f < 13$ MHz: (Spectral components) $8 \text{ kV} > 4 \text{ kV} > 2 \text{ kV}$
2. $13 < f < 130$ MHz: (Spectral components) $4 \text{ kV} > 8 \text{ kV} > 2 \text{ kV}$
3. $320 < f < 560$ MHz: (Spectral components) $2 \text{ kV} > 8 \text{ kV} > 4 \text{ kV}$
4. At the frequencies beyond $13$ MHz, the spectral components are no longer monotonically increase with increasing discharge voltages.

(2) Human-with-metal model using a thin and sharp metal (L = 14 cm). The measured results are shown in Figure 4.29.

It can be concluded that

1. At frequencies $f < 32$ MHz: (Spectral components) $8 \text{ kV} > 4 \text{ kV} > 2 \text{ kV}$
2. $32 < f < 56$ MHz: (Spectral components) $8 \text{ kV} > 2 \text{ kV} > 4 \text{ kV}$
3. $56 < f < 130$ MHz: (Spectral components) $2 \text{ kV}$ greater than the other two with no specific pattern
4. \( f > 130 \text{ MHz} \): (Spectral components) \( 2 \text{ kV} \text{ > 8 kV > 4 kV} \)

(3) Human-with-metal model using a key (L = 5.5 cm). This key is all metal. The measured results are shown in Figure 4.30.

It can be concluded that

1. At frequencies \( f < 13 \text{ MHz} \): (Spectral components) \( 8 \text{ kV > 4 kV > 2 kV} \)
2. \( 24 < f < 180 \text{ MHz} \): (Spectral components) \( 4 \text{ kV > 2 kV > 8 kV} \)
3. \( 240 < f < 560 \text{ MHz} \): (Spectral components) \( 2 \text{ kV greater than the other two with no specific pattern} \)
4. At the frequencies beyond 13 MHz, the spectral components are no longer monotonically increase with increasing discharge voltages.

(4) Human-with-metal model using a metal wand with identical size of spark-gap generator (generator #1) (L = 17 cm, D = 2.54 cm). The measured results are shown in Figure 4.31.

It can be concluded that

1. At frequencies \( f < 100 \text{ MHz} \): (Spectral components) \( 8 \text{ kV > 4 kV > 2 kV} \)
2. \( f > 100 \text{ MHz} \): (Spectral components) \( 2 \text{ kV > 8 kV > 4 kV} \)
3. At frequencies beyond 100 MHz, the spectral components are no longer monotonically increase with increasing discharge voltages.

(5) Comparison of different ESD generators (#1: spark-gap arcing ESD, #2: IEC 801-2 1984 ESD) and actual human-with-metal model at 2 kV. The measured results are shown in Figure 4.32. Piezoelectric Generator #1 uses spark gap arcing to simulate human ESD whereas generator #2 uses IEC 801-2 (1984) principle, RC discharge. It can be concluded that from the plot of test results, one can compare the extent to which the different generators can actually simulate human-with-metal discharges.
(6) Comparison of different ESD generators (#1: spark gap arcing ESD, #2: IEC 801-2 1984 ESD) and actual human-with-metal model at 4 kV. The measured results are shown in Figure 4.33.

(7) Comparison of human-with-metal discharges at 2 kV. The measured results are shown in Figure 4.34. The column chart will be introduced to compare the spectral contents at different frequencies for different metal objects. The column chart is shown in Figure 4.35.

It can be concluded that

1. At frequencies (f < 13, 100 < f < 240 MHz): (Spectral components) Generator#1-size metal > Key > Thin&Sharp metal > Screw driver
2. 13 < f < 56 MHz: (Spectral components) Generator#1-size metal > Thin&Sharp metal > Key > Screw driver
3. 240 < f < 560 MHz: (Spectral components) Key > Generator#1-size metal > Thin&Sharp metal > Screw driver
4. From the results of this comparison: other than the metal wand with identical size of generator #1, a key creates higher spectral contents to EUT than other metal objects at 2 kV.

(8) Comparison of human-with-metal discharges at 4 kV. The measured results are shown in Figure 4.36. Its column chart is shown in Figure 4.37.

It can be concluded that

1. At frequencies f < 10 MHz: (Spectral components) Generator#1-size metal > Key > Thin&Sharp metal > Screw driver
2. 10 < f < 24 MHz: (Spectral components) Generator#1-size metal > Key > Screw driver > Thin&Sharp metal
3. 75 < f < 180 MHz: (Spectral components) Key > Screw driver > Generator#1-size metal > Thin&Sharp metal
4. 180 < f < 560 MHz: (Spectral components) Key is greater than other metal objects
5. From the results of this comparison: other than Generator#1-size metal, a key still creates higher spectral contents to EUT than other metal objects at 4 kV.

(9) Comparison of human-with-metal discharges at $8 \text{ kV}$. The measured results are shown in Figure 4.38. Its column chart is shown in Figure 4.39.

It can be concluded that

1. At frequencies $f < 1.3 \text{ MHz}$: (Spectral components) Key > Screw driver > Generator#1-size metal > Thin&Sharp metal

2. $1.3 < f < 7.5$ and $56 < f < 320 \text{ MHz}$: (Spectral components) Generator#1-size metal > Key > Screw driver > Thin&Sharp metal

3. $18 < f < 56 \text{ MHz}$: (Spectral components) Generator#1-size metal > Thin&Sharp metal > Key > Screw driver

4. From the results of this comparison: there is no specific pattern for $8 \text{ kV}$

(10) Comparison of different human weights at $2 \text{ kV}$: $60 - 80 \text{ kg}$. The measured results are shown in Figure 4.40.

It can be concluded that

At $1 \text{ MHz}$, the spectral component of a $80 \text{ kg}$ human is $1.3 \text{ dB}$ higher than that of $70 \text{ kg}$ human, and is $3.6 \text{ dB}$ higher than that of $60 \text{ kg}$ human.

(11) Comparison of different human weights at $4 \text{ kV}$: $60 - 80 \text{ kg}$. The measured results are shown in Figure 4.41.

It can be concluded that

At $1 \text{ MHz}$, the spectral component of a $80 \text{ kg}$ human is $1.5 \text{ dB}$ higher than that of $70 \text{ kg}$ human, and is $4.7 \text{ dB}$ higher than that of $60 \text{ kg}$ human.

(12) Comparison of different human weights at $8 \text{ kV}$: $60 - 80 \text{ kg}$. The measured results are shown in Figure 4.42.

It can be concluded that
At 1 MHz, the spectral component of a 80 kg human is 1.8 dB higher than that of 70 kg human, and is 5.3 dB higher than that of 60 kg human.

(13) Comparison of the same human but with clothes ON and OFF at 2 kV. The measured results are shown in Figure 4.43.
It can be concluded that
At 1 MHz, the spectral components in condition with clothes ON is 2.2 dB higher than that of clothes OFF.

(14) Comparison of the same human but with clothes ON and OFF at 4 kV. The measured results are shown in Figure 4.44.
It can be concluded that
At 1 MHz, the spectral components in condition with clothes ON is 3.9 dB higher than that of clothes OFF.

