Virtual instrument for estimation of HVAC and HVDC test parameters according to IEC 60060-1:2010

Yuri Reis Oliveira\textsuperscript{1,2}, Mário Thelio Silva\textsuperscript{2}, Carlos Roberto Hall Barbosa\textsuperscript{1}

\textsuperscript{1}PUC-Rio, R. Marquês de São Vicente, 225, Gávea, Brazil
\textsuperscript{2}Cepel, Av. Olinda, 3800, Adrianópolis, Brazil

hall@puc-rio.br

Abstract. High and ultra high voltage tests are commonly carried out to determine external and internal dielectric performances of electric power equipment. The standardization of these tests in different laboratories is obtained by following the standards with the requirements necessary to perform the tests. Among such requirements, the test voltage parameters must be measured within acceptable uncertainties. For a correct analysis of the test and presentation of the results it is necessary that the measuring system and the instrument used be able to estimate all parameters according to standard IEC 60060-1:2010, depending on each type of voltage and test, AC, DC or impulse. However, simpler conventional instruments, such as multimeters, are not capable of measuring and indicating all parameters required by current standards. Thus, dedicated instruments and software are needed, capable of performing the analysis of these parameters within the acceptable uncertainty limits. The use of software or measurement algorithms for voltage impulse testing is already described in IEC 61083-1 and -2 standards. Specifically, part 2 presents the reference waveforms used for the validation of the software used in the tests. Similarly, IEC 61083-4 is being developed for high voltage AC and DC tests, with standard waveforms for validation of the measurement software. The objective of this work is presenting the HVAT AC-DC virtual instrument developed in LabVIEW environment, capable of estimating the required AC and DC test parameters of the ABNT NBR IEC 60060-1:2013 standard and analyzing the robustness of such a virtual instrument through low and high voltage tests.

1. Introduction

Currently, electrical tests in HVAC and HVDC are performed for the purpose of testing the dielectric strength or determining the voltage withstand of high voltage equipment and must be performed in accordance with the specific standard \cite{1}, but their measurement systems and software should be evaluated in accordance with standards \cite{2} and \cite{3}, respectively. IEC 60060-1:2010 \cite{1} describes the requirements of high voltage electrical tests, as well as the characterization parameters of the voltage waveforms in direct current, alternating current and voltage pulses. IEC 60060-2-2010 \cite{2} describes the calibration procedures and the requirements for a measurement system, while IEC 61083-4 \cite{3} defines the software validation method used in tests with alternating current and/or continuous current. For validation of the algorithm, the standard includes a digital data generator called TDG (Test Data Generator) containing standard waveforms that must be processed by the measurement algorithm and the reference values of the generated digital data. This paper discusses the development of the algorithm for the measurement of the AC and DC voltage parameters related to the high voltage tests.
2. Test parameters in High Voltage

The HV tests shall have all parameters monitored during the test as required and defined in the test procedures described in standard [1]. These parameters shall be monitored by means of measuring systems conforming to standard [2] which establishes the requirements of dynamic behavior and appropriate levels of uncertainty. The monitoring of such parameters is of fundamental importance for the analysis of possible faults in the equipment under test, which may occur during the test.

2.1. HVAC test parameters

The previous version of IEC 60060-1 only recommended the RMS (root mean square) of the test voltage signal and therefore the test voltage was evaluated only quantitatively. However, in the current review, a qualitative evaluation was included and thus the test voltage waveform was evaluated, requiring sinusoidal voltage with distortion of only 5% and a difference between the positive and negative peak values less than 2%, that is, an offset that is so small that it can be considered negligible. Therefore, the parameters that must be monitored during the test are:

- RMS value, according to equation (1);
- Crest value, according to equation (2);
- Test voltage, according to equation (3);
- Total Harmonic Distortion (THD), according to equation (4);
- Crest factor, according to equation (5); and
- Frequency.

\[
V_{\text{rms}} = \frac{1}{T} \int_0^T v(t)^2 \, dt \quad (1)
\]

\[
V_{\text{crest}} = \frac{V_{\text{max}} + |V_{\text{min}}|}{2} \quad (2)
\]

\[
V_p = \frac{V_{\text{crest}}}{\sqrt{2}} \quad (3)
\]

\[
THD = \frac{1}{V_{1\text{max}}} \sum_{n=2}^m V_{n\text{max}}^2 \quad (4)
\]

\[
1,344 \leq \frac{V_{\text{crest}}}{V_{\text{rms}}} \leq 1,485 \quad (5)
\]

A better visualization of the parameters of the alternating voltage can be seen in Figure 1.

