IEEE Standard 4

IEEE Standard for High-Voltage Testing Techniques

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Fall 2016 IEEE Switchgear Committee Meeting
October 9 – 13, Pittsburgh, PA

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Scope of IEEE Standard 4

- Dielectric tests with direct voltages
- Dielectric tests with alternating voltages
- Dielectric tests with impulse voltages
- Tests with impulse currents
- Tests with combinations of the above
- Capacitance and dielectric loss measurements
- Applies only to apparatus with rated voltage > 1 kV
- Procedures given for applying atmospheric correction factors
- Procedures given for testing external insulation subjected to wet, dry or contaminated conditions

History of IEEE Standard 4

- Roots go back to the earliest Standardization Report of the American Institute of Electrical Engineers (AIEE) in 1889
- First version of Standard 4 as a separate HV test and measurement standard was published by AIEE in 1928
- Present 2013 version is the eighth edition as a separate standard
- The two most recent preceding versions were published in 1995 and 1978 respectively
- An amendment (IEEE Std 4a) was published in 2001, re-introducing the 1978 atmospheric correction factors (request of IEEE Switchgear Committee)

Position Within the IEEE

- Maintained by the High Voltage Testing Techniques (HVTT) Subcommittee of the Power Systems Instrumentation and Measurement (PSIM) Committee
- Referenced by all IEEE power apparatus committees
- PSIM Officers:
  - Jim McBride, JMX Services - Chair
  - Ernst Hanique, DNVGL KEMA Laboratories, - Vice Chair
  - Jeffrey Britton, Phenix Technologies - Secretary
  - Farnoosh Rahmatian, NuGrid Power Corp. - Awards Committee
  - Eddy So, NRC Canada - Standards Coordinator
- HVTT Officers:
  - Jeffrey Britton, Phenix Technologies - Chair
  - Jim McBride, JMX Services - Vice Chair
  - Yixin Zhang, HVATOZ Consulting - Secretary

Present Status of the Document

- IEEE Standard 4-2013 was published on May 4th, 2013
- Present version is comprised of:
  - 199 pages
  - 15 Clauses in the Main Body
  - 1 Normative and 4 Informative Annexes
  - 20 Tables
  - 54 Figures
  - 119 Numbered Equations
  - 244 Bibliographical References
- Remains valid through 12/31/2023

Relationship to IEC Standards

IEEE Std. 4 Includes Information Also Covered in the Following IEC Standards…

- IEC 60060-1 High-voltage test techniques – Part 1: General definitions and test requirements
- IEC 60060-2 High-voltage test techniques – Part 2: Measuring systems
- IEC60052 Recommendations for voltage measurement by means of standard air gaps

Relationship to IEC Standards

Continued…

- IEC 60507 Artificial pollution tests on high-voltage insulators to be used on a.c. systems
- IEC 61245 Artificial pollution tests on high-voltage insulators to be used on d.c. systems
- IEC 62475 High-current test techniques – definitions and requirements for test currents and measuring systems

Relationship to IEC Standards

Continued…

In General…

- IEEE directive is to produce standards that are in technical alignment with the equivalent IEC standards, to the degree possible
- Standard 4 and the associated IEC standards are generally technically equivalent
- A major goal of Standard 4 is to include more tutorial information, with the aim of educating test engineers in proper high-voltage testing technique

Changes in New Revision

- The new document represents a major revision over the 1995 version
- Significant reorganization of the material
- Major shift from the concept of determining the measurement “error” to estimating the measurement “uncertainty” using internationally accepted methodology (ISO/IEC Guide 98-3)
- More emphasis is placed on creating and maintaining a “Record of Performance” for measuring systems to track and document accuracy and stability over time

Changes in New Revision

Continued…

- Use of a sphere gap as a calibration device for alternating and impulse peak voltage magnitude has been removed, however a sphere gap used in accordance with the standard is still considered an “approved measuring device”
- The sphere gap is no longer considered valid for use when measuring direct voltages, with rod-rod gaps being specified
- More information is given on methods for determining linearity of measuring systems when a full voltage reference measuring system is unavailable

Changes in New Revision

Continued…

- The 1978 methodology for atmospheric correction of test results has been replaced into the main standard as an alternative method, for equipment manufacturers needing to perform routine tests on older equipment designs, which were originally designed and tested in accordance with the 1978 atmospheric correction procedures
- The most significant technical change is in the methodology used to determine impulse parameters for lightning impulses having oscillations near the peak ("k-factor", or "Test Voltage Factor" method)

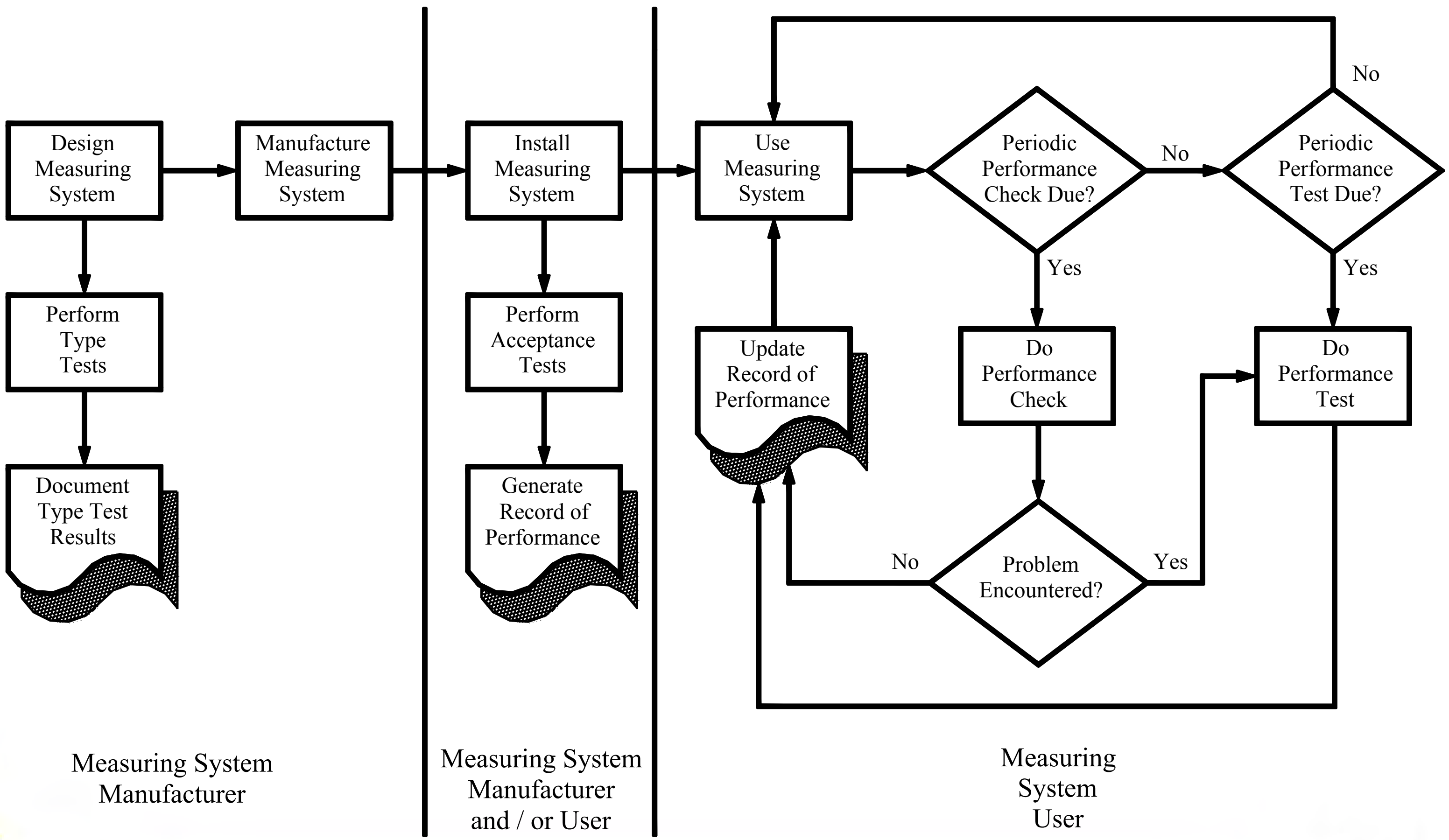
Reorganization of Material

- In the 1995 edition of Standard 4, material on testing techniques, measuring system requirements and potential sources of error in measurements was spread across different clauses throughout the standard
- In the 2013 edition, all material that is germane to a given waveform (e.g. AC, DC, Impulse Voltage, Impulse Current) is covered in separate, respective clauses
- Result is a standard that is much more “user-friendly” to engineers and test technicians who must interpret and apply the standard requirements

Uncertainty versus Error

- The uncertainty of a measurement result gives the boundary limits within which the “true” value of the measurand, within a given level of confidence, is expected to lie
- The methodology includes errors in repeatability (random fluctuation) for a series of measurements (Type A uncertainty) as well as other known sources of uncertainty (manufacturer’s specifications, resolution, thermal stability, environmental effects, etc.) arising from the measuring equipment (Type B uncertainty)
- Type A and Type B components are combined in a root sum square calculation, then multiplied by a “coverage factor” to obtain the desired confidence level
- Note that measuring uncertainty is distinct from test voltage tolerance

Record of Performance for a Measuring System



Record of Performance for a Measuring System

Continued…

Type Tests

Verification of Operating Temperature Range

Frequency Response

Verification of Duty Cycle

Proximity Effects

Acceptance Tests

Acceptance Tests

Determination of Measuring System Short Term Stability

Withstand Voltage Test

Performance Tests

Performance Tests

Determine or Verify Measuring System Scale Factor

Determine or Verify Measuring System Linearity

Example of Required Contents of Record of Performance for an AC High-Voltage Measuring System

Use of "Test Voltage Factor Method" for Evaluation of Lightning Impulses with Oscillations

- Previous versions of Standard 4 ignored the effects of oscillations near the peak if the frequency of the oscillation was higher than 500 kHz
- Below 500 kHz, the measured peak voltage was taken as the peak value of the voltage
- Above 500 kHz, a "Mean Curve" was drawn through the oscillations, to estimate an "effective" peak value
- This discontinuity could result in inconsistent test results
- The new method prescribes a standard approach based on a specified weighting function applied to the test voltage record in the frequency domain to remove the discontinuity at 500 kHz

Future Tasks for IEEE 4

- Need to consider harmonization with IEC 60060-1 on the definition of “peak value of an alternating voltage” (e.g. Maximum value {IEEE} versus average of positive and negative peak values {IEC})
- Expansion of the standard to include testing parameters for UHV voltages above 800 kV class (e.g. longer permissible Lightning Impulse front times, problems with wet testing procedures)
- Improvements and verification of atmospheric correction factor procedures, especially for UHV test voltage levels

Thank You!

Use of K-factor Method in Processing Impulse Test Waveforms with Overshoot

Jim McBride
President
JMX Services, Inc.

