Past, present and future of IEC and IEEE high-voltage and high current testing standards

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Introduction

Recently, IEC and IEEE have published a number of revised and new standards for high-voltage and high-current testing. These standards include IEC 60060 1:2010, IEC 60060 2:2010, IEC 61083 2:2013, IEC 62475:2010 and IEEE Std.4 2013. Significant changes and additions have been introduced to these revised and new standards. Many members of CIGRE WG D1.35 were involved in the revision and development of these standards as members of IEC TC 42 and IEEE PSIM Subcommittee HVTT, particularly in the development of the new techniques and new procedures that are now adopted in the standards. This Guide has been written by members of CIGRE WG D1.35 to give high-voltage test engineers a broader knowledge of how to apply the latest high-voltage and high-current testing standards.

In the preparation of this Guide, the contributors have tried to point out areas of difficulty in interpretation of certain clauses of these standards that should be considered for future revisions to make HV testing standards more clear and user friendly. This Guide first presents a brief account of the history of these standards with the aim to allow readers to gain a better appreciation of the technical background. The following sections summarize the major changes made to the standards in their latest revisions to provide a general picture of the revisions. The individual sections provide detailed information on the important requirements and procedures that have now been incorporated into the standards. They also describe some of the specific technical background with a list of published references. Finally, some discussion is given on the practical implications of these changes. Practical examples are provided to illustrate some of the new techniques and new procedures. The guide also lists areas of possible improvements to the standards for future revisions.

History of high-voltage and high-current tests

The history of high-voltage standardization has been reviewed along with test and measurement techniques that provided the technical basis for the standards. The following areas of standardization have been reviewed:

- DC high-voltage tests and measurements and DC high-voltage supplies,
- AC test sources and measurement systems,
- Impulse voltage tests and measurements, including early history of definitions of impulse waveforms, definitions of impulse peak voltage and the history of introduction of the test voltage function (k-factor function),
- Use of sphere-gaps as measurement devices
- Introduction of the concept of reference measuring systems, and its significance, and
- The history of developing IEEE Standard 4, in parallel with the corresponding IEC standards.

Outline of major changes made in recent editions of the standards

The major changes of definitions and requirements made in the standards are listed with the aim to give an overall picture of the revised and new standards. These include:

IEC 60060-1:2010

- The definitions for basic lightning impulse voltage parameters, U_p, T_1 and T_2, have not changed. The test voltage function (sometimes known as the k-factor) as described in the literature published in the period leading up to the approval of the standard, has been introduced •••

to enable more accurate and consistent determination of the test voltage and time parameters of lightning impulses with superimposed oscillations of any frequency content. A number of new definitions related to this new procedure have been added, e.g., test voltage function, extreme value, relative overshoot and average rate of rise.

- The peak value of an alternating voltage is now defined as half of the peak-to-peak voltage. The earlier definition, “maximum value”, could lead to misinterpretation for cases where even harmonics of the test source are present. This harmonic distortion may lead to different positive and negative peak values. A maximum value of 2 % is allowed for the difference between positive and negative peak values. The test voltage value is the peak value divided by √2.
- No changes in the definition of switching impulse voltage parameters have been introduced in IEC 60060-1:2013, and the previous definition of time to peak has been retained, i.e. “time interval from the true origin to the time of maximum value of a switching-impulse voltage”.
- IEEE Std 4 2013 and IEC 60060-1:2010 differ slightly on evaluation of switching impulse. For the case that the impulse is a standard switching impulse, i.e. the time to peak is 250 μs ± 50 μs, IEC identifies a simplified method using a mathematical formula adopted from IEEE Std 4-1995. This method is also given by IEEE Std 4 2013, but is stated as the definition.
- For non-standard switching impulses, IEC clearly states that other methods of evaluation should be used, e.g. “For non-standard impulses, the time to peak can be determined by various methods of digital curve fitting dependent on the actual shape”. Other changes of content include:
- Formulae have been introduced for the parameters of the atmospheric correction factor to make the computer calculation of the correction factor feasible.
- The iterative procedure for calculating the atmospheric correction factor of a test voltage is introduced, and is intended for withstand tests. This procedure is intended to reduce the error of the correction factor due to the error in the estimated U_{50} (50 % breakdown voltage) that is needed for the calculation. The error becomes significant when the correction is significant.
- Only one wet test procedure has been retained.
- Test procedures for combined and composite voltages have been elaborated.
- AC and DC Artificial pollution test procedure references are removed as they are described in IEC 60507.

IEC 60060-1:2010

- Estimation of common components of uncertainties in high-voltage measurements are now specified in detail
- Requirements on voltage linearity tests are more clearly specified.
- New requirements on dynamic performance, i.e., frequency response of power frequency AC voltage measurement systems, have been added.
- Step response parameter evaluation methods for characterization of voltage dividers and current shunts have been moved into an informative annex, with a number of definitions related to the step response measurement having been revised.
- An annex on evaluation of the dynamic performance of impulse measurement system by the convolution method has been added.
- The Standard Sphere-Gap is no longer accepted as a Reference Measuring Device but can still be used for Performance Checks.
- Calibration procedure for DC-systems using a rod/rod gap is removed.
- Measurement of impulse currents has been transferred to a new standard IEC 62475:2010, High-current test techniques – Definitions and requirements for test currents and measuring systems.