(15) Comparison of the same human but with clothes ON and OFF at 8 kV. The measured results are shown in Figure 4.45.
It can be concluded that
At 1 MHz, the spectral components in condition with clothes ON is 4.6 dB higher than that of clothes OFF.

(16) Comparison of different relative humidities at 2 kV. The measured results are shown in Figure 4.46.
It can be concluded that
In the condition of human-with-metal discharges at 2 kV, the difference of spectral components at 1 MHz between relative humidity 35% and 80% is 2.7 dB. All curves are very close to each other.

(17) Comparison of different relative humidities at 4 kV. The measured results are shown in Figure 4.47.
It can be concluded that in the condition of human-with-metal discharges at 4 kV, the difference of spectral components at 1 MHz between relative humidity 35% and 80% is 3.4 dB. All curves are very close to each other.

(18) Comparison of different relative humidities at 8 kV. The measured results are shown in Figure 4.48. It can be concluded that in the condition of human-with-metal discharges at 8 kV, the difference of spectral components at 1 MHz between relative humidity 35% and 80% is 2.9 dB. All curves are very close to each other.

4.5.1 Summary

(1) The measured results further show that human-with-metal discharges at different voltages do not produce a monotonic increase in spectral amplitude with increasing voltage (whereas, based on the previously presented results, the human finger discharges are more directly related to ESD voltage level.)

(2) Spectra of narrowband frequency-domain measurements provide information for determining the extent to which the generators can accurately simulate the actual human-with-metal conditions.

(3) Experimental results with several different metal objects seem to show that larger volumes of metal with a sharper point create discharges with higher amplitude of spectral contents.

(4) 80 kg human creates 1.3 to 5.3 dB higher spectral components than those of 70 and 60 kg humans at different discharge voltages.
(5) In the condition of human-with-metal model, a human wearing clothes creates 2.2 to 4.6 dB higher spectral components than those of a human wearing no clothes at different discharge voltages.

(6) In the condition of relative humidity of 35%, human-with-metal model creates 2.7 to 3.4 dB higher spectral components than those of relative humidity of 80% at different discharge voltages.
Figure 4.28  Human-with-metal model using a screwdriver

Figure 4.29  Human-with-metal model using a thin and sharp metal
**Figure 4.30**  Human-with-metal model using a key

**Figure 4.31**  Human-with-metal model using a metal wand with identical size of spark-gap generator
Figure 4.32  Comparison of different ESD generators (#1: spark-gap arcing ESD, #2: IEC 801-2 1984 ESD) and actual human-with-metal model at 2 kV.

Figure 4.33  Comparison of different ESD generators (#1: spark gap arcing ESD , #2: IEC 801-2 1984 ESD) and actual human-with-metal model at 4 kV.
Figure 4.34  Comparison for human-with-metal discharges at 2 kV (G #1: generator #1)

Figure 4.35  Column chart (Human-with-metal at 2 kV) (G #1: generator #1)
Figure 4.36  Comparison for human-with-metal discharges at 4 kV (G #1: generator #1)

Figure 4.37  Column chart (Human-with-metal at 4 kV) (G #1: generator #1)
Figure 4.38  Comparison for human-with-metal discharges at 8 kV (G #1: generator #1)

Figure 4.39  Column chart (Human-with-metal at 8 kV) (G #1: generator #1)
Figure 4.40  Comparison for different human weights at 2 kV: 60 - 80 kg

Figure 4.41  Comparison for different human weights at 4 kV: 60 - 80 kg
Figure 4.42  Comparison for different human weights at 8 kV: 60 - 80 kg

Figure 4.43  Comparison for the same human but with clothes ON and OFF at 2 kV
Figure 4.44  Comparison for the same human but with clothes ON and OFF at 4 kV

Figure 4.45  Comparison for the same human but with clothes ON and OFF at 8 kV
Figure 4.46  Comparison for different relative humidities at 2 kV

Figure 4.47  Comparison for different relative humidities at 4 kV
Figure 4.48  Comparison for different relative humidities at 8 kV
CHAPTER 5

STATISTICAL ANALYSIS OF EXPERIMENTAL DATA

5.1 Introduction

Error analysis is the study and evaluation of the uncertainty in measurements. An important aspect of error analysis is the help it can provide toward designing experiments that will provide reliable and sufficiently complete information on the experimental results. Another objective of error analysis is to find out how error may be reduced and to provide clues for further experimentation. Finally, it could also serve as the basis for the formulation of tentative hypotheses, subject to further experimental verification [32].

This chapter attempts to introduce some fundamentals of statistical methods in engineering for the demonstration of the significance of previously presented experimental measurements of ESD events.

5.2 The Concept of Error Analysis

Every measurement contains an element of error. If the precision of the equipment is adequate, no matter what its accuracy, a discrepancy will always be observed between two measured results. The definitions of the key words error, precision, accuracy, and discrepancy must be understood clearly with respect to measurements [33].

Error: estimated uncertainty
Precision: sharp definition
Accuracy: closeness to truth
Discrepancy: difference between two results
The error of measurement is usually stated in quantitative terms using an accepted measure of the uncertainty which is defined mathematically. The most common of such measures in scientific work is the standard deviation, but others like the spread of raw data are sometimes used, as will be discussed later in this chapter.

Precision is used in measurements to describe the consistency or reproducibility of results. High precision means a tight cluster of the repeated results while low precision indicates a broad scattering of values. An instrument may possess high precision by virtue of a clearly legible, finely divided, distinct scale from which readings are taken. At the same time its accuracy may be poor; for example, because of an internal defect or misadjustment.

The measurement of accuracy is not possible without a reference value. The reference value can be either an assigned value by common agreement among a group of experts or a result which is approximated by a sequence of actual experiments. Considering the operational meaning of the error of a particular measurement, the error of the measurement is simply the difference between the value obtained and the assigned value. The concept of accuracy can be clarified by defining the total error

\[
\text{total error} = x - R = (x - \mu) + (\mu - R)
\]  

(5.1)

where

- \( x \): the measurement
- \( R \): reference value
- \( \mu \): the population mean of repeated measurements

The experimental error of the process of measurements can be defined by \( x - \mu \) and the bias or systematic error by \( \mu - R \). Many statistical authors assumed that the accuracy as the more or less complete absence of bias; the smaller the bias, the greater is the accuracy [34]. According to this thought, a measurement can be accurate even though it has an experimental error. It implies that \( \mu - R = 0 \) or \( \mu = R \). This separates imprecision (lack of precision) from the measurement of accuracy. Thus, inaccuracy is measured by the magnitude of the bias.
5.2.1 The Mean of Raw Data

The mean has more significance from a statistical point of view than appears on the surface of the meaning of arithmetic average. The basis of the use of the term "best value" or "most probable value" is found in terms of quantities called deviations. Study of the deviations gives insight into the role played by the mean.