IEEE Switchgear Committee Fall 2016
Pittsburgh, PA
Discussions on IEEE-Std. 4 -2013 :HVTT Subcommittee
October 10th , 2016

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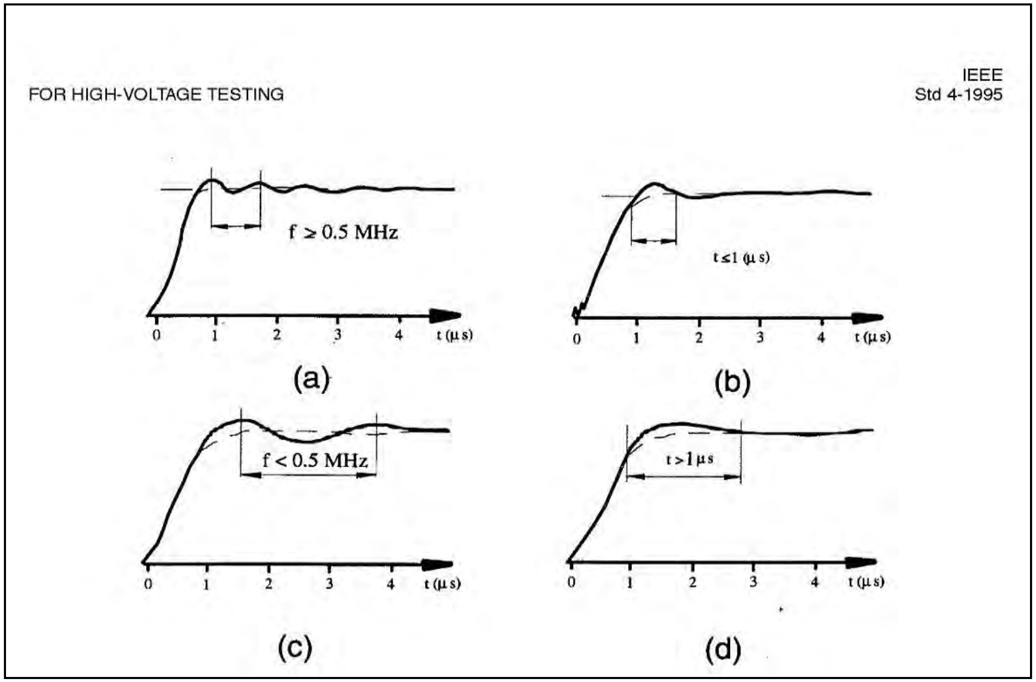
Problems with IEEE 4 - 1995 Overshoot Definition



f < 0.5 MHz = Peak

f > 0.5 MHz = Mean Curve

1. *No gradual transition between selection of Peak Value or Mean Curve*
2. *No well defined method to generate the Mean Curve*
3. *No Clear Definition of Overshoot*

Steps to Perform K-Factor Overshoot Analysis

1. *Perform double exponential curve fit to recorded data to generate "Base Curve".*
2. *Subtract Base Curve from recorded data to generate "Residual Curve"*
3. *Filter Residual Curve with Insulation System Specific K-Factor Filter*
4. *Add Filtered Residual Curve to Base Curve to generate "Test Voltage Curve"*
5. *Read impulse parameters from Test Voltage Curve*
6. *Determine relative overshoot magnitude from the difference between the recorded maximum and the Base Curve maximum*

Important Steps in the Analysis

1. *Time placement of the curve fit is critical*
   Curve fit should start at the actual zero.

2. *Filtering of the Residual Curve*
   IIR (zero phase), FIR (linear phase)

3. *Selection of the K-Factor Curve*
   (Most of testing for current
   curve was below 200kV)

IEEE P4/D007, January 2012

The graphic expression of the *k*(*f*) function is shown in Figure 1

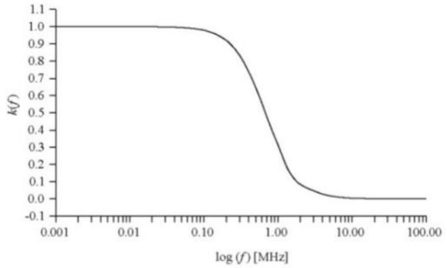


Figure A.1—Frequency dependency of the test voltage function *k*(*f*)

The test voltage equation, (A.1) is applicable to impulses both with and without overshoot. For impulses without overshoot the applied voltage is a smooth curve and has the form of a base curve without any residual oscillations to process. Such curves are unaffected by the residual filter function and yield impulse parameters that are unaffected by that function. The procedures are therefore transparent to smooth curves and so it is not necessary to pre-sort impulse prior to parameter derivation.

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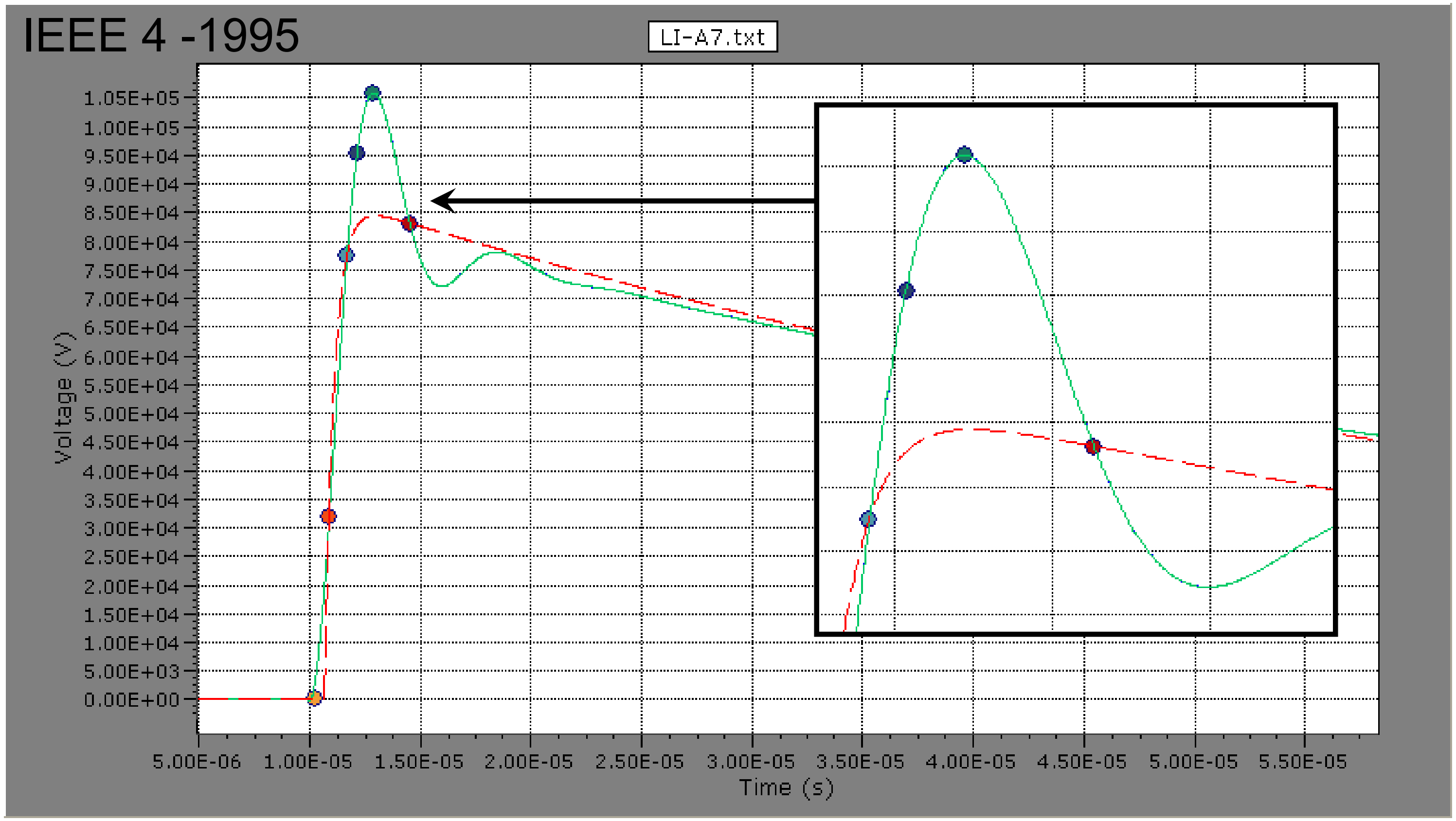
Lightning Impulse Waveform LI-A7 – 20% OS 200kHz



<u>New K-Factor Parameters</u>

Peak = 104.4 kV

$T_1 = 2.140\ \mu s$

$T_2 = 38.4\ \mu s$

$\beta' = 20.2\ \%$

<u>IEEE 4 - 1995 Parameters</u>

Peak = 105.9 kV

$T_1 = 2.114\ \mu s$

$T_2 = 37.2\ \mu s$

$\beta' = 20.2\ \%$ @ 180 kHz

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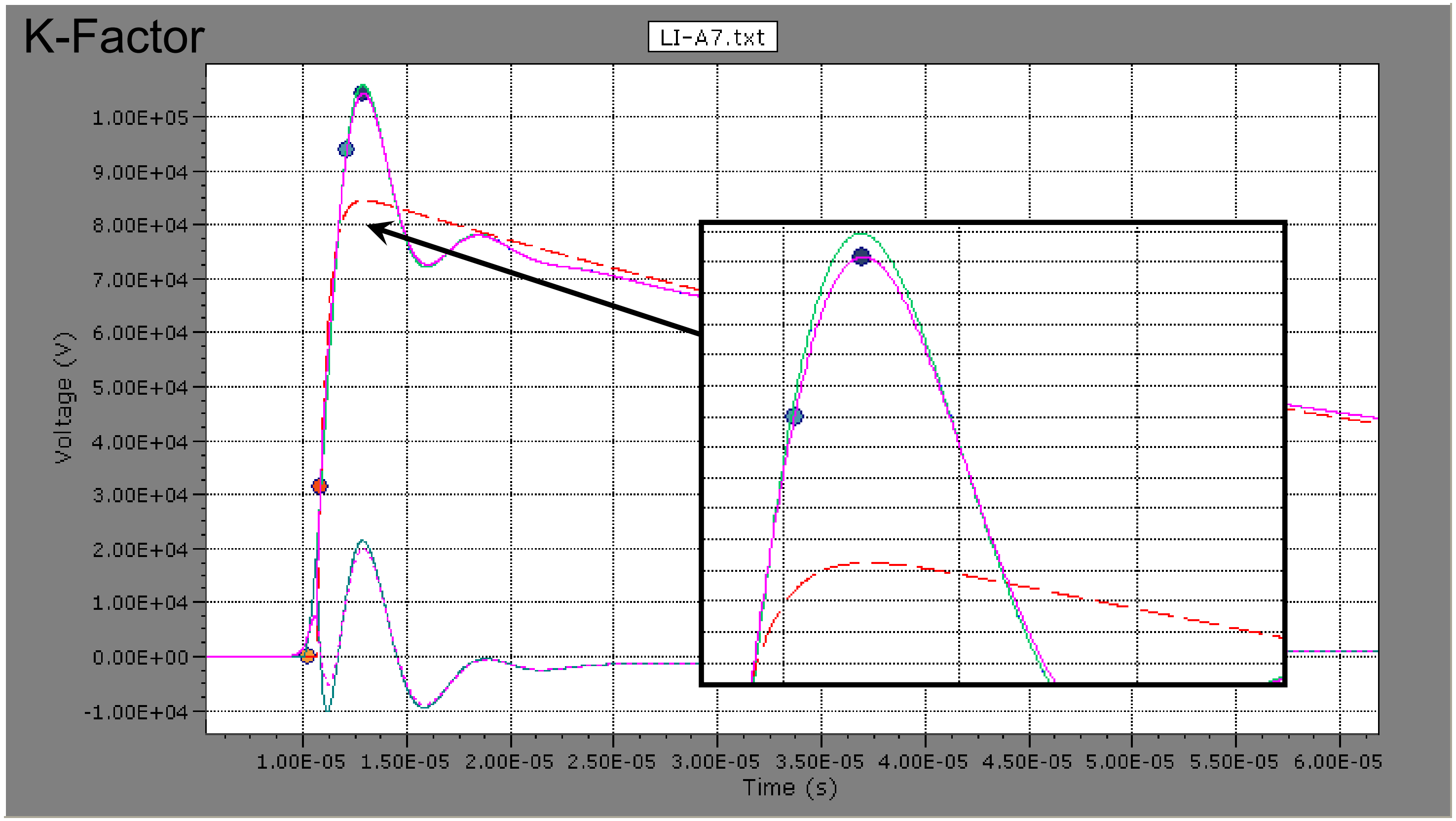
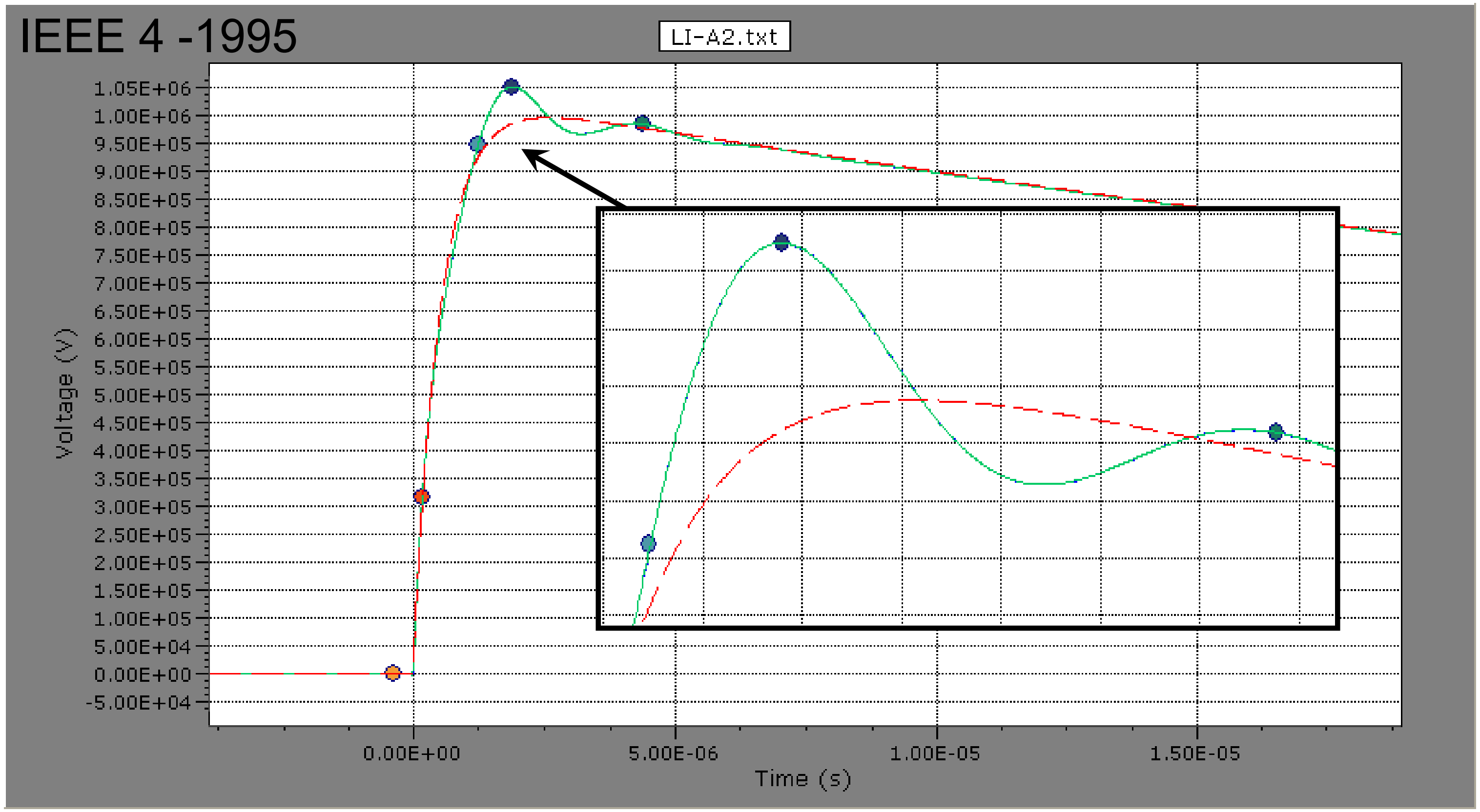
Lightning Impulse Waveform LI-A7 – 20% OS 200kHz