IEC 62475:2010

- The current measurement part of this standard covers more applications than the obsolete 60060-2:1994, which covered only measurement of impulse current waves as used in arrestor testing.
- The new standard also covers requirements for testing with any type of high current as well as giving the requirements for a high-current measurement system.
- The types of high currents which have been added now include: steady-state direct current, steady-state alternating current, short-time direct current, short-time alternating current, and impulse currents.
- The standard also covers current measurement in high-voltage dielectric testing.
- The standard has adopted a similar structure to that of IEC60060-2:2010.
- Estimation of measurement uncertainties is specified similarly to IEC 60060-2:2010.

IEC 61083-2:2013

- IEC 61083 part 2 has been updated with a new Test Data Generator (TDG) to evaluate impulse measuring system software evaluation methods.
- The new version has more impulse voltage waveforms, and includes waves with different overshoot amplitudes and frequencies. Frequencies are selected to prove performance around the transition frequency of 500 kHz. The new TDG can help users prove that their software is making proper evaluations of the key parameters in a consistent and comparable way.
- Reference values of lightning impulse waveforms have also been revised according to the new definition of the impulse test voltage in IEC 60060-1:2010
- Waveforms of impulse currents are added to the TDG to represent a range of those used for arrestor testing that have been added over the last few years. More current waveforms, including lightning current impulses, are now included, in order to cover the range of current waveforms used in the new standard IEC 62475:2010.
- An annex on estimation of uncertainty contribution of software (waveform parameter calculation) has been added. •••

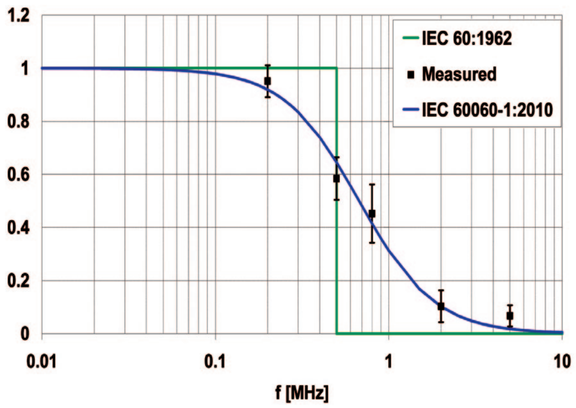

Figure 1 Amplitude calculation factor for a range of oscillation frequencies superimposed on a lightning impulse, together with the old and new test voltage functions.

IEEE Std 4-2013

- IEEE Std 4-2013 continues to cover both the requirements for testing and the requirements for measurement systems, which are covered separately by IEC 60060-1:2010 and IEC 60060 2:2010.
- Efforts have been made to harmonize IEEE Std 4-2013 with the two parts of IEC 60060, in terms of principles and fundamental requirements. Minor differences, however, still exist. A summary of the differences is given in the brochure.
- The new edition of IEEE Std 4 still contains a significant amount of tutorial information to give practical suggestions to the test engineer.

Important definitions and requirements

This chapter discusses important definitions and requirements that have either undergone significant changes or deserve close attentions of users for correct interpretation and better use of the standards.

Lightning impulse test voltage function

A test voltage function, now defined in IEC 60060-1:2010 and IEEE Std.4-2013, takes the following form:

$$k(f)=1/\left(1+2.2f^2\right),$$

which is shown by the blue line in Figure 1. This formula is used to calculate the effective peak voltage as a function of the frequency of the oscillation where f is the frequency in MHz. The introduction of this function removes the problems related to the stepwise change at 0.5 MHz in the previous edition of the standard and makes a smooth transition that has a mathematical definition of the function shown above. This newly defined function and the associate analysis procedure allows the determination of impulse parameters without subjective determination of the existence or characteristics of overshoot and its frequency. The new associated procedure in the standards is also more precisely specified in order to eliminate discrepancies of impulse parameters obtained by different software packages.

An integral part of requirements for impulse voltage tests in IEC 60060-1:2010 are the requirements for software specified in IEC 61083-2: 2013. The Test Data Generator (TDG) of IEC 61083-2: 2013 is a software package for generation of test data. The TDG produces digital records of a number of different impulse waveforms for testing an impulse measurement software package. IEC 61083 2:2010 specifies the reference values of test impulses generated from the TDG. The IEC 61083-2:2013 also provides error limits for acceptance of evaluation software for measuring different types of impulses.

Definitions of switching impulse

The definition of time to peak for switching impulse in IEC 60060-1: 2010 is “time interval from the true origin to the time of maximum value of a switching-impulse voltage”. It has been found that it is often difficult to determine this time to peak, Tp, from even from digital records of impulses with low uncertainty, due to the fact that the digitally recorded voltage values in the impulse peak region can be approximately equal for a long period of time, and many data points of the same amplitude will be found around the true peak value. To overcome the problem of calculating the Tp from digital records of the standard switching impulses, the empirical formula introduced in a previous edition of IEEE Std. 4 (retained in IEEE Std 4-2013), is now included in IEC 60060-1:2010 for evaluation of switching impulses that conform to the standard waveform.