Let \( v_1, v_2, \ldots, v_n \) be a group of \( n \) independent determinations of a quantity. Each of the \( v_i \) (where \( i = 1, 2, \ldots, n \)) is called a variate in statistical work. The group of \( n \) variates constitutes the raw data. The deviation of a variate, \( v_i \), from its arbitrarily selected reference value, \( v \), is defined as \( x_i = v_i - v \). It may be a positive or negative quantity. Therefore, \( x_1 = v_1 - v, \ x_2 = v_2 - v, \ldots, x_n = v_n - v \)

The sum of the \( n \) deviations is

\[
x_1 + x_2 + \ldots + x_n = \sum_{i=1}^{n} x_i = (v_1 + v_2 + \ldots + v_n) - nv
\] (5.2)

If the value \( v \) has the property that the sum of the deviations is zero, then

\[
0 = (v_1 + v_2 + \ldots + v_n) - nv
\] (5.3)

and the resulting \( v \) is

\[
v = \frac{1}{n} (v_1 + v_2 + \ldots + v_n) = \bar{v}
\] (5.4)

It is seen that the mean is that value for which the sum of the deviations is zero. It may be thought of as the "most probable value" of the quantity around which positive and negative deviations are equally likely to occur and to balance out to zero.

Another point of view, based on the squares of the deviations, also leads to a fulfilling rationale for "most probable value". Usually statistics develop mathematical relations by methods in which a minimum is imposed on the sum of the squares of the deviations. The square of the deviation is

\[
x_i^2 = (v_i - v)^2 = v_i^2 - 2v_i v + v^2
\] (5.5)

The sum, \( S \), of the squares of all \( n \) deviations is

\[
S = \sum_{i=1}^{n} x_i^2 = \sum_{i=1}^{n} v_i^2 - 2v \sum_{i=1}^{n} v_i - nv^2
\] (5.6)
Let \( v \) be variable and find that value of \( v \) which makes \( S \) a minimum, by imposing \( \frac{dS}{dv} = 0 \). Since all the \( v_i \) are constant,

\[
\frac{dS}{dv} = -2 \sum_{i=1}^{n} v_i + 2nv = 0
\]

Thus, for minimum sum of the squares of the deviations,

\[
v = \frac{1}{n} \sum_{i=1}^{n} v_i = \bar{v}
\]

(5.8)

It is because of the property of the mean that it may be called the "most probable value". It should be emphasized that these properties of the mean based on relationships to the deviations do not ensure that the mean is the best estimate of the quantity being measured.

5.2.2 The Spread of Raw Data

It is customary to express measured results in the form

\[
\bar{v} \pm \delta
\]

(5.9)
as the simplest manner of providing further information since all the detail of the \( n \) variates may be lost when a single number (such as the mean) is used to summarize the raw data. The quantity \( \delta \) conveys information about the extent by which the variates differ from their mean. There are four quantities commonly used for \( \delta \), and each of them give information concerning the spread or dispersion of the data about the mean.

(1) The limit of error, \( L \):

\[\delta = L, \text{ such that all variates of the set of the data lie between } \bar{v} - L \text{ and } \bar{v} + L.\]

There is no need for the upper and lower limits of error to be the same for a given set of variates.

(2) The probable error, \( P \):

\[\delta = P, \text{ such that half the variates lie between } \bar{v} - P \text{ and } \bar{v} + P.\]

There also need not be an equal number of variates above and below the mean. Obviously, \( P \) can never exceed the limit of error, \( L \). The probable error will be discussed in Section 5.3.2.

(3) The average deviation, \( A \):

\[\delta = A, \text{ which is defined in terms of the magnitudes of the deviations by}\]
\[ A = \frac{1}{n} (|x_1| + |x_2| + \ldots + |x_n|) = \frac{1}{n} \sum_{i=1}^{n} |x_i| \]  

(5.10)

A is the arithmetic average of all the n deviations taken into account without regard to sign. While the average deviation never exceeds the limit of error, L, it may be equal to, greater than, or less than the probable error, P, depending upon how the variates are distributed.

For small samples (less than 15 observations) like the ESD measurements used in this thesis, the use of the average deviation is not recommended [34].

(4) The \textit{standard deviation}, \( \sigma \):

\[ \delta = \sigma, \text{ which is defined in terms of the squares of the deviations from the mean by} \]

\[ \sigma = \sqrt{\frac{1}{n-1} (x_1^2 + x_2^2 + \ldots + x_n^2)} = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} x_i^2} \]  

(5.11)

It is the usual choice in most scientific work. The square of the standard deviation is called the \textit{variance}, denoted by \( \sigma^2 \) or \( V(x) \). The quantity \( n - 1 \) in the denominator of Eq. (5.11) is known as the number of \textit{degrees of freedom}, used for the estimation of the variance. The standard deviation is usually larger than the average deviation, A. and the probable error, P. Moreover, larger deviations are thereby emphasized more than smaller ones. Therefore, it represents a more conservative measure of the spread of the data but is not as pessimistic as L.

\section*{5.3 Statistical Measures of Precision}

There are many methods most commonly used for the expression of precision including previously mentioned standard deviation, the average deviation, the probable error and the following expression of the standard error, the probability intervals, and confidence intervals. The data in Table 5.1 are measurements of spectral contents of the human-with-metal ESD events using a key at 2 kV (unit in dB\( \mu \text{V}/\text{MHz} \)). Those sets can be converted to \( \text{V/MHz} \) in Table 5.2 and will be used as the examples for calculation of the statistical measures. Results are tabulated in Table 5.3.
Table 5.1 Measurements of spectral contents of human-with-metal discharges using a key at 2 kV (unit in dBuV/MHz)

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Table 5.2  Measurements of human-with-metal discharges using a key at 2 kV (unit in V/MHz)

Note: 1 V = 120 dBμV (dB above 1 μV)

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Table 5.3 Calculation results of statistical measures for human-with-metal discharges using a key at 2 kV

<table>
<thead>
<tr>
<th>MHz</th>
<th>Mean ((\bar{x})) (Volt)</th>
<th>Variance ((\sigma^2)) (Volt)</th>
<th>Standard Deviation ((\sigma)) (Volt)</th>
<th>Standard Error of the Mean (Volt)</th>
<th>Percent Coefficient of Variation of the Mean (%)</th>
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<tr>
<td>1</td>
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<td>0.0002</td>
<td>0.0141</td>
<td>0.0045</td>
<td>0.9000</td>
</tr>
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<td>0.0005</td>
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</tbody>
</table>
5.3.1 The Standard Deviation and Standard Error

The variance and standard deviation are the sample estimates calculated in accordance with Eq. (5.11). They are proper estimates of the corresponding population parameters, regardless of the nature of the frequency distribution. It is only when we attach certain interpretations to these estimates that the nature of the distribution becomes a pertinent issue.