New K-Factor Parameters	IEEE 4 - 1995 Parameters
Peak = 104.4 kV	Peak = 105.9 kV
T_1 = 2.140 µs	T_1 = 2.114 µs
T_2 = 38.4 µs	T_2 = 37.2 µs
β′ = 20.2 %	β′ = 20.2 % @ 180 kHz

Lightning Impulse Waveform LI-A2 –Slow Oscillations



<u>New K-Factor Parameters</u>

Peak = 1037.6 kV

T_1 = 1.711 μs

T_2 = 47.5 μs

β′ = 5.1 %

<u>IEEE 4 - 1995 Parameters</u>

Peak = 1050.0 kV

T_1 = 1.772 μs

T_2 = 46.7 μs

β′ = 5.2 % @ 401 kHz

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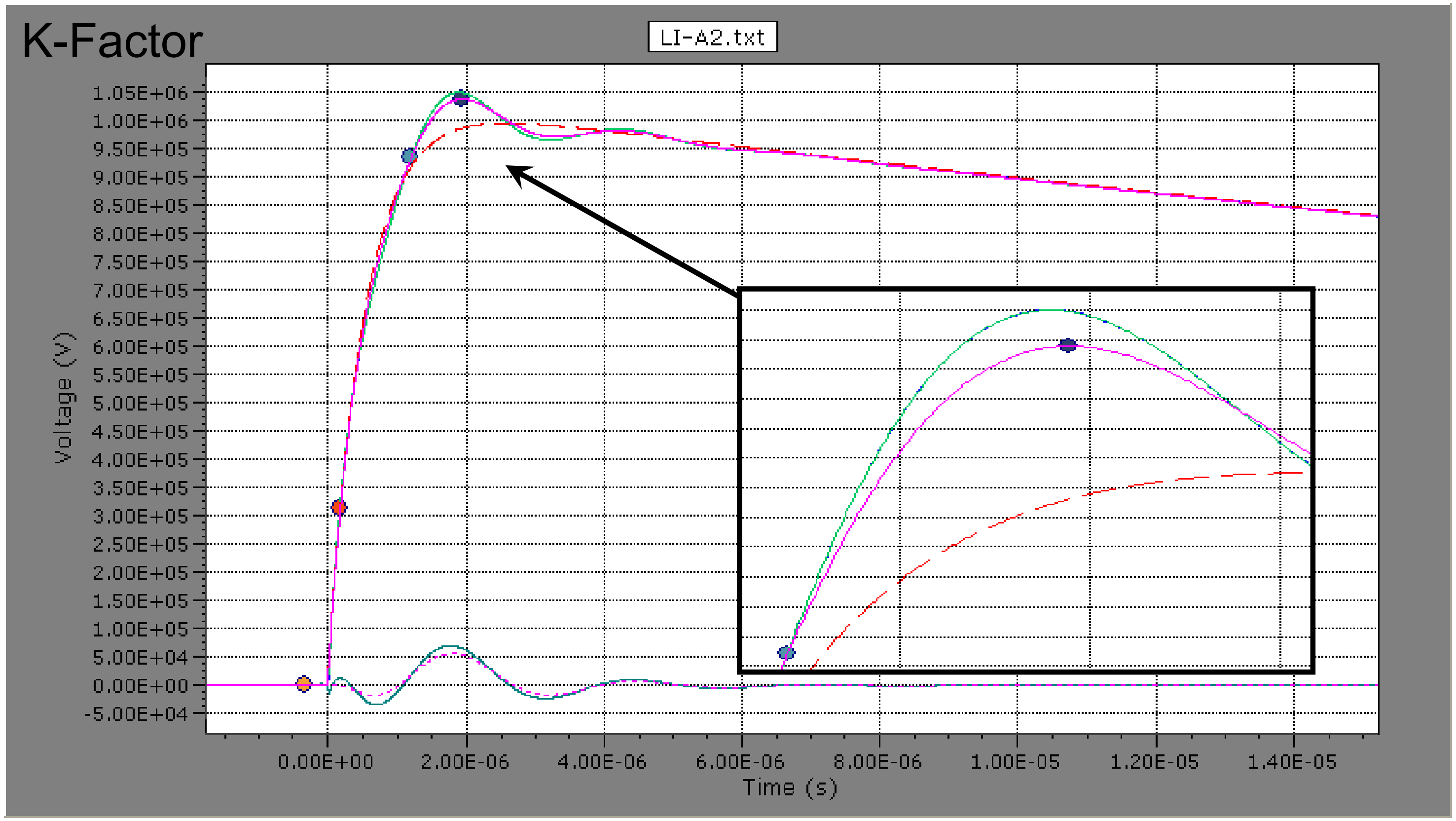
Lightning Impulse Waveform LI-A2 –Slow Oscillations



