Uncertainty Evaluation of the Electrical Transient Rise Time

Pedro Oliveira Costa Machado Neto¹, Paulo Cesar Ramalho Brandão², Juan Carlos Mateus Sanchez³, Lúnia Coelho de Almeida de Lima⁴, Carlos Eduardo Cardoso Galhardo⁵

Universidade Católica de Petrópolis, Petrópolis, Brasil
Instituto Nacional de Metrologia, Qualidade e Tecnologia, Brasil
pedro_oliveira_machado@outlook.com

Abstract. This paper deals with the uncertainty evaluation of the rise time of one pulse of an electrical fast transient burst (EFT/B), as carried out by the National Institute of Metrology, Quality and Technology (Inmetro) of Brazil. The uncertainty sources considered in this evaluation were: the oscilloscope resolution and calibration of voltage and time scale, in the Y- and X-axes, respectively; the bandwidth of the measurement system; the oscilloscope sampling rate; and the repeatability of ten different measurements. Two sets of measurements were taken from two different oscilloscope settings: in the first one, the interpolation function was enabled, and in the other one was disabled. In both cases two components stood out for their huge relative contribution: time reading and repeatability. Considered together, these two components added up approximately 87% of the expanded uncertainty for interpolated samples, and 95% for non-interpolated samples. Also, the results indicate that the oscilloscope interpolation function, if available, must be used, as the expanded uncertainty decreases by 27%. A discussion of the uncertainty budget example in Annex C of the IEC 61000-4-4 standard is presented, concluding that, once the oscilloscope interpolation function is enabled, the other uncertainty components should be considered. The combined relative contribution of these components is larger than the relative contribution of repeatability.

Keywords. uncertainty; rise time; IEC 61000-4-4; voltage measurement; horizontal accuracy.

1. Introduction
Since Edison [1] and Tesla [2] revolutionized the world by creating and improving electrical generation, transmission and distribution, many problems have been solved, but many others have taken place. Some apparatus pollute the electromagnetic environment with many disturbances that can affect anything connected to the electric network [3]. The electrical fast transient (EFT) immunity test is broadly applied in many product regulations, from quality assurance to legal metrology. In order to obtain consistent results from laboratories worldwide, the EMC standard [5] must guarantee that the disturbance signals have a specific shape and that its parameters must lie within specified ranges.

One of the most notorious phenomena in electric circuits is the EFT. Studies about this disturbance in power systems date back to the beginning of the 20th century [4]. Due to the recent widespread use of electronic technology, the EFT becomes relevant even to equipment connected to the mains voltage. To ensure that an equipment under test (EUT) is EFT-immune, it must be submitted to the conditions and setup described in the IEC standard 61000-4-4, which also indicates the susceptibility evaluation according to four possible classifications of the test results [5]. The EFT is a disturbance whose
characteristics have a high probabilistic component; in other words, in the real world two EFT are not the same. However, in order to ensure traceability and metrological reliability of EFT immunity results, the transient generators must be calibrated [6], and the standard working group needs to establish a common framework to grant reproducibility of the tests results of different laboratories. To accomplish this, the EMC reference standard [5] lists six parameters and their respective tolerance margins, which must be met by the EFT signal generator: voltage peak, pulse rise time, pulse duration, repetition frequency, burst duration and burst period. The uncertainty evaluation [7] exhibited in this paper follows the guidelines contained in the annex C of the IEC standard [5], in order to bring forward an effective uncertainty value for the pulse rise time of an electrical transient generator.

The analysis described in this paper examines two uncertainty sources which are only superficially mentioned in the IEC standard [5]: voltage measurement and horizontal accuracy of the oscilloscope. The results show that, for the measurement setup used, the relative contribution of these components to the rise time uncertainty budget amount to 3.00% for non-interpolated samples, and 9.10% for interpolated samples.

The following sections describe in detail the Inmetro’s calibration setup and method, applied in order to acquire and process the calibration data (Section 2), and show detailed considerations on each uncertainty component (Section 3), the results of the uncertainty evaluation (Section 4), and finally, the main conclusions (Section 5).

2. Inmetro’s Measurement Setup and Method

2.1. Measurement Setup

Inmetro’s Laboratory of Electromagnetic Compatibility (Lacem) uses the equipment listed in Table 1 to acquire the EFT/B signal. Although the IEC 61000 4-4 [5] establishes five different calibration levels (250 V, 500 V, 1 kV, 2 kV and 4kV), two different repetition frequencies (5 kHz and 100 kHz) and two different calibration load impedance attenuators (50 Ω and 1000 Ω), this paper only presents, for the sake of space, the results for one test set up. In Figure 1 the diagram of the measurement calibration setup is presented.