From the variance and standard deviation, the standard error can be developed step by step. From Eq. (5.4), we have

\[
\bar{v} = \frac{1}{n} (v_1 + v_2 + ... + v_n) = \frac{1}{n} v_1 + \frac{1}{n} v_2 + ... + \frac{1}{n} v_n
\]  

(5.12)

For any number of statistically independent variates, the variance, V, is

\[
V(ax + by + cz + ...) = a^2 V(x) + b^2 V(y) + c^2 V(z) + ...
\]  

(5.13)

This applies to Eq. (5.12)

\[
V(\bar{v}) = (\frac{1}{n})^2 V(v_1) + (\frac{1}{n})^2 V(v_2) + ... + (\frac{1}{n})^2 V(v_n)
\]  

(5.14)

But \(V(v_1) = V(v_2) = ... = V(v_n)\), since all variates belong to the same statistical population, and this common variance is equal to \(V(v)\), the variance of this population. Therefore,

\[
V(\bar{v}) = (\frac{1}{n})^2 V(v) + (\frac{1}{n})^2 V(v) + ... + (\frac{1}{n})^2 V(v)
\]

\[
= n \left[ (\frac{1}{n})^2 V(v) \right] = \frac{V(v)}{n}
\]  

(5.15)

From Eq. (5.15), it follows that

\[
\sigma_{\bar{v}} = \frac{\sigma_v}{\sqrt{n}}
\]  

(5.16)

The standard deviation \(\sigma_{\bar{v}}\) is often referred to as the standard error of the mean.

In the case of Table 5.2, measurement of precision may take either one of two aspects (a) our interest may be focused on the measuring technique by which the data are obtained, for example, in order to compare it with an alternative technique; or (b) we may be concerned with the reliability of the best value of the ratio derived from this set of data. In case (a), the standard deviation that characterizes the statistical population underlying these measurements is a logical criterion for the expression of precision. The standard
deviation is shown in Figure 5.2 which releases information of how the measured data are deviated from the mean at each test frequency locally. In case (b), if we take as the best value for the ratio the arithmetic average of the values obtained, we are particularly interested in the uncertainty of the average. In this case, the appropriate measure is the standard error of the average. The standard error in Table 5.3 is shown in Figure 5.3. Finally, if we wish to express the standard error of the mean as a fraction of the measured value, we obtain the percent coefficient of variation of the mean, often denoted by the symbol \( \%CV \)

\[
\%CV = 100 \frac{\sigma_x}{\bar{x}}
\]  

(5.17)

The plot of the percent coefficient of variation of the mean for human-with-metal discharges at 2 kV using a key is shown in Figure 5.4. In Figure 5.4, it is observed that the uncertainty of the mean is relatively high at 10 MHz compared to that in the range from 1 to 56 MHz. The uncertainty starts to further increase from 75 MHz, and a maximum of 16% is found at 420 MHz. In Figure 5.1, the mean of measurement results is plotted with max-min bars. In this plot, the maximum to minimum range is compared to the mean.

### 5.3.2 Probability Intervals

One of the basic problems in the theory of errors is to determine the frequency with which errors of any given size may be expected to occur.

Suppose that a particular measuring process leads to results with normally distributed errors. For a particular sample, the measurements can be expressed as

\[
x = \mu + \varepsilon
\]

(5.18)

where \( \mu \) = the mean

\( \varepsilon \) = a random variable of zero mean and standard deviation \( \sigma \)

Therefore, it can be said that \( x \) itself is a normally distributed variable with mean \( \mu \) and standard deviation \( \sigma \). If the precision, excluding the effects of possible systematic errors in the measuring process, is considered, there will be an interesting quantity

\[
\varepsilon = x - \mu
\]

(5.19)
Figure 5.1  Plot of the mean with max-min bars for human-with-metal discharges at 2 kV using a key

Figure 5.2  Plot of the standard deviation for human-with-metal discharges at 2 kV using a key
Figure 5.3  Plot of the standard error for human-with-metal discharges at 2 kV using a key

Figure 5.4  Plot of the percent coefficient of variation of the mean for human-with-metal discharges at 2 kV using a key
Now it is supposed that a certain positive quantity, D, is given, and the question is asked how frequently the error ε, or \( x - \mu \), will be less than D. The inequality can be expressed as

\[
|x - \mu| < D
\]

(5.20)

or

\[
\mu - D < x < \mu + D
\]

(5.21)

The interval extending from \( \mu - D \) to \( \mu + D \) is a probability interval for the random variable \( x \). Generally, if \( D = k\sigma \), the probability interval for the normally distributed variable \( x \) is

\[
\mu - k\sigma < x < \mu + k\sigma
\]

(5.22)

For skew distributions, a probability interval may be considered of the form:

\[
\mu - k_1\sigma < x < \mu + k_2\sigma
\]

(5.23)

But for variables with skew distributions, the concept of a probability interval lacks the intuitive simplicity of the symmetrical case.

Referring to Eq. (5.22) and to an interval \( x_1 \) and \( x_2 \), in the normal distribution, the \( k \) interval will be

\[
\frac{x_1 - \mu}{\sigma} \text{ to } \frac{x_2 - \mu}{\sigma}
\]

(5.24)

For example, the normal variate \( x \) of mean 140 and standard deviation 25, be located between 160 and 170. Therefore, the \( k \) interval is between 0.80 to 1.20.

From Table A.1 of Appendix [35], \( k(1.20) - k(0.80) = 0.8849 - 0.7881 = 0.0968 \). In other words, 9.68 percent of all values of a standard normal deviate fall between 0.80 and 1.20.

The quantity \( k\sigma \) is defined as the probable error.

Two circumstances militate against the use of the probable error as a measure of precision, even for symmetric distributions. In the first place, the numerical factor, \( k \), is appropriate only for the normal distribution, for example, 0.6745, if the 50 percent probability is to be maintained. Secondly, if the standard deviation is estimated from a sample of small or moderate size, the factor 0.6745 is incorrect even for the normal distribution. It is not recommended to use this method to estimate the precision of the measurement.
5.3.3 Confidence Intervals

It is assumed that a measurement is made and leads to a value \( x \). Realizing that \( x \) is not necessarily equal to the true value \( \mu \) (the systematic errors are ignored in the present discussion), we wish to make a pertinent statement, not about the location of \( x \) but rather about the location of \( \mu \).

Suppose that \( x \) lies between \( \mu - k\sigma \) and \( \mu + k\sigma \); the relation can be presented as

\[
\mu - k\sigma < x < \mu + k\sigma
\]  

(5.25)

Therefore,

\[
x - k\sigma < \mu < x + k\sigma
\]  

(5.26)

The quantity \( \mu \) being fixed, the relation expresses the probability that the random interval extending from \( x - k\sigma \) to \( x + k\sigma \) will bracket \( \mu \). The true significance of Neyman and Pearson’s theory [36] is more readily understood by considering Figure 5.5.

![Confidence Intervals Diagram](image)

**Figure 5.5** Confidence intervals
Each "trial" represents an independent measurement of the quantity \( \mu \). The lower limit of the segment represents the quantity \( x - k\sigma \) and the upper limit, \( x + k\sigma \). For each trial, the corresponding segment either does or does not intersect the horizontal line representing the true value \( \mu \). Each such segment represents a confidence interval for the unknown quantity \( \mu \), based on the measured quantity \( x \).