<u>New K-Factor Parameters</u>

Peak = 1037.6 kV

T_1 = 1.711 µs

T_2 = 47.5 µs

β′ = 5.1 %

<u>IEEE 4 - 1995 Parameters</u>

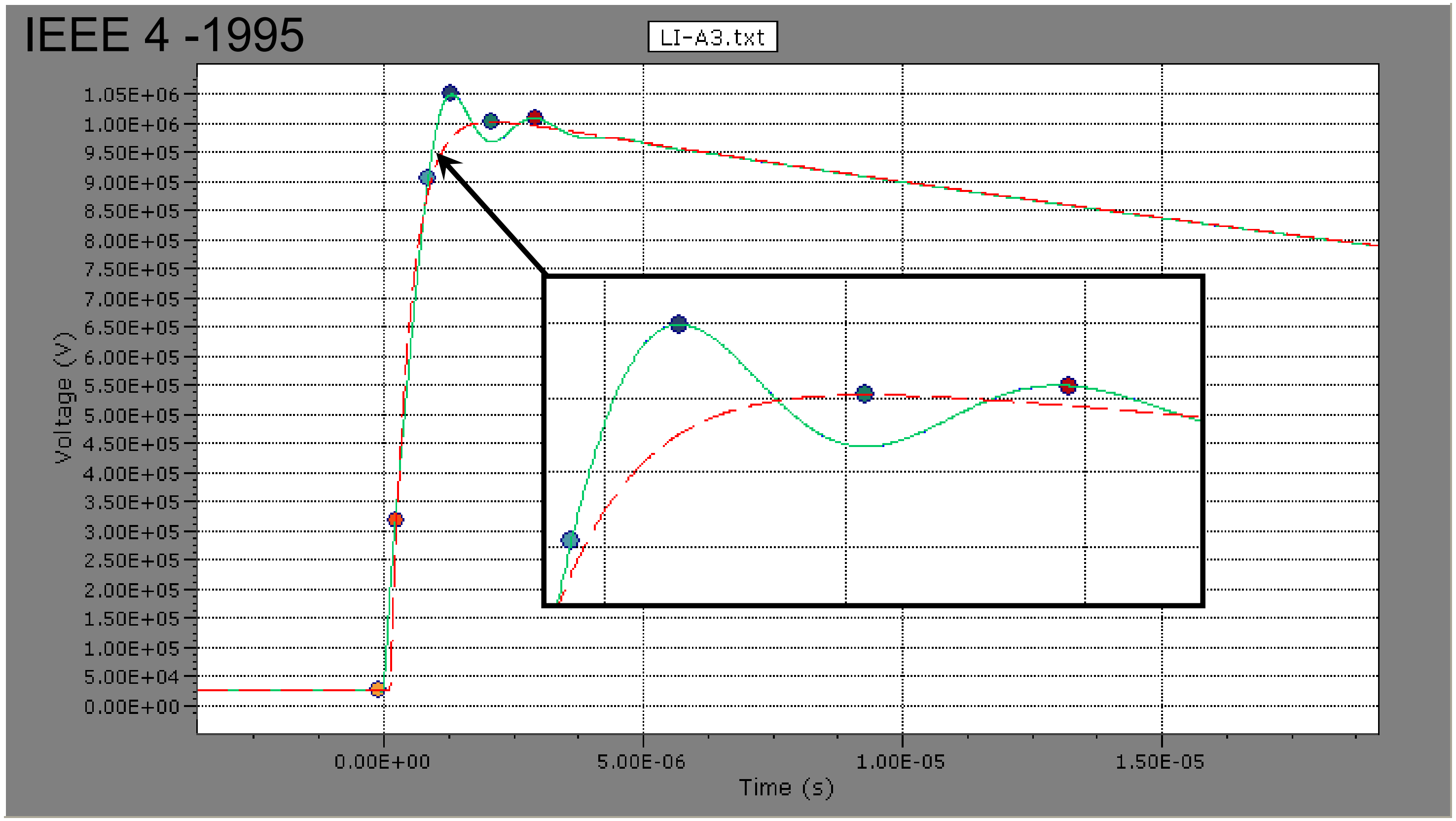
Peak = 1050.0 kV

T_1 = 1.772 µs

T_2 = 46.7 µs

β′ = 5.3 % @ 401 kHz

Lightning Impulse Waveform LI-A3 – Fast Oscillations



<u>New K-Factor Parameters</u>

Peak = 1000.5 kV

T_1 = 1.110 µs

T_2 = 48.15 µs

β′ = 4.4 %

<u>IEEE 4 - 1995 Parameters</u>

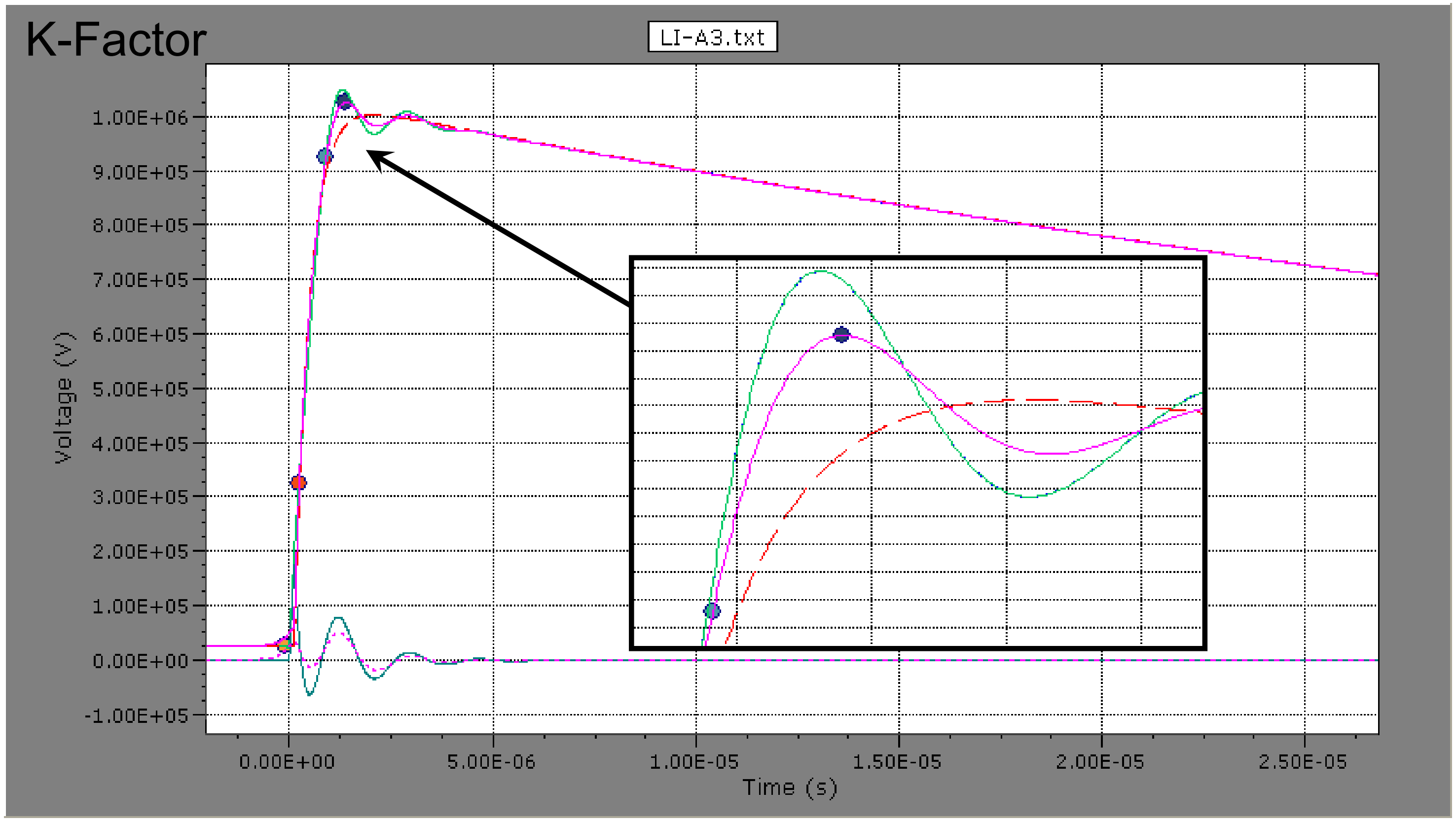
Peak = 977.2 kV

T_1 = 1.049 µs

T_2 = 49.8 µs

β′ = 4.6 % @ 614 kHz

Lightning Impulse Waveform LI-A3 – Fast Oscillations



<u>New K-Factor Parameters</u>

Peak = 1000.5 kV

$T_1 = 1.110\ \mu s$

$T_2 = 48.15\ \mu s$

$\beta' = 4.4\ \%$

<u>IEEE 4 - 1995 Parameters</u>

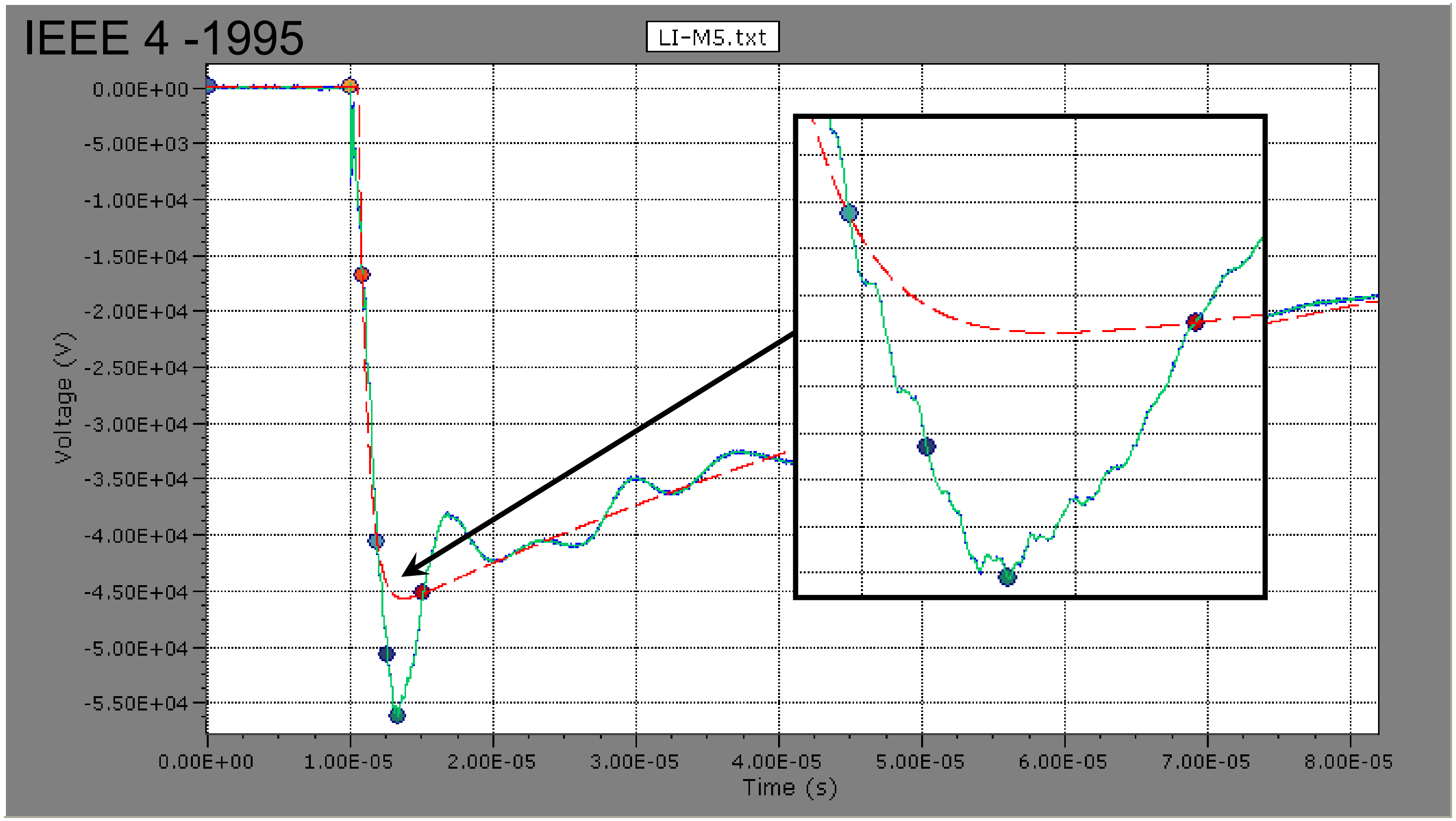
Peak = 977.2 kV

$T_1 = 1.049\ \mu s$

$T_2 = 49.8\ \mu s$

$\beta' = 4.6\ \%$ @ 614 kHz

Lightning Impulse Waveform LI-M5 – TX Wave



New K-Factor Parameters

Peak = -55.0 kV

T_1 = 2.831 µs (2.75 µs)

T_2 = 42.2 µs

β′ = 18.9 %

IEEE 4 - 1995 Parameters

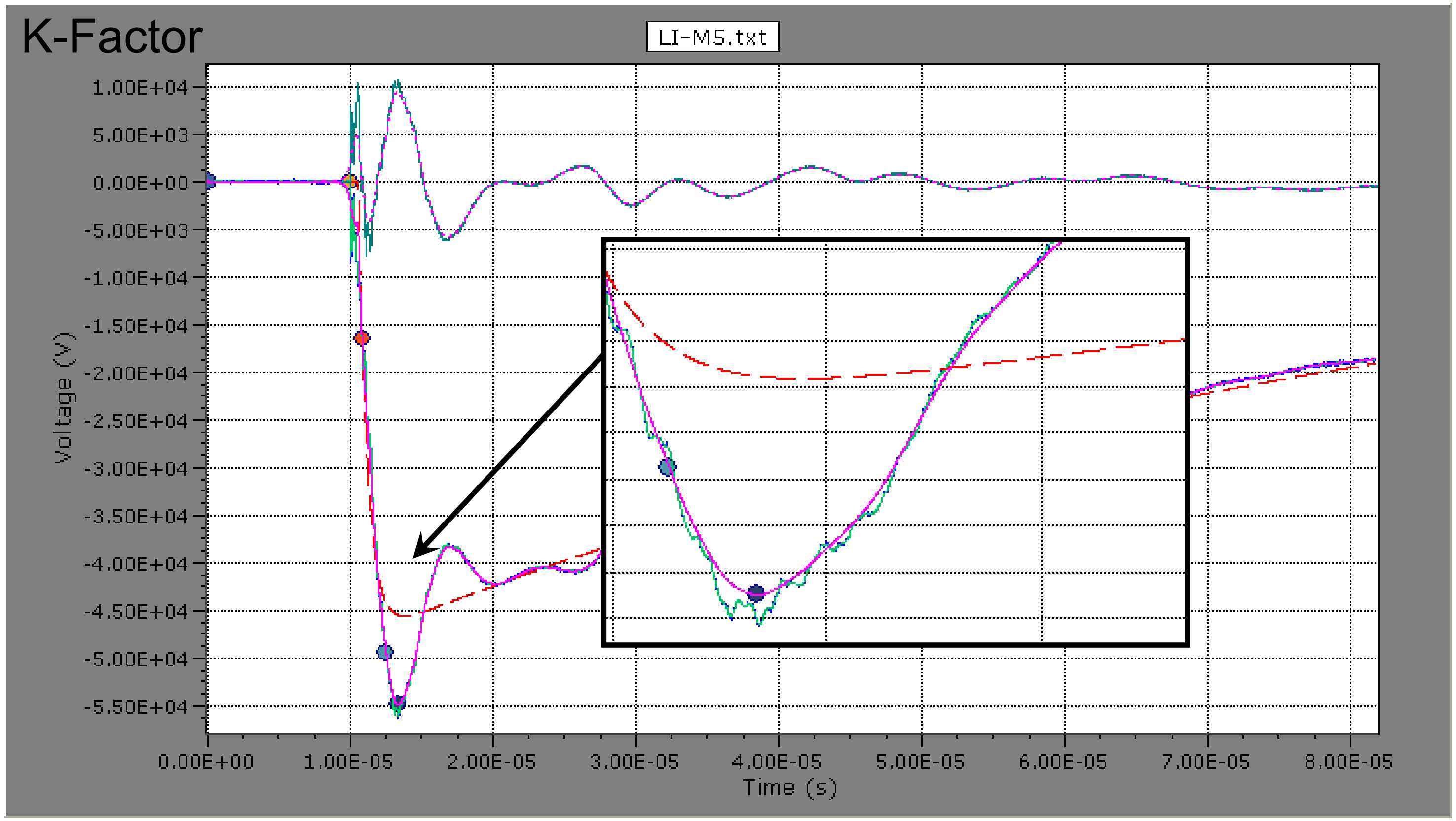
Peak = -56.3 kV

T_1 = 2.923 µs

T_2 = 41.4 µs

β′ = 18.9 % @ 144 kHz

Lightning Impulse Waveform LI-M5 – TX Wave



<u>New K-Factor Parameters</u>

Peak = -55.0 kV

T_1 = 2.831 μs (2.75 μs)