![Figure 1- Voltage signal parameters for testing in HVAC.](image-url)
The evaluation of THD waveform distortion is not mandatory, as there are no studies that indicate acceptable limits for this parameter. Therefore, the only parameter that evaluates the waveform is the crest factor, described as the ratio between crest value and RMS value. The acceptable limits for this factor are $\sqrt{2} \pm 5\%$, according to equation (5). However, instruments that are currently used in measurement systems, such as conventional bench multimeters, cannot measure all the parameters described in standard [1], so the use of dedicated software for HVAC testing is the most economical alternative to replace multimeters [4].

2.2. HVDC test parameters

The requirements of the test voltage in HVDC, according to standard [1], shall be analyzed and monitored during the tests. Therefore, if the test equipment does not meet the expectations, the laboratory will be backed up by this data to provide the diagnosis related to the test. According to standard [1], the following parameters must be analyzed:

- Test voltage - Arithmetic mean value, according to equation (6);
- Ripple amplitude - Half of the difference between the maximum and minimum values of the test voltage, according to equation (7).
- Ripple factor – Ratio between the ripple amplitude and the value of the test voltage (equation 8).

\[
V_m = \frac{1}{T} \int_{t_0}^{t_0+T} V(t) \, dt \tag{6}
\]
\[
\Delta \delta = \frac{V_{\text{max}} - V_{\text{min}}}{2} \tag{7}
\]
\[
\delta = \left( \frac{V_{\text{max}} - V_{\text{min}}}{2 \cdot V_m} \right) \cdot 100 \tag{8}
\]

These parameters are shown more clearly by means of Figure 2.

![Figure 2 - Voltage signal parameters for HVDC tests, in red.](image)

However, many laboratories do not monitor the ripple amplitude and ripple factor during the tests, due to the need for instruments that have the capacity to indicate the value of the test voltage and the value of the ripple amplitude. The ripple factor is the parameter of great importance for the qualitative evaluation of the DC voltage, and must be kept within the range of $\pm 3\%$. According to [5, 6], in some tests in which the DC voltage has a high ripple factor, partial discharges occurs at lower than normal voltage levels due to the high value reached by $V_{\text{max}}$, which instantly causes dielectric rupture.
2.3. IEC 61083-4 Standard Draft
In 2009, the IEC TC 42 technical committee met to initiate the design of standard IEC 61083-4 [3], which establishes and describes the software validation method dedicated to the measurement of voltage and current test parameters. This standard is applied in the evaluation of the quality of measurement software dedicated to HVAC and HVDC testing, and it provides a TDG (Test data generator) software with digital data of standardized waveforms. These standardized waveforms are used for software validation because they emulate scanned data from data loggers, typically waveforms with 8-bit vertical resolution and fixed sampling intervals of 20 $\mu$s [4] [7].

The validation of the software is done by processing standard waveforms included in standard [3], which are used as inputs, comparing the result of this processing, that is, the output data, to the reference values, and must be within the acceptance range proposed for each parameter. It should be noted that the standard IEC 61083-4 is still a draft, expected to be published in 2020.

3. Virtual instrument HVAT-AC DC
The HVAT AC-DC (High Voltage Analysis Tests) system (interface shown in figure 3) is a dedicated application, developed in G language of Labview software. The programming routines in LabVIEW are called virtual instruments (VIs) and their subroutines are called subVis, so in this work such terms will be used.