A "trial" may consist of "n" replicate measurements "x" from a population whose mean is \( \mu \) and whose standard deviation is \( \sigma \). In this case, we obtain a confidence interval for \( \mu \), based on the average, \( \bar{x} \), of the \( n \) measurements by first writing the probability statement

\[
\mu - k \frac{\sigma}{\sqrt{n}} < \bar{x} < \mu + k \frac{\sigma}{\sqrt{n}}
\]  
(5.27)

which is then transformed into the confidence statement

\[
\bar{x} - k \frac{\sigma}{\sqrt{n}} < \mu < \bar{x} + k \frac{\sigma}{\sqrt{n}}
\]  
(5.28)

In the general case, a trial is defined as a set of "n" replicate measurements. The objective is to bracket the unknown \( \mu \) by means of a confidence interval based on the sample. By analogy with Eq. (5.28), it is considered an interval defined by

\[
\bar{x} - k' \frac{s}{\sqrt{n}} < \mu < \bar{x} + k' \frac{s}{\sqrt{n}}
\]  
(5.29)

The estimate "s" has been substituted for the value of \( \sigma \). Since "s" is a function of the "n" observation "x", it will vary from trial to trial. Consequently, the length of the confidence interval, equal to \( 2k's / \sqrt{n} \), is no longer constant from trial to trial.

From Eq (5.29)

\[
|\bar{x} - \mu| < k' \frac{s}{\sqrt{n}}
\]  
(5.30)

or

\[
\left| \frac{\bar{x} - \mu}{s/\sqrt{n}} \right| < k'
\]  
(5.31)

Thus, \( k' \) is associated with a new distribution function that of the ratio of an observed deviation from the mean, \( \bar{x} - \mu \), to its estimated standard error, \( s/\sqrt{n} \). This distribution
function has been tabulated and is known as Student's $t$. The letter $k'$ therefore is substituted by "t". Eq. (5.29) can be rewritten as

$$\bar{x} - t \frac{s}{\sqrt{n}} < \mu < \bar{x} + t \frac{s}{\sqrt{n}}$$  \hspace{1cm} (5.32)

and Eq. (5.31) as

$$\left| \frac{\bar{x} - \mu}{s / \sqrt{n}} \right| < t$$  \hspace{1cm} (5.33)

Unlike the standard normal distribution, Student's $t$ is not a single distribution. It depends on the number of degrees of freedom associated with the estimate $s$. Thus, tables of Student's $t$ always contain a parameter, denoted "degrees of freedom", and represented by the symbol DF or $n$. If a confidence interval is based on a single sample of size "$n$", the standard deviation is based on $n - 1$ degrees of freedom. In such cases, the appropriate value for Student's $t$ is taken from the table, using $n - 1$ degrees of freedom, and whatever level of probability is desired.

Tables of Student's $t$ appear in a variety of forms. Because their most frequent use is in the calculation of confidence intervals or in connection with significance testing, they generally appear in the form of percentiles. (Please see Table A.2 of Appendix A [37]).

5.3.3.1 Illustration

In using this table one must remember that the construction of a symmetrical confidence interval involves the elimination of two equal probability areas, one in each tail of the distribution curve. Thus, a 95 percent confidence interval extends from the 2.5 percentile to the 97.5 percentile. The $t$ values corresponding to these two points are equal in absolute value, but have opposite algebraic signs.

Example 1:

A number of 24 measurements for some event with

Average = 1.08148

Standard Deviation = 0.00258
Standard Error of the Mean = $\frac{0.00258}{\sqrt{24}} = 0.00053$

The standard deviation is estimated with $24 - 1 = 23$ degrees of freedom. If a 95 percent confidence interval is desired, i.e., a confidence interval associated with a probability of 0.95, it is found that the appropriate value of Student's $t$ in Table A.2 of Appendix A for 23 degrees of freedom and a probability of 0.975 (not 0.95). This value is found to be $t = 2.069$. Application of Eq. (5.32) then yields the following confidence interval for the mean:

$$[1.08148 - (2.069)(0.00053)] < \mu < [1.08148 + (2.069)(0.00053)]$$

or

$$1.0804 < \mu < 1.0826$$  \hspace{1cm} (5.34)

Example 2:

After understanding how the confidence intervals work, we can use the raw data from Table 5.2 associated with calculation results of Table 5.3 to evaluate the performance of the experimental results of human-with-metal ESD using a key at 2 kV.

The following calculation is based on $10 - 1 = 9$ degrees of freedom, and assuming that a 95 percent confidence level is desired. From Table A.2 of Appendix A, it can be found that the value of $t = 2.262$. Consequently, Table 5.3 is turned into the conclusion results of Table 5.4 and the plot of 95 percent confidence intervals with the mean in Figure 5.6.

From Table 5.4, it is observed that the maximum differences of the 95 percent confidence intervals of test frequencies at 1.3 and 10 MHz are 0.02 V. Most of the differences from their means are 0.01 V and 0 V.
Table 5.4  Calculation results of 95 percent confidence intervals with the mean of human-with-metal discharges using a key at 2 kV (unit in Volt)

<table>
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<th>Conf. int.</th>
<th>Mean ($\bar{\chi}$)</th>
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<td></td>
<td></td>
<td></td>
</tr>
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Figure 5.6 Plot of 95 percent confidence intervals with the mean for human-with-metal discharges using a key at 2 kV

5.4 The Measurement of Accuracy

It has been pointed out in Section 5.2 that the concept of accuracy is that of the closeness to that of a reference value. When the reference value is numerically known, the measurement of accuracy is relatively simple. By sufficient repetition of the measuring process we can readily estimate its precision. But the evaluation of accuracy in the absence of an exactly known reference value is reduced to a guess. The method most frequently employed by physicists in the determination of basic physical constants is the comparison of results obtained by different and independent measuring processes [34]. Here it is attempted to use the human-with-metal (HM) model using a key as the reference value (illustrated in Table 5.3) representing the ESD signals existing in the real world that the commercial ESD generators want to simulate. The metal object can be selected according to actual needs in the necessary test conditions. The measurements of spectral contents of
the non-IEC type ESD generator (#1) [19] are listed in Table 5.5. Data of Table 5.5 are converted to the unit of V/MHz in Table 5.6. The statistical measures of non-IEC type ESD generator discharges at 2 kV are listed in Table 5.7. Let us consider the condition at 1 MHz, for example:

Let \( B \) represent the bias of the measurements of the generator.

\[
B = \mu - R
\]  
(5.35)

where \( \mu \) is the mean of the measured spectral data of the generator, and \( R \) is the reference data of human-with-metal discharges. Referring to Table 5.4, then \( B = \mu - 0.50 \), and an estimate from Table 5.7 of this bias is given by

\[
\hat{B} = \hat{\mu} - 0.50 = 0.41 - 0.50 = -0.09
\]  
(5.36)

The variance of \( \hat{B} \) is

\[
V(\hat{B}) = V(\hat{\mu})
\]  
(5.37)

and its standard error is:

\[
\sigma_{\hat{B}} = \sigma_{\hat{\mu}}
\]  
(5.38)

We do not know the actual value of \( \sigma_{\hat{\mu}} \) but we have an estimate for this quantity, with 9 degrees of freedom (assuming 10 measurements at each testing frequency):

\[
\hat{\sigma}_{\hat{\mu}} = 0.0071 \text{ (standard error from Table 5.7); and } DF = 9
\]  
(5.39)

Hence

\[
\hat{\sigma}_{\hat{B}} = 0.0071
\]  
(5.40)

Using the Eq. (5.32), we can now construct a confidence interval for the bias \( B \) which is:

\[
\hat{B} - t \sigma_{\hat{B}} < B < \hat{B} + t \sigma_{\hat{B}}
\]  
(5.41)

Suppose we use a 95 percent confidence coefficient with 9 degrees of freedom; therefore \( t = 2.2620 \) (Appendix A, Table A.2) and it can be applied to the value of \( B \).

\[
[-0.09 - (2.262)(0.0071)] < B < [-0.09 + (2.262)(0.0071)]
\]

or

\[-0.1061 < B < -0.0739
\]  
(5.42)

This interval does not include the value “zero” in this calculation; it is thus concluded that the bias is significantly different from zero and negative, which means that the analytical results for the spectral contents at 1 MHz of this ESD generator tended to
give slightly low results. In general, the bias may include the value "zero" in some applications. In other words, the data provide evidence for the existence of a real bias. The following calculation results in Table 5.8 will show the details for the whole frequency response.