T_2 = 42.2 μs

β′ = 18.9 %

<u>IEEE 4 - 1995 Parameters</u>

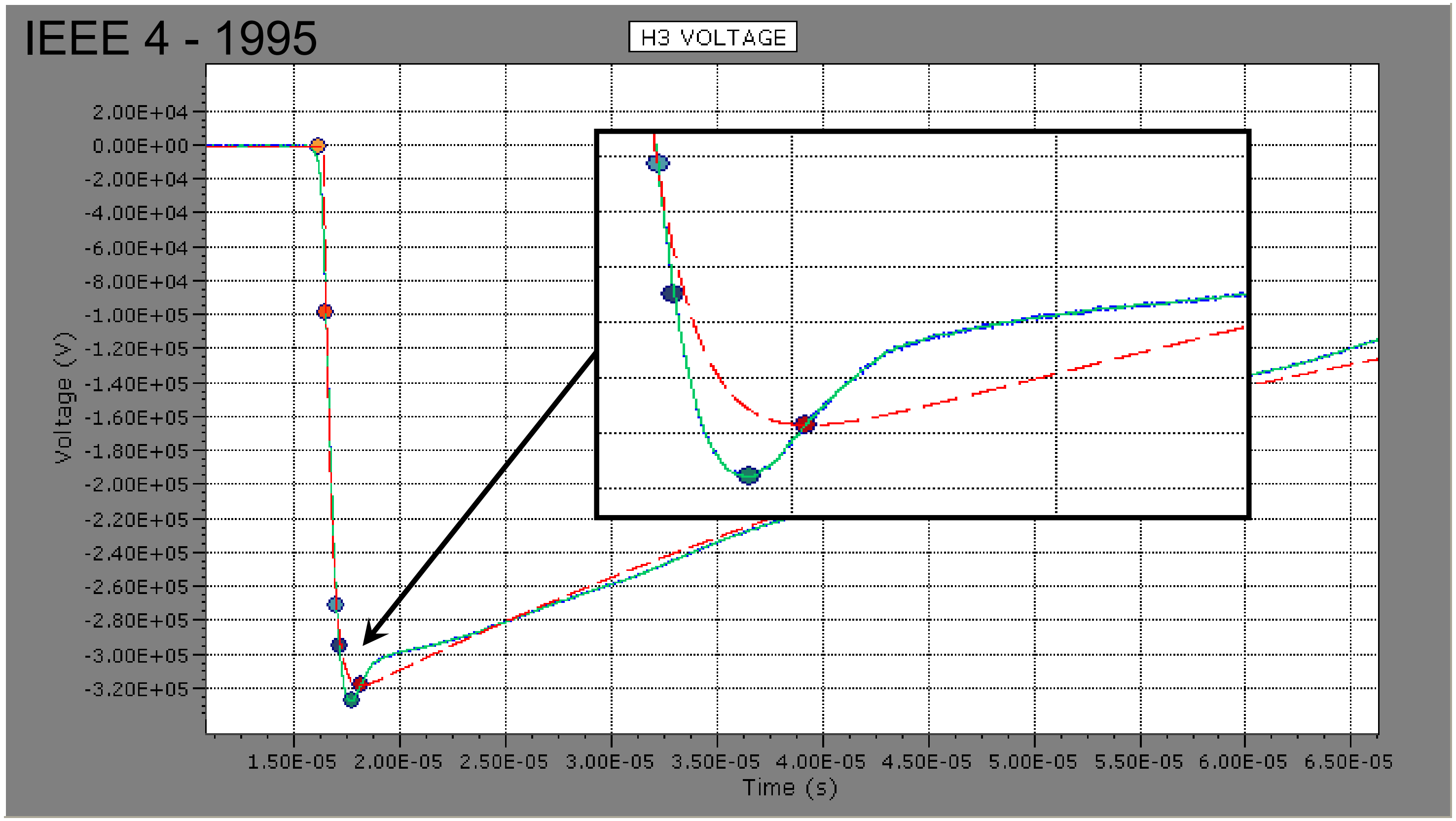
Peak = -56.3 kV

T_1 = 2.923 μs

T_2 = 41.4 μs

β′ = 18.9 % @ 144 kHz

Lightning Impulse Waveform – TX 138kV/69kV/T12.47kV



<u>New K-Factor Parameters</u>

Peak = -324.1 kV

T_1 = 1.052 µs

T_2 = 36.2 µs

β′ = 2.8 %

<u>IEEE 4 - 1995 Parameters</u>

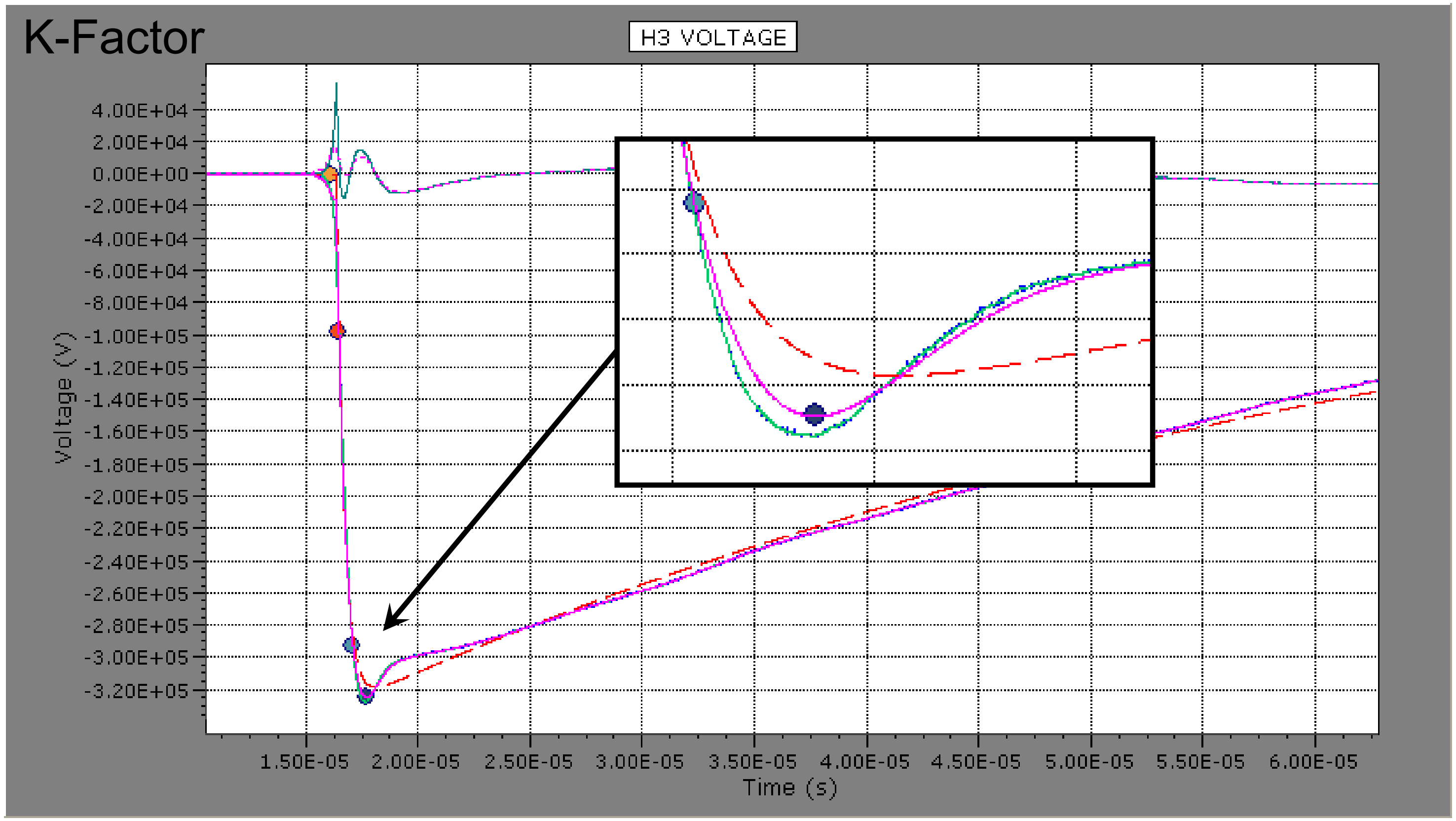
Peak = -327.0 kV

T_1 = 1.052 µs

T_2 = 35.8 µs

β′ = 2.8 % @ 1.1 µs

Lightning Impulse Waveform – TX 138kV/69kV/T12.47kV



<u>New K-Factor Parameters</u>

Peak = -324.1 kV

$T_1 = 1.052\ \mu s$

$T_2 = 36.2\ \mu s$

$\beta' = 2.8\ \%$

<u>IEEE 4 - 1995 Parameters</u>

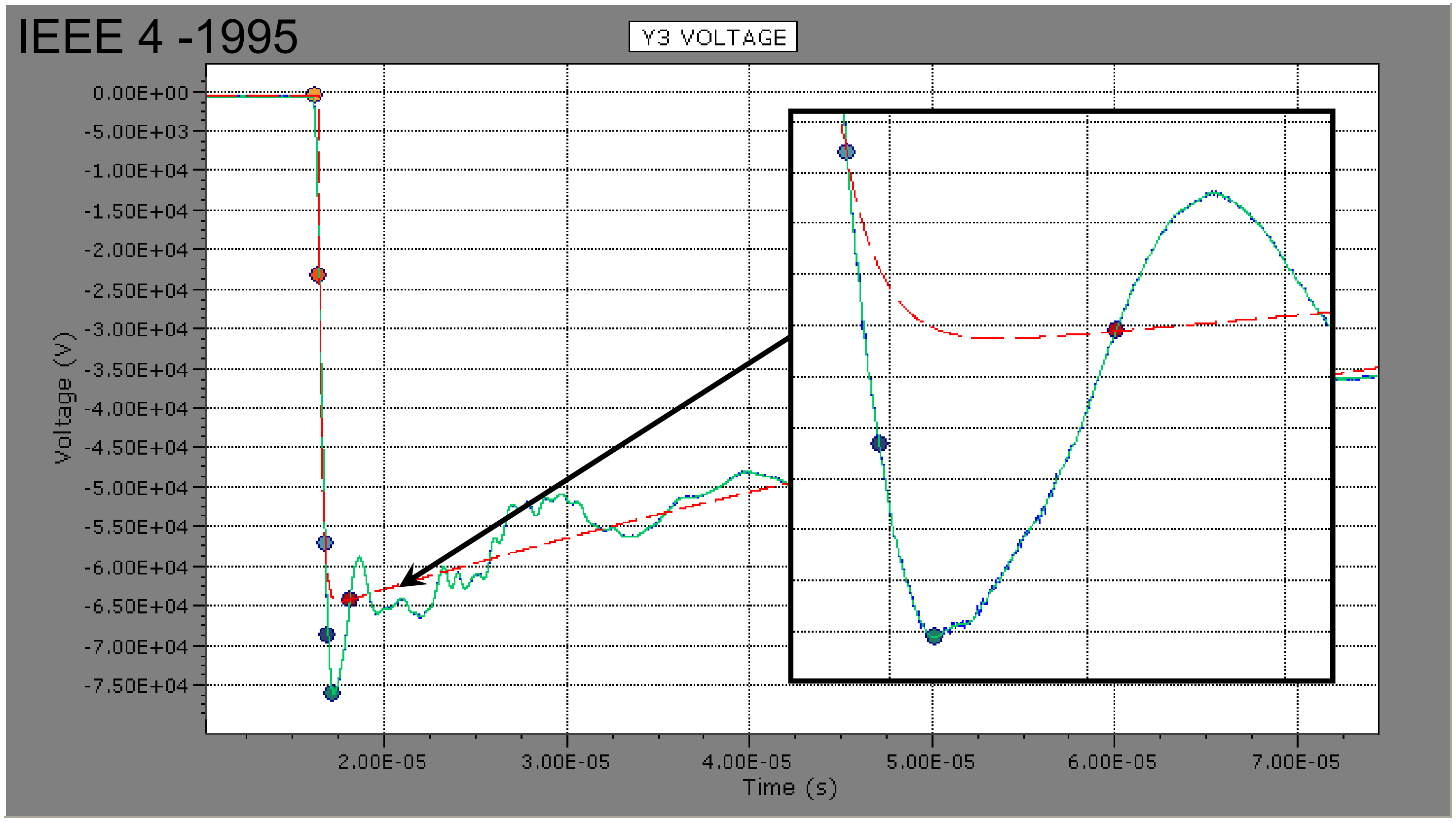
Peak = -327.0 kV

$T_1 = 1.052\ \mu s$

$T_2 = 35.8\ \mu s$

$\beta' = 2.8\ \%$ @ $1.1\ \mu s$

Lightning Impulse Waveform – TX 138kV/69kV/T12.47kV



<u>New K-Factor Parameters</u>

Peak = -72.9 kV

$T_1 = 0.777\ \mu s$

$T_2 = 51.5\ \mu s$

$\beta' = 15.4\ \%$

<u>IEEE 4 - 1995 Parameters</u>

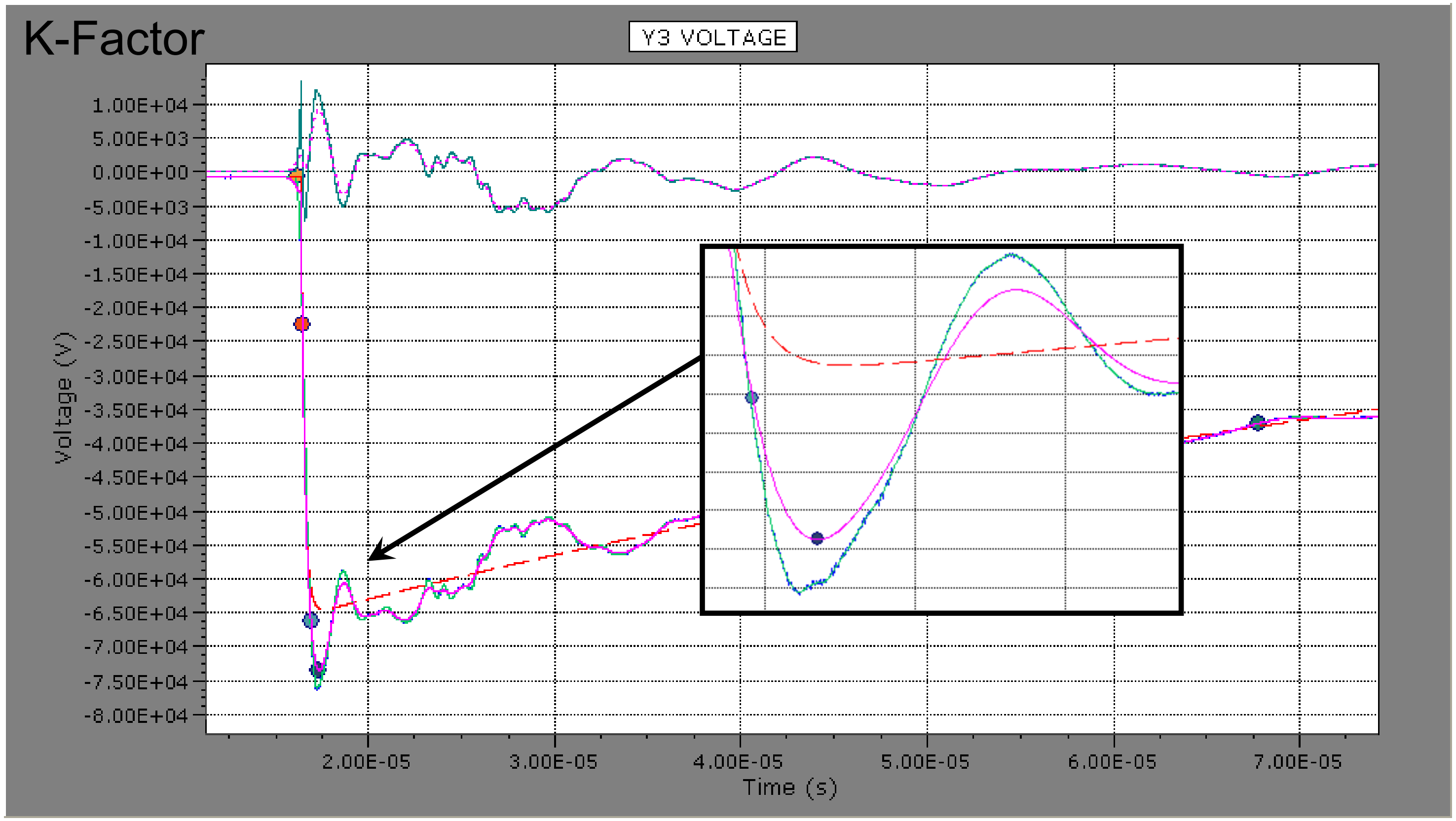
Peak = -75.6 kV

$T_1 = 0.810\ \mu s$

$T_2 = 49.7\ \mu s$

$\beta' = 15.5\ \%$ @ $1.36\ \mu s$

Lightning Impulse Waveform – TX 138kV/69kV/T12.47kV



<u>New K-Factor Parameters</u>

Peak = -72.9 kV

T_1 = 0.777 μs

T_2 = 51.5 μs

β′ = 15.4 %

<u>IEEE 4 - 1995 Parameters</u>

Peak = -75.6 kV

T_1 = 0.810 μs

T_2 = 49.7 μs

β′ = 15.5 % @ 1.36 μs

Tail Chopped Impulse Waveforms

IEC recommends that waveforms from tail chopped impulses have the section past the chop point be replaced by a scaled version of the tail from a previously recorded full impulse. The parameters are then evaluated from the tail patched version of the impulse by the same basic method as full impulses.

IEEE-4 allows for two methods of evaluating tail chopped impulses.

1) Voltage Reduction Ratio (Preferred Method)

2) Tail Patch Method (Alternative Method same as IEC)

Voltage Reduction Ratio (IEEE Preferred Method)

1) *Find the Voltage Reduction Ratio using the V_t and V_e from the last previously recorded full lightning impulse(FLI) by the below equation:*

$$R_v = V_t / V_e$$

2) *Determine V_e for the tail chopped impulse.*
3) *Determine V_t from $V_t = V_e \times R_v$*
4) *Determine T_1 from the previously recorded FLI.*
5) *Determine the virtual origin from the following equation:*

   $O_1 = T_{30\%} - 0.3\ T_1$

6) *Chop Time is given by $T_c = T_{point\ of\ chop} - T_{O_1}$*

K-Factor Filter Dependency on Insulation Type

IEEE P4/D007, January 2012

The graphic expression of the $k(f)$ function is shown in Figure 1

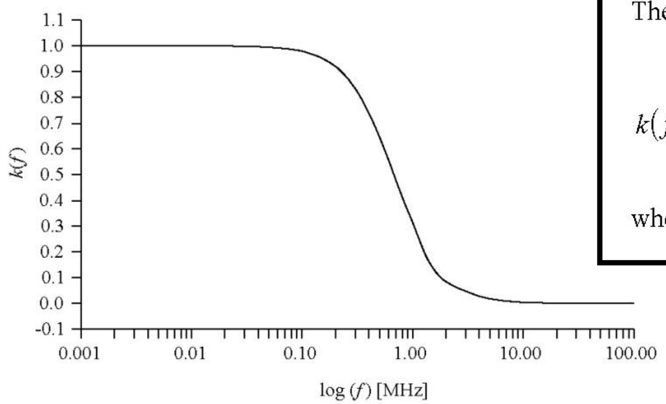


Figure A.1—Frequency dependency of the test voltage function $k(f)$

The frequency dependent function of the test voltage factor is given by:

$$k(f) = \frac{1}{1 + af^2}$$

where f is the frequency in MHz and a is a coefficient with a value of 2.2.

The test voltage equation, (A.1) is applicable to impulses both with and without overshoot. For impulses without overshoot the applied voltage is a smooth curve and has the form of a base curve without any residual oscillations to process. Such curves are unaffected by the residual filter function and yield impulse parameters that are unaffected by that function. The procedures are therefore transparent to smooth curves and so it is not necessary to pre-sort impulse prior to parameter derivation.

Base K-Factor filter shown above may need to be adjusted for the type of insulation material being tested. The base curve to be used for a particular apparatus test may need to be developed by the appropriate apparatus committees.

Streamer Initiated Discharges

7.4.2 Voltage/time curves for impulses of constant prospective shape