![Figure 3 – Analysis interface](image)

The measurement algorithm was divided into the following subroutines: Data input, Preprocessing, Data processing and Parameter estimation. Figure 4 shows the general flow diagram of the HVAT-AC DC system.

![Figure 4- General flowchart of the measurement algorithm.](image)

The data input subroutine controls the data recording and digitizing instrument (Tektronix TDS oscilloscopes of the 7000 family). The pre-processing module, aiming at reducing the noise level for a more accurate estimate, used the Moving Average and Savitzky-Golay filters [8] [9]. The methods chosen to compose the HVAT-AC DC system were selected based on the tests using the TDG and low voltage signals. In Table 1, all Vis tested can be viewed.
Table 1 – VIs selected for the development of the algorithm and the respective estimated parameters.

| VIs                              | Parameters          |
|----------------------------------|---------------------|
|                                  | Test Voltage | RMS Voltage | Medium Voltage | THD | Vmax and Vmin | Ripple Factor | Ripple Amp | Frequency |
| Amplitude And L.                 | X           | X           |                |     |               |              |            |           |
| Statistics                       | X           | X           |                |     |               |              |            |           |
| Cycle Average And RMS            | X           | X           |                |     |               |              |            |           |
| Basic Average DC-RMS             | X           | X           |                |     |               |              |            |           |
| RMS*                             | X           | X           |                |     |               |              |            |           |
| AC & DC Estimator                | X           | X           |                |     |               |              |            |           |
| AC & DC Estimator modif.         | X           | X           |                |     |               |              |            |           |
| Calculation*                     | X           | X           |                |     |               |              |            |           |
| Average DC-RMS                   | X           | X           |                |     |               |              |            |           |
| Harmonic Dist. Anal.             | X           | X           | X              |     |               | X            |            |           |
| Medi. FFT *                      | X           | X           | X              |     |               | X            |            |           |
| Fourier Coefficients *           | X           | X           | X              |     |               | X            |            |           |
| Amplitude and Levels             | X           | X           | X              |     |               | X            |            |           |
| Wavef. Peak Detection            | X           | X           |                |     |               |              |            |           |
| Peak Detector                    | X           | X           |                |     |               |              |            |           |
| Fourier Series*                  | X           | X           |                |     |               |              |            |           |

* VIs created by the author in [10].

The algorithm was developed in a comparative and experimental way, since the method to estimate each parameter of the test voltage, that is, the pre-processing subVIs and data processing, were selected based on tests with standard waveforms and tests in low voltage [10]. All methods of Table 1 were submitted to practical experiments to determine which had the best stability conditions and the smallest error. The following experiments were performed: TDG [3], low voltage test for selection of methods and the high voltage test for final analysis of the HVAT-AC DC system and its robustness. In the TDG tests, all methods were tested and thus the subVIs which showed the smallest errors in the TDG tests were separated and tested in the low voltage tests.

By analyzing the behavior of the subVIs in the low voltage tests, considering their stability and measurement error in all situations evaluated, the subVIs that obtained a stability and measurement error consistent with the results presented previously in the TDG tests were selected. The subVIs chosen will compose the processing routine of the measurement algorithm, together with the preprocessing elements that presented the best behavior. Thus, after the low voltage experiments, the high voltage test was performed with the resulting algorithms, in order to analyze their robustness.

4. Robustness analysis in high voltage

The high voltage analysis was performed for the scale factor determination test of a high voltage measuring system (SM1), composed of a high impedance resistive divider associated with the TDS 5104B oscilloscope using the configuration 1 V/division, 20 ms/division, which, according to the RBC-15/0090 calibration certificate, presents uncertainties equal to 0.02 V and 0.06 ms, respectively, and the software developed HVAT AC-DC.

The divider used in SM1 belongs to the Reference Laboratory in High Voltage Measurement (CA2) of CEPEL, being part of the reference measuring system SMR7, with metrological traceability in laboratories such as LAMAT of Inmetro and MIKES, Finnish laboratory that is a world reference in high voltage calibration. This divider is currently used as a calibration standard in HVAC and HVDC at levels up to 10 kV, having the scale and uncertainty factors equal to 2936.4 V/V, 1 V/V for HVAC
and 2930 V/V, 0.33 %, respectively. Thus, the SM1 system is composed by divider from the SMR7 system and the HVAT AC-DC software.