**Comparative Results**

Compare the measured data of the non-IEC type ESD generator using spark-gap arcing principle at 2 kV in Table 5.6 and 5.7 with those of the human-with-metal (HM) discharges using a key at 2 kV in Table 5.2 and 5.3. The bias information is plotted in Figure 5.7.

In the range of (1 to 1.8), (4.2 to 7.5), (13 to 18), (56 to 75) MHz, the bias information shows that the ESD generator #1 is intended to shift away from the closeness of human-with-metal discharges. On the other hand, in the frequency ranges of (42 to 56), (130 to 560) MHz, the discharges of ESD generator #1 are very close to those of human-with-metal event using a key. The related information of 95 percent confidence intervals is also plotted in Figure 5.8. In Figure 5.8, the differences of maximum 0.02 V are found from 1 to 5.6 MHz. Differences of 0.01 V are from 7.5 to 32 MHz. From 32 MHz, there is no difference found.
Table 5.5  Measurements of spectral contents of non-IEC type ESD generator
(generator #1) discharges at 2 kV (Note: unit in dBμV/MHz)

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Table 5.6  Measurements of non-IEC type ESD generator (generator #1) discharges at 2 kV (Note: unit in V/MHz)

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Table 5.7  Calculation results of statistical measures for measurements of generator #1 discharges at 2 kV

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Table 5.8 Calculation results of upper and lower limits of the bias compared ESD generator ≠ \#1 discharges to human-with-metal discharges using a key at 2 kV (Note: unit in Volt, \#HM: human-with-metal discharges)

<table>
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<th>MHz</th>
<th>Conf. int.</th>
<th>Mean of HM*</th>
<th>Mean of ESD generator</th>
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<th>Upper limit of bias</th>
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Table 5.9  Calculation results of 95 percent confidence intervals for measurements of accuracy of ESD generator #1 discharges at 2 kV

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<th>Mean of ESD generator</th>
<th>Upper limit</th>
<th>Lower limit</th>
<th>Upper or lower differences</th>
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<td>0.02</td>
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<td>0.42</td>
<td>0.38</td>
<td>0.02</td>
</tr>
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<td>4.2</td>
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<tr>
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</tr>
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<td>0.05</td>
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<td>0.03</td>
<td>0.03</td>
<td>0.00</td>
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<tr>
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<td>0.01</td>
<td>0.01</td>
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<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
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</table>
Figure 5.7  Plot of upper and lower limits of the bias between the ESD generator #1 and the human-with-metal discharges using a key at 2 kV.

Figure 5.8  Plot of 95 percent confidence intervals with the mean for the ESD generator #1 discharges at 2 kV.
5.5 Summary

Using statistical analysis in the frequency domain, one can investigate further information of how accurate the experimental data are and can take insight into the spread of differences from the estimates to the actual desired quantities. However, for small samples the use of the average deviation and the use of probability intervals as a measure of precision is not recommended.

Statistical analysis of ESD events in the time domain is extremely difficult if not impossible. The main difficulty is the pictorial (non-quantitative) results of ESD events. The quantitative data obtainable are peak current in Amps and rise time in nanoseconds, which are not sufficient to specify the ESD events adequately [38]. Furthermore, if the rise time of ESD transients is equal to or less than that of the measurement instrument, it will result in error in both peak current and rise time.

In the calculations of the examples of this chapter it is found that

1. For the standard deviation, standard error, and percent coefficient of variation of the mean for human-with-metal discharges using a key at 2 kV

   In Figure 5.2, the standard deviation displays information on how the measured data deviate from the mean at each test frequency locally. The maximum of the standard deviation of 0.0245 V is found at 10 MHz. The standard error of the mean can be calculated as a fraction of the measured values for the uncertainty of the measurement. It is the percent coefficient of variation of the mean. In Figure 5.4, it is observed that the uncertainty of the mean starts to increase from 75 MHz, and a maximum of 16% is found at 420 MHz.

2. For the 95 percent confidence intervals of human-with-metal discharges using a key at 2 kV

   From Table 5.4, it is observed that the maximum differences of the 95 percent confidence intervals of test frequencies at 1.3 and 10 MHz are 0.02 V. Most of the differences from their means are 0.01 V and 0 V.
(3) For the 95 percent confidence intervals of ESD generator #1 discharges at 2 kV

The 95 percent confidence intervals of ESD generator #1 are plotted in Figure 5.8. In Figure 5.8, differences of maximum 0.02 V are found from 1 to 5.6 MHz. Differences of 0.01 V are from 7.5 to 32 MHz. From 32 MHz, there is no difference found.

(4) For the measurement of accuracy using the bias information for comparing ESD generator #1 to human-with-metal discharges using a key at 2 kV

It is observed that among the ranges of (1 to 1.8), (4.2 to 7.5), (13 to 18), (56 to 75) MHz in Figure 5.7, the bias information showing that the ESD generator #1 has a tendency to shift away from the closeness of human-with-metal discharges. On the other hand, among the frequency ranges of (42 to 56), (130 to 560) MHz, the discharges of ESD generator #1 are very close to those of human-with-metal event using a key at 2 kV.
CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

6.1 Conclusions

This thesis introduces the method of narrowband frequency domain measurement of ESD events, and also describes (a) two case studies as well as (b) the Fourier Transform analysis of two well known ESD waveforms specified in the IEC 801-2 (1984) and 801-2 (1991) (now IEC 1000-4-2). Spectral components of ESD events measured by the spectrum analyzer are analyzed in the frequency domain from 1 MHz to 1 GHz.

After the evaluation, this thesis comes up with the following conclusions:

(1) Discrepancy of double-peak waveform

The results of FFT analysis on the IEC waveforms reveal that there is a possible 29.8 dB discrepancy in the IEC 801-2 (1991) standard. To eliminate this discrepancy, the current specifications of the complete waveform up to 5 RC (250 ns) must be specified.

(2) Current slew rate (di/dt); the ratio of the peak current (A) to the rise-time (ns)

At an identical ESD voltage level, the FFT levels can be different. Also, from the analysis of Case Study (1), two different waveforms with equal current slew rate can have different spectra in the frequency domain. Therefore, the current slew rate is not the only indicator of likely ESD failure.
(3) Measurement of very fast pulse

The rise time of some very fast ESD pulses, such as those shown in Case Study (1), which is equal to or less than that of the oscilloscope can not be measured accurately using a modern gigahertz oscilloscope. With the narrowband frequency domain method, the spectral components can be readily measured.