The voltage/time curve for impulses of constant prospective shape is the curve relating the disruptive discharge voltage of a test object to the time to chopping, which may occur on the front, at the peak, or on the tail. The curve is obtained by applying impulse voltages of constant shape but with different peak values, as shown in figure 9.

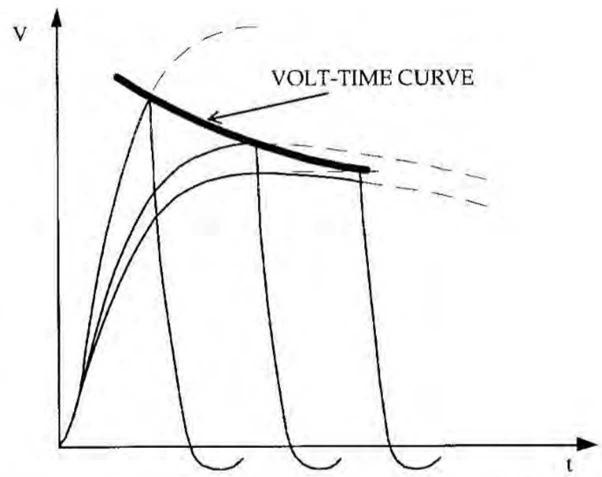


Figure 9—Voltage/time curve for impulses of constant prospective shape

There has been a good bit of discussion regarding the effect of overshoot on the streamer initiated discharges on non-uniform gaps. Peaks have more influence on rapid breakdowns. Tails of the waves have more influence on slower breakdowns.

Overshoot Tolerance Limits

IEC

If not otherwise specified by the relevant Technical Committee, the relative overshoot magnitude shall not exceed 10 %.

For certain test circuits and test objects, standard wave shapes within the stated tolerances may be impossible to realize. In such cases extension of front time T1 or overshoot may be necessary. Guidance for such cases should be given by the relevant Technical Committee.

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In most cases overshoot or oscillations can be limited to 5% of the peak voltage. In some cases higher limits may have to be tolerated, but in all cases the overshoot or oscillation shall be limited to 10%.

It is recommended that the overshoot during impulse tests be less than 5%. However, due to the addition of the test voltage factor procedure (see Annex A) for overshoot measurement, the overshoot limit may be increased to 10% to allow waveforms accepted by the historical "smooth curve" overshoot method. The test voltage factor method allows for increased accuracy in reading waveforms with overshoot. It should be noted that in some cases this increased tolerance may result in over or under stressing of the apparatus under test. Advice on overshoot tolerances for particular apparatus should be addressed by the relevant apparatus standard.

Conclusions

1. *New K-Factor Method makes a smooth transition through the 500kHz / 1.0μs transitions caused by the IEEE 4-1995 definitions.*
2. *The K-Factor method reads parameters from the well-defined Test Voltage Curve and is less influenced by high frequency noise on the record curve.*
3. *K-Factor filters are needed for various insulation materials to be tested if the relevant apparatus committees choose to generate curves for particular insulation systems.*
4. *Exact K-Factor curves for complex insulation materials such as transformers may be difficult to develop. It may be better to use the base K-Factor curve to best match what has historically been used.*

Questions ?

K Factor/Manual Waveform Calculation Methods

Arthur Molden
AMEESCO CONSULTING
MBILM LLC

2014 IEEE PES Panel Session
Discussion on IEEE Std.4-2013: High-Voltage Testing Techniques

K Factor/Manual Waveform Calculation Methods

Why use a manual method?

The alternatives are to develop ones own software or purchase a proprietary impulse recording system.

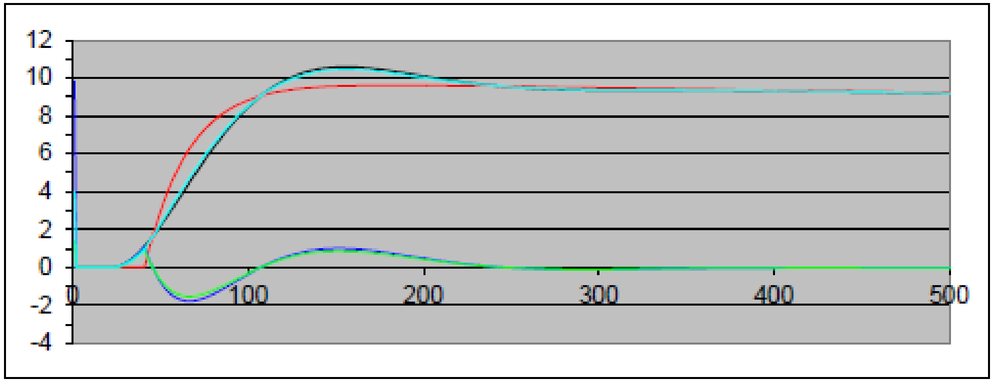
- Software development would be quite expensive to undertake
- Proprietary impulse recording systems are quite expensive to purchase
- The manual method requires only a pencil and paper
- However, the pencil and paper method does not produce very reliable results

A more reliable way to implement the manual method would be to use a spreadsheet program. In such a program an impulse record in csv format can be imported and graphed (or charted) and the spreadsheet functions manipulated to perform k-factor parameter extraction. This implementation of the manual method improves on the quality and repeatability of the result.