The high voltage analysis by comparing the scale factor of the reference measurement system (SMR) was performed following the procedures of the standards [1, 2]. According to standard [2], the scale factor in a voltage level can be defined by comparison with an SMR that must be connected in parallel to the measurement system to be approved (SMA). Thus, simultaneous measurements are performed with the two systems. In these HV experiments, SM1 was considered as the measurement system to be approved (SMA) and the reference measurement system used was the SMR2 of the laboratory CA2, with scaling factor and uncertainty in the range of 10 kV for HVAC and 1223.1 V / V, 0.4 V / V and for HVDC 977.3 V / V, 0.4 V / V respectively, which is composed of a universal divider and an Agilent 3458A multimeter, which has a vertical resolution of 24 bits with uncertainty equal 0.000033 V and 0.0025 V for measurements of test voltage (mean value) and RMS voltage (RMS value) respectively, both with the 10 V scale selected.

4.1. Determination of the scale factor in HVAC
The determination of the scale factor in HVAC was performed by comparing at high voltage with a properly calibrated SMR. Ten simultaneous readings were performed on the measuring instruments in each SM, both being subjected to approximately 10 kV, in Table 2 shows such measures of the effective value obtained during the scale factor determination test, as well as the average scale factor and its samples. The scale factor was set at the 10 kV level for AC voltage.

| SMR2  | SM1   |
|-------|-------|
| $V_N$ (V) | $V_N F_N$ (kV) | $V_X$ (V) | $F_{lx}$ ($F_N / V_X$) |
| 8,25849 | 10,101124 | 3,43521 | 2940,5 |
| 8,23812 | 10,076209 | 3,43739 | 2931,4 |
| 8,25477 | 10,096574 | 3,43765 | 2937,1 |
| 8,25086 | 10,091792 | 3,43957 | 2934,0 |
| 8,26639 | 10,110787 | 3,43430 | 2944,1 |
| 8,27270 | 10,118505 | 3,44403 | 2938,0 |
| 8,26716 | 10,111729 | 3,44910 | 2931,7 |
| 8,26990 | 10,115080 | 3,44523 | 2936,0 |
| 8,23575 | 10,073311 | 3,44280 | 2925,9 |
| 8,24246 | 10,081518 | 3,43116 | 2938,2 |

Average: 2936,5
σ:(%) 0,1757

4.2. Determination of the scale factor in HVDC
As for the determination of the scale factor in HVAC, the SMR2 was used as the standard duly calibrated in the scale factor determination in HVDC. Initially a continuous voltage was applied at the 1 kV level, maintained for 10 minutes, in order to allow thermal stabilization, this procedure being exclusively necessary in HVDC scale factor determination tests. After thermal stabilization, the array was subjected to a continuous voltage at the level of approximately 10 kV and then the 10 simultaneous readings were made on the SM measuring instruments.

Table 3 shows the average reading value of the instruments together with the scale factor corresponding to that reading and the mean scale factor, which is assigned to the 10 kV level in the HVDC.
Table 3 - Values obtained during the SM1 scale factor determination test for HVDC.

|       | SMR2       | SM1       |       |
|-------|------------|-----------|-------|
|       | $V_N$ (V)  | $V_N F_N$ (kV) | $V_X$ (V) | $F_{i,x}$ ($V_{SM}/V_X$) |
| 9,918958 | -9,693798 | -3,29715 | 2940,1 |
| 9,917566 | -9,692437 | -3,29599 | 2940,7 |
| 9,911129 | -9,686146 | -3,29252 | 2939,4 |
| 9,919832 | -9,694652 | -3,29436 | 2942,8 |
| 9,909712 | -9,684762 | -3,29237 | 2941,6 |
| 9,910636 | -9,685665 | -3,29521 | 2939,3 |
| 9,914529 | -9,689469 | -3,2927  | 2942,7 |
| 9,930831 | -9,705401 | -3,29236 | 2947,9 |
| 9,917391 | -9,692266 | -3,29410 | 2942,3 |
| 9,920345 | -9,695153 | -3,29816 | 2939,6 |
|       | **Average:** | 2941,1 |       |
|       | $\sigma$ (%) | **0.0875** |       |

Note: The analysis of significant digits was performed based on the uncertainty values corresponding to each SM and instrument presented in this work.