(4) Human-with-metal and human-finger discharges

The experimental results show that human-with-metal discharges at different voltages do not produce monotonic increase in spectral components at the high frequencies. The human finger discharges are more directly related to the ESD voltage level. The measured results also show that human-with-metal discharges produce higher spectral energy than those of human-finger discharges.

(5) Comparison of spectra of experimental results of narrowband frequency domain method with the IEC data

In the narrowband frequency domain method, the measurements clearly show that air only (without contact) and air-with-contact ESDs are different whereas the IEC standards using the oscilloscope make no distinction between the two. In the IEC contact discharges at different voltage levels, the frequency domain results show that beyond 100 MHz the spectral level are almost the same with the 2 kV curve showing slightly higher values.

The measurement results of the IEC simulator also show that the spectral level at 1 MHz is about twice (6 dB) that of the human-with-metal discharges. Beyond 10 MHz, the IEC simulator does not match the human-with-metal discharges.

(6) Simulation of actual human ESD

Spectra of narrowband frequency domain measurements provide information for determining the extent to which the ESD generators can accurately simulate the actual human-with-metal conditions.
(7) Influential factors of human ESD

a) Experimental results with several different metal objects seem to show that larger volumes of metal with a sharper point create discharges with higher amplitude of spectral contents.

b) The 80 kg human creates 1.3 to 5.3 dB higher spectral components than those of 70 and 60 kg humans at different discharge voltages.

c) In the condition of human-with-metal model, a human wearing clothes creates 2.2 to 4.6 dB higher spectral components than that of a human wearing no clothes at different discharge voltages.

d) In the condition of relative humidity of 35%, the human-with-metal model creates 2.7 to 3.4 dB higher spectral components than that of relative humidity of 80% at different discharge voltages.

(8) Statistical analysis of experimental data

Using statistical analysis in the frequency domain can investigate further information of how accurate the experimental data are and can take insight into the spread of differences from the estimates to the actual desired quantities, whereas statistical analysis of ESD events in the time domain is extremely difficult if not impossible.

(9) In the calculation of the percent coefficient of variation of the mean

It is observed that the uncertainty of the mean is relatively high at 10 MHz compared to the range from 1 to 56 MHz. The uncertainty starts to further increase from 75 MHz, and a maximum of 16% is found at 420 MHz.

(10) In the calculation of confidence intervals

It is observed that the maximum differences for the spectral contents of human-with-metal discharges using a key at 2 kV with the 95 percent confidence intervals of test frequencies at 1.3 and 10 MHz are 0.02 V. Most of the differences from their means are 0.01 V and 0 V.
On the other hand, the differences for the spectral contents of the ESD generator #1 compared to those of the human-with-metal event using a key of maximum 0.02 V are found from 1 to 5.6 MHz. Differences of 0.01 V are found from 7.5 to 32 MHz. From 32 MHz, there is no difference indicated.

(11) In the measurement of accuracy

In the range of (1 to 1.8), (4.2 to 7.5), (13 to 18), (56 to 75) MHz, the bias information shows that the ESD generator #1 is intended to shift away from the closeness of human-with-metal discharges. On the other hand, in the frequency ranges of (42 to 56), (130 to 560) MHz, the discharges of ESD generator #1 are very close to those of the human-with-metal event using a key.

6.2 Recommendations for Future Studies

The spectral performance of the ESD generators and the human ESD events at different voltage levels has been investigated in the frequency domain. However, there are many aspects which may affect the measurement of the ESD events and the measure of precision. Further improvement is needed to enhance the measuring technique and experimentation.

(1) Calibration of the measurements of radiated fields

The test method in the thesis employed a human body to describe the coupling geometry which standardizes the human to test target coupling capacitance, \( C_d \), as in the actual human ESD situation, which is a constant in the same test. To simulate the human with metal ESD or human finger ESD, this constant must be kept consistent, i.e. the constant is identical in the human and the generator mode. In the IEC case, the ground return wire is not simulating a human body and no one knows the frequency response of this wire. It is recommended to study the radiated pattern of how the ground return wire is related to the frequency response of the equivalent antenna.
(2) Criteria of the ESD spectrum for the ESD immunity testing

For ESD immunity engineering, either overtest or undertest is undesirable in some parts of the industry, i.e., military, aeronautical, and medical electronics if the ESD characteristics is not accurately measured. The important point is that the frequency domain test method allows one to analyze an ESD in the area that the time domain method cannot. If you cannot analyze an ESD accurately, it is not valid to say whether or not the test is overtest or undertest. It is recommended to further investigate an overall spectrum which contains broadband energy at all frequencies. By using this spectrum, ESD engineers can design a product with the utmost protection from the most severe human ESD situations.

(3) Effects of the reference ground screen

The parabolic shield was used to control the distributed capacitance, $C_d$, from human hand to the test target consistently. At low frequency range it will not influence the injection current. The shield is different from the IEC specification which is a ground screen of $1.5 \times 1.5$ m around the current sensor. It is recommended to explore the relationship between the reference ground and the $C_d$.

(4) Real-time acquisition system

The biggest drawbacks of frequency domain measurements using a spectrum analyzer is the need of a repeatable signal.

In order to get test data for a spectrum from 1 MHz to 1 GHz, more discharges must be performed. The number of discharges depends on the consistency of the amplitude of the spectral components. It indicated that “At each frequency setting, 10 discharges were performed.” During these 10 discharges, we obtain the minimum, maximum, and average. The standard deviation and other statistical information are also obtained from the test data. However, a real-time spectrum analyzer is the ultimate solution for the consistency. One zap and the complete spectrum is shown to be analyzed readily. It is recommended to further develop such a system by which to reduce the test procedures and the inaccuracy.
# APPENDIX A

## Table A.1  Cumulative Probabilities of the Standard Normal Deviate

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APPENDIX B

Description of the International ESD Standards IEC 801-2 (1991) and IEC 1000-4-2

International Standard IEC 1000-4-2 is based on the IEC 801-2 (second edition: 1991): Electromagnetic compatibility for industrial process measurement and control equipment - Part 2: Electrostatic discharge requirements. No technical changes, only editorial amendments, have been made with this transfer and reference to IEC 801-2 (1991) or IEC 1000-4-2 is equivalent.

The objective of this standard is to establish a common and reproducible basis for evaluating the performance of electrical and electronic equipment when subjected to electrostatic discharges. In addition, it includes electrostatic discharges which may occur from personnel to objects near vital equipment.

Test levels

Contact discharge is the preferred test method. Air discharge shall be used where contact discharge cannot be applied. Test voltages are different for each method due to the differing methods of test. The voltages are given as following:

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Table B.1 IEC 1000-4-2 specified test levels

* IEC does not differentiate air only and air-with-contact discharges.