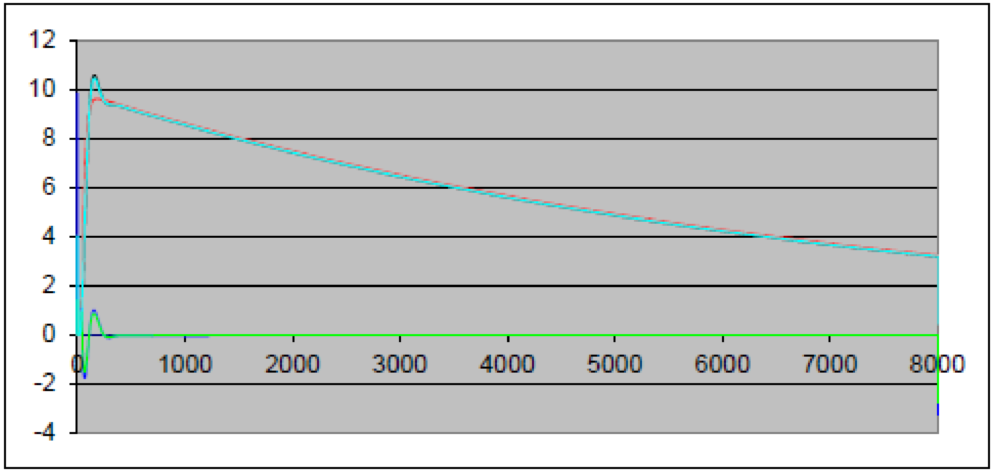
K Factor/Manual Waveform Calculation Methods

Imported CSV File		X Shift	Std4 A	Std4 alpha	Std4 beta
Data Point Count=8008			9.84	1.4	4
t	**V(t)**	**Vm(t)**	**R(t)**	**Rf(t)**	**Vt(t)**
0.00E+00	-1.350E-13	0.00	-1.35E-13	-1.17E-13	-1.17E-13
9.99E-09	6.182E-10	0.00	6.18E-10	5.34E-10	5.34E-10
2.00E-08	2.185E-09	0.00	2.18E-09	1.89E-09	1.89E-09
3.00E-08	4.511E-09	0.00	4.51E-09	3.90E-09	3.90E-09
4.00E-08	7.521E-09	0.00	7.52E-09	6.49E-09	6.49E-09
5.00E-08	1.110E-08	0.00	1.11E-08	9.59E-09	9.59E-09
5.99E-08	1.516E-08	0.00	1.52E-08	1.31E-08	1.31E-08
6.99E-08	1.962E-08	0.00	1.96E-08	1.69E-08	1.69E-08
7.99E-08	2.441E-08	0.00	2.44E-08	2.11E-08	2.11E-08
8.99E-08	2.948E-08	0.00	2.95E-08	2.55E-08	2.55E-08
9.99E-08	3.477E-08	0.00	3.48E-08	3.00E-08	3.00E-08
1.10E-07	4.025E-08	0.00	4.03E-08	3.48E-08	3.48E-08
1.20E-07	4.589E-08	0.00	4.59E-08	3.96E-08	3.96E-08
1.30E-07	5.165E-08	0.00	5.16E-08	4.46E-08	4.46E-08
1.40E-07	5.751E-08	0.00	5.75E-08	4.97E-08	4.97E-08
1.50E-07	6.345E-08	0.00	6.35E-08	5.48E-08	5.48E-08
1.60E-07	6.945E-08	0.00	6.95E-08	6.00E-08	6.00E-08
1.70E-07	7.551E-08	0.00	7.55E-08	6.52E-08	6.52E-08
1.80E-07	8.159E-08	0.00	8.16E-08	7.05E-08	7.05E-08
1.90E-07	8.771E-08	0.00	8.77E-08	7.57E-08	7.57E-08
2.00E-07	1.510E-03	0.00	1.51E-03	1.30E-03	1.30E-03
2.10E-07	8.020E-03	0.00	8.02E-03	6.93E-03	6.93E-03
2.20E-07	2.193E-02	0.00	2.19E-02	1.89E-02	1.89E-02
2.30E-07	4.351E-02	0.00	4.35E-02	3.76E-02	3.76E-02
2.40E-07	7.248E-02	0.00	7.25E-02	6.26E-02	6.26E-02
2.50E-07	1.086E-01	0.00	1.09E-01	9.37E-02	9.37E-02
2.60E-07	1.515E-01	0.00	1.51E-01	1.31E-01	1.31E-01
2.70E-07	2.010E-01	0.00	2.01E-01	1.74E-01	1.74E-01
2.80E-07	2.567E-01	0.00	2.57E-01	2.22E-01	2.22E-01
2.90E-07	3.186E-01	0.00	3.19E-01	2.75E-01	2.75E-01
3.00E-07	3.861E-01	0.00	3.86E-01	3.33E-01	3.33E-01
3.10E-07	4.592E-01	0.00	4.59E-01	3.97E-01	3.97E-01
3.20E-07	5.376E-01	0.00	5.38E-01	4.64E-01	4.64E-01
3.30E-07	6.210E-01	0.00	6.21E-01	5.36E-01	5.36E-01
3.40E-07	7.091E-01	0.00	7.09E-01	6.12E-01	6.12E-01
3.50E-07	8.018E-01	0.00	8.02E-01	6.92E-01	6.92E-01
3.60E-07	8.988E-01	0.00	8.99E-01	7.76E-01	7.76E-01
3.70E-07	9.998E-01	0.00	1.00E+00	8.63E-01	8.63E-01
3.80E-07	1.105E+00	0.00	1.10E+00	9.54E-01	9.54E-01
3.90E-07	1.213E+00	0.38	8.29E-01	7.16E-01	1.10E+00
4.00E-07	1.325E+00	0.75	5.72E-01	4.94E-01	1.25E+00
4.10E-07	1.440E+00	1.11	3.33E-01	2.87E-01	1.39E+00
4.20E-07	1.558E+00	1.45	1.10E-01	9.50E-02	1.54E+00
4.30E-07	1.679E+00	1.78	-9.62E-02	-8.31E-02	1.69E+00
4.40E-07	1.803E+00	2.09	-2.87E-01	-2.48E-01	1.84E+00
4.50E-07	1.928E+00	2.39	-4.63E-01	-4.00E-01	1.99E+00
4.60E-07	2.056E+00	2.68	-6.25E-01	-5.40E-01	2.14E+00
4.70E-07	2.187E+00	2.96	-7.74E-01	-6.68E-01	2.29E+00
4.80E-07	2.318E+00	3.23	-9.10E-01	-7.85E-01	2.44E+00
4.90E-07	2.452E+00	3.49	-1.03E+00	-8.92E-01	2.59E+00
5.00E-07	2.587E+00	3.73	-1.15E+00	-9.89E-01	2.74E+00
5.10E-07	2.723E+00	3.97	-1.25E+00	-1.08E+00	2.89E+00
5.20E-07	2.861E+00	4.20	-1.34E+00	-1.15E+00	3.04E+00
5.30E-07	3.000E+00	4.42	-1.42E+00	-1.22E+00	3.19E+00

Ve	Vmp	Vt(t)	Beta (MH	Beta (%)	k(f)	Beta*k(f	Vt	T1	T2	T1_Calc
10.57	9.61	10.44	0.268	9.06	0.8635	7.8258	10.44	0.97	45.3	0.95



Source	Vt (volts	T1 (us)	Beta (%)	T2 (us)
Art M	10.44	0.97	9.1	45.3
Jim Mc	10.31	0.92	9.0	44.9



IEEE Standard 4

Resistivity vs. Conductivity During Wet Withstand Tests

Jeffrey A. Britton
Chief Engineer, Phenix Technologies Inc.
Chair, IEEE High Voltage Testing Techniques Subcommittee
Fall 2016 IEEE Switchgear Committee Meeting
October 9 – 13, Pittsburgh, PA

IEEE PES Power & Energy Society

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Questions raised by Bob Behl from IEEE Switchgear Committee with reference to IEEE Std. 4-2013, Clause 11.2 “Wet Tests”, Table 5

Table 5—Precipitation conditions (standard and conventional procedures)

Procedure	Precipitation rate (mm/min)			Collected water parameters		Wet withstand test duration(s)
	Vertical component	Horizontal component	Limits for any individual measurement	Temperature (°C)	Resistivity ohm-m [µS/cm]	
Standard test procedure	1.0 to 2.0	1.0 to 2.0	± 0.5 from average	Ambient ± 15	100 ± 15	60
Previous European practice	3 ± 0.3	–	3 ± 0.75	Ambient ± 15	100 ± 10	60
Previous practice in USA	5 ± 0.5	–	5 ± 1.25	Ambient ± 15	178 ± 27	10

Units of Resistivity Versus Conductivity

- IEEE practice has been to specify the Resistivity of the water [ohm-m], whereas IEC practice has been to specify Conductivity [μS/cm]
- It was noted that the units of Resistivity under "Collected Water Parameters" <u>incorrectly</u> specify both [ohm-m] and [μS/cm]
- A corrigendum was therefore requested to correct this, as a minimum required action, essentially reverting to the IEEE Std.4-1995 version of the table

IEEE Standard 4-2013 - Table 5
If corrected to remove [μS/cm]

Table 5—Precipitation conditions (standard and conventional procedures)

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Standard test procedure	1.0 to 2.0	1.0 to 2.0	± 0.5 from average	Ambient ± 15	100 ± 15	60
Previous European practice	3 ± 0.3	–	3 ± 0.75	Ambient ± 15	100 ± 10	60
Previous practice in USA	5 ± 0.5	–	5 ± 1.25	Ambient ± 15	178 ± 27	10

IEEE versus IEC Practice

- IEC 60060-1 does specify a water conductivity of 100 µS/cm, which coincidentally happens to be equivalent to 100 ohm-m resistivity
- Although specified in different units, both the IEEE and IEC procedures specify ±15% limits on their respective nominal values
- Unfortunately, the ±15% tolerance limits do not align with the different units. ±15 µS/cm actually equates to -13.04 to +17.65 ohm-m!
- *It was therefore proposed by Mr. Behl and accepted by the HVTT Subcommittee to revise Standard 4 to specify units of conductivity in the next revision, for better alignment with IEC*

Previous Practice in USA

Table 5—Precipitation conditions (standard and conventional procedures)

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Previous Practice in USA

- It was noted in the communication received from Mr. Behl that the old method of using 178 ohm-m for a 10 second wet withstand test does not make physical sense when compared with using 100 ohm-m (lower resistivity) for a 60 second (longer duration) test
- *Logically, a shorter duration test should have to be performed with water having a lower resistivity (or higher conductivity)*
- It was suggested that a 10 second test using water having a <u>conductivity</u> of 178 μS/cm would therefore make physical sense
- Going back to Std. 4-1968, where the electrical parameters of the water were first specified, I was unable to find any inconsistency in the resistivity numbers. It is therefore believed that the 178 ohm-m test is simply a correct reporting of the historical practice

Contributions to Uncertainty of Measurement

Johannes Rickmann
Phenix Technologies

2014 IEEE PES Panel Session

Discussions on IEEE Std.4-2013: High-Voltage Testing Techniques

IEEE PES Power & Energy Society

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IEEE STD 4 1995 vs 2013

- IEEE STD 4-1995: Error
- IEEE STD 4-2013: Uncertainty

- Error: The difference between the measured value of a quantity and the true value of that quantity under specified conditions
- Accuracy: The degree of agreement between a measured value and the true value
- Uncertainty: An estimated limit based on an evaluation of the various sources of error
  - Measure of the dispersion of measuring results, or gives the range within which the measurement result confidently believed to lie.
  - Measure of quality of a calibration
  - Allows comparison of results with other laboratories