The formula takes the following form:

$$T_p = KT_{AB} \qquad (1)$$

Where K is a dimensionless constant given by

$$K = 2.42 - 2.08 \times 10^{-3} T_{AB} + 1.51 \times 10^{-4}\, T_2$$

where T_{AB} and T_2 are in microseconds and $T_{AB} = t_{90} - t_{30}$, where t_{90} and t_{30} are the instants corresponding to voltage levels of 90 % and 30 % of peak voltage respectively, and the numerical constants 2.08 and 1.51 have dimension s^{-1}.

AC test voltage

The AC peak voltage is now defined in IEC 60060-1:2010 as the “average of the magnitudes of the positive and negative peak values, as opposed to, “the maximum value” in the 1989 edition.

The definition of peak voltage in IEEE Std 4-2013, remains the same as in its previous version, IEEE Std 4-1995, which is essentially identical to the corresponding definition in IEC 60060-1:1989.

The practical impact of the difference between IEC 60060-1:2010 and IEEE Std 4-2013 is insignificant in the vast majority of AC tests, where the AC voltage waveforms are symmetrical to the zero voltage level.

The requirement for the crest factor, which is defined as the ratio of the peak voltage to the rms value, remains the same for the new editions of both IEC 60060-1 and IEEE Std 4. The ratio between peak and rms should be within 5% of √2. •••

Atmospheric correction factor

A number of formulae have been introduced to replace the graphs for convenient implementation of computer calculation of atmospheric correction factor values. Changes have also been made to a few formulae. These charges were made in both IEC 60060-1 and IEEE Std.4.

Another important change is the introduction of the iterative procedure for determining the atmospheric correction factor for high-voltage withstand tests, where the 50 % probability breakdown voltage, U_{50}, has to be estimated. The use of this procedure reduces the error in the calculated correction factor caused by the inaccuracy of the U_{50} estimated by the method in the previous edition of the standard. This change only affects the values of the correction factor that significantly deviate from unity. For example, correction factors for tests performed at high altitudes, e.g., 1000 m above the sea level.

Requirements for measurement systems

Requirements for measurement systems are specified in IEC 60060-2:2010. The main structure of IEC 60060 2:2010 is similar to that of the previous edition IEC 60060 2:1994, although there have been significant additions of contents to some clauses, for example, the additional requirements in Clause 5 on estimation of measurement uncertainties.

IEC 60060-2: 2010 still retains the approach of calibration of a measuring system by calibrations of its components, with the requirements given in Clause 5.2.2. This approach is provided as the alternative method to the method of comparison of the complete measuring system with a Reference Measuring System, which is specified as the preferred method. When planning the calibrations and combining the results for the complete system, the interactions between the components and the influence of the transmission system (measurement cables), have to be considered to arrive at the correct values.

Measurement Uncertainty

The uncertainty calculation has been significantly revised in the latest edition of IEC 60060 2:2010. The reasons for this major revision are mainly two fold.

First, the revision is to provide testing personnel a simple and practical method of estimating measurement uncertainties that is consistent with ISO 98-3, Guide on Uncertainty of Measurement (ISO GUM). The method is intended to cover most common cases of high-voltage testing.

Second, the approach described in the previous edition of IEC 60060-2 (Appendix H in IEC 60060 2:1994) is no longer considered consistent with the current edition of ISO GUM.

In the 1994 edition of IEC 60060 2, specified fixed limits were given for individual uncertainty components, for example, a 1 % limit was specified for non-linearity of voltage measurement systems. Fixed numbers of repeated measurements were also specified. An example of this is that the number of repeated applied impulses during an impulse voltage calibration was specified to be at least 10. With the adoption of the ISO GUM approach in the 2010 edition, these limits are no longer specified as long as the total expanded uncertainty (expanded uncertainty is a defined term) is within the required limit. The removal of these limits becomes possible because of the adoption of the statistically more rigorous approach of the ISO GUM.

The 2010 edition of IEC 60060 2 also adopts an approach that is intended to provide practical help to users of the standard to better adapt to the new method of estimating measurement uncertainties. It lists typical sources of uncertainty contributions in measuring systems. It also added two completely new Annexes, Annex A and Annex B, dedicated to the topic of measurement uncertainty, providing an easy-to-understand explanation of the ISO GUM, and examples of uncertainty calculation.

The latest version IEEE standard 4 also gives detailed explanation and examples how the degrees of freedom and sensitivity coefficients are determined and used.

Conclusion

Significant improvements have been made in the recently revised IEC and IEEE standards for high-voltage and high-current tests and measurements. These improvements reflect the change of industry needs, such as the testing in the UHV range, as well as advancement of technologies, such as digital measurement techniques. A much higher degree of harmonization has also been achieved between the corresponding IEC and IEEE standards, which would no doubt bring benefits to the power industry. Revision of standards is a continuing process. A number of areas that future revision of the standards should consider have also been identified in this document. ■

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