** "x" is an open level. The level has to be specified in the dedicated equipment specification. If higher voltages than those shown are specified, special test equipment may be needed.
Test generator

The test generator consists of:

- energy storage capacitance (150 pF ± 10%): representing the capacity of a human body charged to the test voltage value
- discharge resistance (330 Ω ± 10%)
- charging resistance (between 50 MΩ and 100 MΩ)
- output voltage (up to 8 kV for contact discharge, up to 15 kV for air discharge)
- tolerance of the output voltage indication (5%)
- polarity of the output voltage (positive and negative)
- discharge, mode of operation (single discharge)
- waveshape of the discharge current (double peak, Figure 3 in the Standard)

Waveform parameters

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</table>

Table B.2 IEC 1000-4-2 specified waveform parameters

The value of the characteristics of the discharge current shall be verified with 1000 MHz bandwidth measuring instrumentation. For verification, the tip of the discharge electrode shall be placed in direct contact with the current-sensing transducer, and the generator operated in the contact discharge mode.

Test set-up

The test set-up consists of the test generator, EUT, and auxiliary instrumentation necessary to perform direct and indirect application of discharges to the EUT in the following manner:
a) contact discharge to the conductive surfaces and to coupling planes;
b) air discharge at insulating surfaces.

Additional specifications for the different types of equipment: are table-top and floor-standing. Test set-up for post-installation tests is optional and not mandatory.

Test procedure
a) Direct application of discharges to the EUT

The static electricity discharges shall be applied only to such points and surfaces of the EUT which are accessible to personnel during normal usage. The test shall be performed with single discharges. On preselected points at least ten single discharges shall be applied.

- In the case of contact discharges, the tip of the discharge electrode shall touch the EUT, before the discharge switch is operated.
- In the case of air discharges, the round discharge tip of the discharge electrode shall be approached as fast as possible (without causing mechanical damage) to touch the EUT. After each discharge, the ESD generator (discharge electrode) shall be removed from the EUT. The generator is then retriggered for a new single discharge. This procedure shall be repeated until the discharges are completed. In the case of an air discharge test, the discharge switch, which is used for contact discharge, shall be closed.
b) Indirect application of the discharge

Discharges to objects placed or installed near the EUT shall be simulated by applying the discharges of the ESD generator to coupling planes (horizontal and vertical), in the contact discharge mode.
Appendix C

(1) Source code (in MATLAB) of Figure 4.3:

```matlab
% Plot of IEC 801-2 (1984) single-peak waveform
clf

clear

%----- PWL waveform input (25 points)
t=[0 1.9 2.61 3 8 8.5 9 10 11 12 13 14 17 ... 35.5 45.5 50 ...
   55 60 65 77.5 90 100 110 122.5 1000];
y=[0 .3 .522 .9 8.1 8.56 8.8 8.95 9 9 8.9 8.7 8 ... 4.5 2.8 2.2 ...
   1.5 1.05 .78 .45 .26 .165 .11 .06 4.5e-19];
plot(t,y,'w-');hold on
title('Plot of IEC 801-2 (1984) single-peak waveform')
xlabel('Time, (ns)')
ylabel('Discharge current, (A)')

%----- time domain parameters ----------------------------
plot(3.0,9,'wo');hold on;%-------- 10%
   text(5.0,9,'10% (3.0,9)')
plot(5.5,4.5,'wo');hold on;%-------- 50%
   text(8.4,5,'50%')
   text(8.4,'(5.5,4.5)')
plot(35.5,4.5,'wo');hold on;%------- 50%
   text(38.4,5,'50% (35.5,4.5)')
plot(8.8,1,'wo');hold on;%-------- 90%
   text(9.5,7.8,'90% (8.8,1)')
   text(7.2,7.2,'(6.8,1)')
plot(11.9,'wo');hold on;%-------- peak
   text(11.9,5,'peak (11,9)')
   text(80.8,'Peak current = 9 A')
   text(80.7,'Rise time = 5 ns')
   text(80.6,'Pulse width = 30 ns')
%
%----- observing range
axis([0 150 0 10])
```

(2) Source code (in MATLAB) of Figure 4.4:

```matlab
% Fourier Transform of 1984 single-peak waveform at 2 kV
% The number of calculated output for testing freq. steps are 8025
clf
clear
```
%-----PWLS waveform input: (m=25 points)
m=25, %input data point index (in the time domain)
t=[0 1.9 2.61 3 8 5.9 10 11 12 13 14 17 ...
35.5 45.5 50 ...
55 60 65 77.5 90 100 110 122.5 1000]; %nsec
y=[0.3522.9 8.1 8.56 8.8 8.95 9 9.9 8.8 8.7 8 ...
4.5 2.8 2.2 ...
1.5 1.05 .78 .45 .26 .165 .11 .06 4.5e-19]; %Amps
%
%-----Fourier Transform calculation:
%
%f=1e6:1.245e5:1000e6; %--observed frequencies (1M~1GHz)
%w=2*pi*f;
f1=1e6; %1MHz
fn=1000e6; %1GHz
dt=1.245e5; %
n=(fn-f1)/dt+1; %numbers of dt = 8025
%
for l=1:(n+1); %number of tested freq. points: 8026 -- freq. counter
%
sum=0; %-- set initial value = 0
for J=1:(m-1); %number of slopes (Vn) or segments
    v(J)=(y(J+1)-y(J))/((t(J+1)-t(J))*1e-9); %-- slope for PWL f(t) -> A/sec
    T(J)=(t(J+1)-t(J))*1e-9; %-- duration for f'(t) -> sec
    tau(J)=((t(J)+t(J+1))*1e-9)/2; %-- central point of rectangular pulses -> sec
%
    f(I)=1e6+dt*(I-1); %Hz
    w(I)=2*pi*f(I);
%
    F(J)=(-2*v(J)*sin(w(I)*T(J)/2)*sin(w(I)*tau(J)) ...
      +j*cos(w(I)*tau(J)))/w(I)^2;
    sum=sum+F(J);
end
FT(I)=sum;
end
%
%-----Plot of the "exact" Fourier Transform--------------------------
fx=f; 1e6;
yy=abs(FT)*1e6;
loglog(fx,yy,'w-'); hold on; %-- x-axis (MHz), y-axis (A/MHz)
title('The exact Fourier Transform for IEC 801-2 (1984) waveform at 2 kV')
xlabel('Frequency. (MHz)')
ylabel('A/MHz')
axis([1 1000 1e-6 1])
%-----------------------------------------------
plot(1,294,'wo'); hold on; %----------------------- t = 1 MHz

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(3) **Source code (in PSPICE) of Figure 4.5:**

IEC1984 ESD PULSE @ 2KV, Ip=9A, Tr=5 ns 4.5A @ pulse width=30 ns
* P=2us@200ps steps(10000). Set x=1M-1GHz, y=1uA-1A/MHz

```
101 PWL(0,0 1.9n,0.3 2.61n,0.522 3ns,0.9 8n,8.1 8.5n,8.56 9n,8.8 10n,8.95
+ 11n,9 12n,9 13n,8.9 14n,8.7 17n,8
+ 35.5n,4.5 45.5n,2.8 50n,2.2
+ 55n,1.5 60n,1.05 65n,.78 77.5n,0.45 90n,0.26 100n,0.165 110n,0.11 122.5n,0.06
+ 1u 4.5e-19)
```

R1 1 10 1
.tran 200ps 2us
.four 1MEG V(1)
.probe
.end
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Chapter 5


VITA AUCTORIS

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