Terms used

Standard Uncertainty: Uncertainty of the result of a measurement expressed as a standard deviation

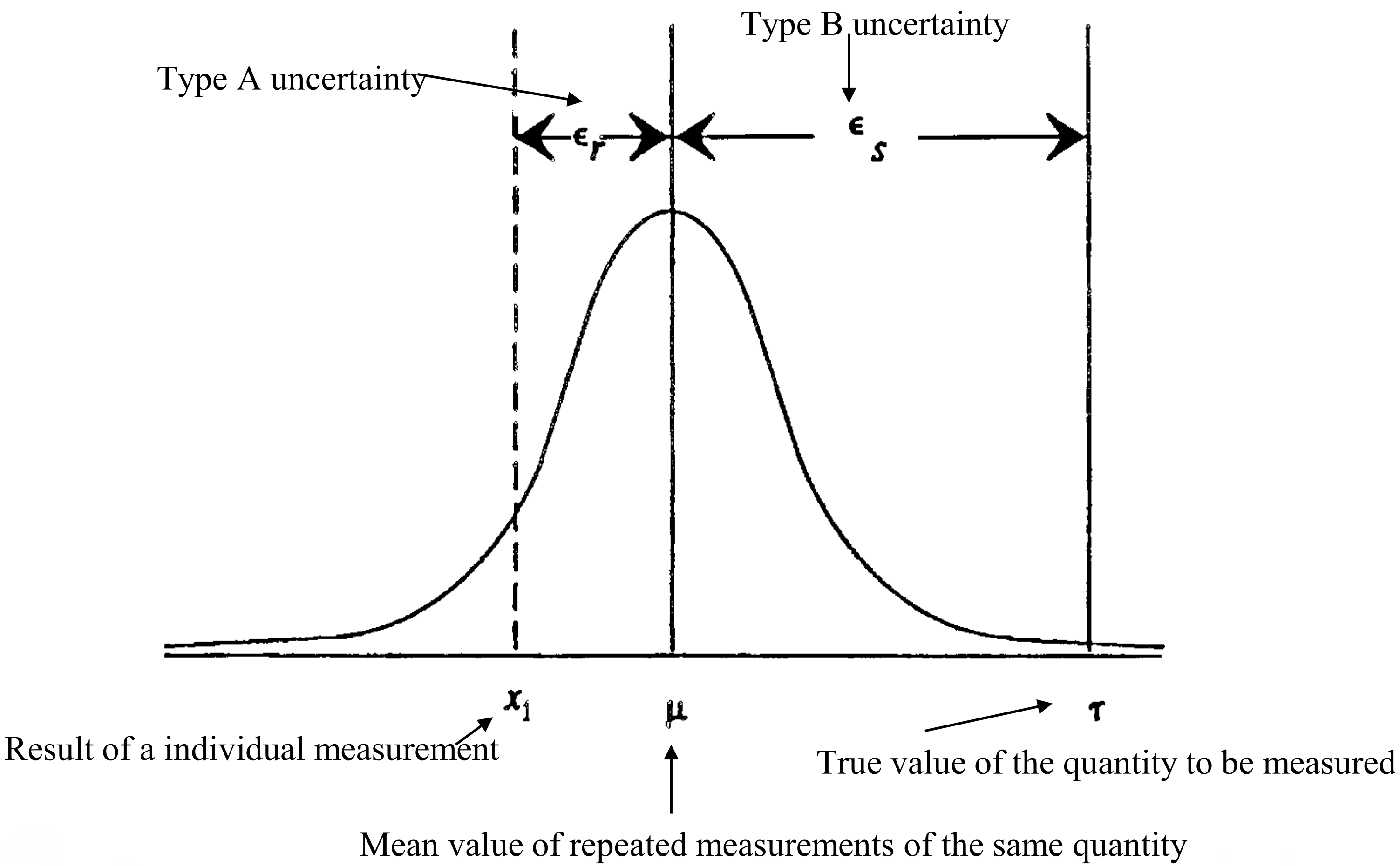
- **Type A uncertainty**: Evaluated by the statistical analysis of series of measurements

- **Type B uncertainty**: Evaluated by means other than statistical analysis of series of measurements

- **Combined Standard Uncertainty**: Combination of the individual standard uncertainties, whether arising from Type A or Type B evaluations, using the square root of the sum of the squares of each contribution.

- **Expanded Uncertainty**: Quantity defining an interval about the result of a measurement result within which the value of the measurand is confidently believed to lie. All Type A and Type B contributions to the measurement are included.

Uncertainties



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Type A Unce rtainty

If the n independent observation $X_{i,k}$ of the input quantity X_i are obtained under the same measurement conditions, the input estimate x_i is usually the sample mean

$$\bar{X}_i = \frac{1}{n}\sum_{k=1}^{n} X_{i,k}$$

with the standard deviation $u(x_i)$ of the uncorrected mean as the standard uncertainty $s(\bar{X}_i)$ associated with the observations:

$$u(x_i) = s(\bar{X}_i) = \sqrt{\frac{1}{n(n-1)}\sum_{k=1}^{n}\left(X_{i,k} - \bar{X}_i\right)^2}$$

$$\boxed{u(x_i) = s(\bar{X}_i) = \sqrt{\frac{1}{(n-1)}\sum_{k=1}^{n}\left(X_{i,k} - \bar{X}_i\right)^2}}$$

n is the number of measurements

$X_{i,k}$ are the measured values for k=1 to n

! Calculated by most scientific calculators and Excel

Type A Unce rtainty

Typical sources of Type A uncertainty:

- random fluctuation
- changes in the output of a calibrator or other voltage source (grid fluctuation)
- temperature of a calibration standard
- fluctuation of the least significant digits of digital measuring instrument
- Uncertainty in discrimination
- Setting a pointer to a mark on a scale
- Interpolation between marked points on a scale

Type B Unce rtainty

A Type B evaluation of standard uncertainty is usually based on scientific judgment using all the relevant information available, which may include:

- previous measurement data
- effects of environmental conditions, temperature different to temperature of calibration
- manufacturer’s specifications like resolution
- data provided in calibration and other reports
- uncertainties assigned to reference data taken from handbooks
- errors in graduation of scale
- Lack of stability, i.e. drift

Corrections for all known contributions to the calibration or measurement result and their uncertainties need to be applied to the test result, like the scale factor of a divider, and it’s uncertainty analysis.

Type B Unce rtainty

$$u_x = \frac{1}{\sqrt{3}} \max_{i=1}^{5} \left| \frac{R_i}{R_m} - 1 \right|$$

Linearity test: provides extension of the validity of the scale factor to full range of use

R_i: individual ratios
R_m: mean value of the five ratios

Dynamic behavior: maximum deviation of the scale factor over the frequency range

F_i: individual ratios
F_m: mean ratio for parameters within the range of use

Short term stability test: provides information on change of scale factor over a short time period of usage

F_{before}: scale factors before short term stability test
F_{after}: scale factors after short term stability test

Type B Unce rtainty

$$u_x = \frac{1}{\sqrt{3}} \max_{i=1}^{5} \left| \frac{R_i}{R_m} - 1 \right|$$

Long term stability: provides information about drift of scale factor

F_{next}: current scale factor
$F_{previous}$: scale factor of previous calibration

Ambient temperature effect: provides information temperature drift of scale factor

F_T: scale factor at considered temperature
F_{cal}: scale factor at the calibration temperature

Proximity effect: provides information on influence of other objects on scale

F_{max}: scale factors at maximum distance to other objects
F_{min}: scale factors at minimum distance to other objects

Combine d Standa rd Unce rtainty

- Individual sources of uncertainty, whether arising from a Type A or Type B evaluation, are combined in a single statement of combined standard uncertainty to obtain the estimated standard deviation of the result.

- The usual method for obtaining the combined standard uncertainty is the root-sum-of-squares (square root of the sum of the squares).

- If the Type B uncertainties are eliminated by calibration, i.e. by applying corrections to compensate for each recognized systematic effect, only the Type A uncertainties remain.

- In the case where not all uncertainty contributions derived from a Type B evaluation can be corrected for and have therefore to be considered, the combined standard uncertainty can be calculated as follows:

$$u_c(y) = \sqrt{\sum_1^n u_i^2(y)} = \sqrt{\sum_1^n c_i^2 u^2(x_i)}$$

$u(x_i)$ = standard uncertainty of input quantity x_i
c_i = sensitivity coefficient of input quantity xi
$u(y)$ = standard uncertainty in the unit of measurand y obtained from the standard uncertainty of the input quantity x_i
n= total number of input quantities

Expa nded unce rtainty

- To provide a level of confidence about the measurement result within which the value of the measurand is confidently believed to lie in, the combined standard uncertainty is multiplied by a coverage factor k, chosen on the desired level of confidence:

  $U = k \times u_c(y)$

  - Assuming a normal distribution a value for k of :
-
  - 1 provides a level of confidence of approximately 68%,
  - 2 provides a level of confidence of approximately 95%
  - 3 provides a level of confidence of approximately 99%.

An Example of Uncertainty Calculation for an AC RMS Measurement System

Uncertainty Components	Units	Distribution Type	Evaluation Type	Semi-Range, a or Range 2a	Divisor, d	Deg. of freedom, Vi	Std. Uncertainty Ui	Sensitivity factor, Ci	CiUi	(CiUi)2	(CiUi)4/Vi
Ref. VT uncertainty	% rdg	normal	B	0.002	2	60.460178	0.001	1	0.001	0.000001	1.65398E-14
Unc. due to VT Temp coefficient uncertainty	% rdg	rect	B	0.00023	1.732	5	0.000132794	1	0.000133	1.76E-08	6.21942E-17
Unc. due to freq setting uncertainty or hamonics	% rdg	rect	B	0.0009	1.732	5	0.00051963	1	0.00052	2.7E-07	1.45817E-14
Ref. VT calibration drift since last calibration	% rdg	rect	B	0.0005	1.732	2	0.000288684	1	0.000289	8.33E-08	3.47263E-15
max correct. of voltmeter for ref VT in determining ref HV VM ratio	% rdg	rect	B	0.01	1.732	6	0.005773672	1	0.005774	3.33E-05	1.85207E-10
max correct. of voltmeter for ref HV VM in ratio determination	% rdg	rect	B	0.01	1.732	6	0.005773672	1	0.005774	3.33E-05	1.85207E-10
ESDM of Ref HV VM ratio determination	% rdg	normal	A	0.000618147	1	4	0.000618147	1	0.000618	3.82E-07	3.65012E-14
Voltage coeff. of Ref. HV VM	% rdg	rect	B	0.001	1.732	5	0.000577367	1	0.000577	3.33E-07	2.22248E-14
Drift/stability of Ref. cap. divider (before and after test of DUT)	% rdg	rect	B	0.005	1.7320508	4	0.002886751	1	0.002887	8.33E-06	1.73611E-11
Unc.. of voltmeter for Ref VT for . Ref HV VM ratio	% rdg	normal	B	0.008	2	60.460178	0.004	1	0.004	0.000016	4.23419E-12
Ref. voltmeter max AC rms correct. for cal of DUT	% rdg	rect	B	0.01	1.732	5	0.005773672	1	0.005774	3.33E-05	2.22248E-10
Test meter least resolution (effective resolution)	% rdg	rect	B	0.074970012	1.732	10	0.043285226	1	0.043285	0.001874	3.51042E-07
Effect of waveform distortion	% rdg	rect	B	0.05	1.732	5	0.02886836	1	0.028868	0.000833	1.38905E-07
Ref. voltmeter AC rms uncerainty in DUT error	% rdg	rect	B	0.05	2	60.460178	0.025	1	0.025	0.000625	6.46086E-09
ESDM of DUT error	% rdg	normal	A	0.024572837	1	4	0.024572837	1	0.024573	0.000604	9.1151E-08
Rounding of reported results	% rdg	rect	B	0.05	1.732	inf	0.02886836	1	0.028868	0.000833	0
Rounding of uncertainty	% rdg	rect	B	0.05	1.732	inf	0.02886836	1	0.028868	0.000833	0
Rounding of Coverage Factor	% rdg	rect	B	n/a	n/a	inf	0.002187447	1	0.002187	4.78E-06	0
					Sums of last three Columns				0.208995	0.005729	5.88173E-07
					Combined Standard Uncertainty					0.07569	
					Effective number of degrees of freedom					55.80249	
					Coverage factor (k)					2.003415	
					Expanded uncertainty (U, % reading)					0.151639	