5. Results

The results of the mean scale factors in HVAC and HVDC at the 10 kV level corresponding to SM, obtained by the measurement algorithm, were compared with the SMR7 scale factors obtained in the MIKES laboratories (certificate M-13E067) and CA2 (certificate CA2-247 / 2013). With this analysis, it was possible to observe the influence of the HVAT AC-DC system on the measuring system, since it is characteristic that benchtop meters have an input impedance equal to 10 MΩ, whereas the oscilloscopes have an impedance equal to 1 MΩ.

According to standard [2], it is only mandatory to change the scale factor determined in new calibrations if the percentage difference between the scale factors is greater than 1%. Based on this, this difference was determined after this analysis. Table 4 shows the difference between scale factors.

Table 4 – Comparation.

| Voltage type | Scale Factor | Error (%) |
|--------------|--------------|-----------|
|               | SMR7  | SM1  |       |
| HVAC         | 2936,4 | 2936,5 | 0.0034 |
| HVDC         | 2930  | 2941,1 | 0.3797 |

Even if the scale factor presented a greater difference in HVDC, it can be verified that the oscilloscope set and algorithm does not have a great influence on the measurement system if it will replace the bench multimeters. All other parameters required by IEC 60060 part 1 recorded in the tests can be viewed in [10], where it can be observed that the determination of the scale factor in HVDC was performed with a high ripple factor in the voltage applied in the dividers. This observation indicates that the SM1 divider, ie, the SMR7 divider, should not be used in the same test arrangement with the rectifier of the CA2 laboratory.

6. Conclusion

Currently in the high voltage test and calibration laboratories, standards IEC 60060:2010 [1,2] define all the requirements and procedures of the tests. Among all the requirements of the laboratories, the measurement of all parameters of the test voltage is presently not observed in full, since most laboratories only carry out the quantitative evaluation of the voltage applied to the test equipment.

This manuscript presented the development and validation of a virtual instrument based in LabVIEW for the estimation of HVAC and HVDC test parameters according to IEC 60060-1:2010,
called HVAT AC-DC system, which controls the acquisition of test signals by Tektronix digital oscilloscopes, and implement signal processing algorithms that calculate all parameters demanded by the standard [1,2]. The results obtained in the TDG and low voltage experiments during the development of the system allowed to select the VIs and their respective configurations for the pre-processing and data processing that were used to compose the final measurement algorithm:

- Harmonic Dist. Anal.: RMS value, Frequency, THD, Crest factor;
- Filter SG + Série de Fourier: Test voltage, Crest value, Vmax (ac) and Vmin (ac), Crest factor;
- Medium & AC & DC modified estimator filter: Medium Voltage, Ripple factor;
- SG + Peak Detector Filter: Ripple and Ripple Factor, Vmax (cc) and Vmin (cc).

The measurement of all parameters for quantitative and qualitative evaluation provided by the HVAT AC-DC system will allow a more careful analysis of the test results, since it will be possible to evaluate not only the voltage value applied but also the voltage waveform applied in the test arrangement, aiming at the total suitability of the IEC 60060-1 [1] standard for the measurement of the HVDC and HVAC test parameters and the future IEC 61083-4 [3] for the validation of measurement routines, ensuring the forefront in the execution of tests in the respective Cepel laboratories.

The richness of the qualitative parameters are observed when analyzing the results in the HVDC test of scale factor determination. When the SMR7 system used as reference for the calibration was inserted in the circuit, the applied voltage presented a ripple factor above that tolerated by IEC 60060-1 [1]. This fact was only observed when using the HVAT AC-DC system.

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