Table 1 – Characteristics of the measurement setup components

| Component          | Model                  | Characteristic                                      |
|--------------------|------------------------|-----------------------------------------------------|
| Oscilloscope       | Tektronix TDS5104B     | 1 GHz BW; 5 GS/s Fs; 50 Ω Z_{in}                    |
| Attenuator         | EMC-Partner VERI1K     | 1 kΩ load; 400 MHz BW                               |
| EFT/B Generator    | EMC-Partner IMU-3000   | 250 V Vpeak; 5 kHz repetition frequency             |

Figure 1 – Setup Diagram
2.2. Methods

2.2.1. Rise time functional relationship. The rise time functional relationship is shown in Equation (1).

\[
t_r = \sqrt{(t_{90\%} - t_{10\%})^2 - (\alpha/B)^2}
\]  

(1)

Where,
- \( t_{90\%} \) - time reading at 10% of peak amplitude
- \( t_{10\%} \) - time reading at 90% of peak amplitude
- \( \alpha \) – impulse response shape of the measuring system
- \( B \) – measuring system bandwidth

The IEC standard [5] shows in its Annex C the same functional relationship which is used to evaluate the measurement uncertainty of the EFT/B generator’s rise time \( (t_r) \). In this paper, other uncertainty sources were considered in the evaluation. These additional sources are mentioned in the IEC standard [5] but are not considered in its example. The combined uncertainty was calculated according to the law of propagation of uncertainty:

\[
u_{t_r} = \sqrt{\sum_{i=1}^{n} (\frac{\partial t_r}{\partial x_i} u_{x_i})^2}
\]  

(2)

As the time rise function, shown in Equation (1), is a result of a subtraction, correlation between uncertainty components was not considered in order to assure a more conservative approach of uncertainty evaluation.

Below, Figure 2 shows all the uncertainty sources considered in this evaluation:

![Ishikawa Diagram](image)

Where,
- \( u_r \) – rise time uncertainty
- \( u_{t10\%} \) - time reading uncertainty at 10% of peak amplitude
- \( u_{t90\%} \) - time reading uncertainty at 90% of peak amplitude
- \( u_R \) – rise time repeatability uncertainty
- \( u_{V10\%} \) - time uncertainty associated with the Y-axis uncertainty at 10% of peak amplitude
- \( u_{V90\%} \) - time uncertainty associated with the Y-axis uncertainty at 90% of peak amplitude
- \( u_{acc10\%} \) - horizontal accuracy uncertainty at 10% of peak amplitude
- \( u_{acc90\%} \) - horizontal accuracy uncertainty at 90% of peak amplitude
- \( u_\alpha \) – impulse response shape of the measuring system uncertainty
- \( u_B \) – measuring system bandwidth uncertainty

A number of ten different signal acquisitions was established. Figure 3 shows the EFT/B pulse in the region where the rise time was measured. In the detail, a broader view of the EFT/B pulse.

![EFT/B Pulse](image)
The process used to get the rise time value for each pulse signal, is described below.

2.2.2. Reference Voltage ($V_{ref}$). The oscilloscope cursors are positioned before the disturbance starts (between points A and B in Figure 3), so as to ignore the undershoot at the beginning of the EFT pulse. The oscilloscope mean measuring function was used between the cursors. The result is assumed as reference voltage.

2.2.3. Voltage Peak ($V_p$). The voltage peak is the point of greatest amplitude. The Max automatic measurement from the oscilloscope is used to find the value.

2.2.4. Calculated $V_{10\%}$ and $V_{90\%}$. Both the reference voltage ($V_{ref}$) and the voltage peak ($V_p$) are corrected by using the vertical scale error reported in the calibration certificate of the oscilloscope (-0.51 mV). Then, Equations (3) and (4) are used to calculate $V_{10\%}$ and $V_{90\%}$ respectively.

\[
V_{10\%} = V_{ref} + 0.1 \times (V_p - V_{ref}) \tag{3}
\]

\[
V_{90\%} = V_{ref} + 0.9 \times (V_p - V_{ref}) \tag{4}
\]

2.2.5. Measured $V_{10\%}$ and $V_{90\%}$. Measured $V_{10\%}$ and $V_{90\%}$ are the actual values displayed by the oscilloscope. They are chosen as close as possible to the corrected calculated values $V_{10\%}$ and $V_{90\%}$ respectively.

2.2.6. Rise Time. Rise time is the difference, in time, between the corresponding measured values of $V_{10\%}$ and $V_{90\%}$.

2.2.7. Kragten Method. The Y-axis uncertainty ($u_c$) is the reported standard uncertainty in the calibration certificate, whose value includes, among others sources, the voltage reading resolution and the vertical resolution, in bits, of the analog-to-digital converter [9].

In order to transfer this Y-axis uncertainty to the time axis, Kragten Method [8] is used. For each measurement, $u_c$ was added/subtracted from the measured voltage levels $V_{10\%}$ and $V_{90\%}$ (Equations 5 and 6). As this method is applied to mathematical models, the values read on the oscilloscope were used to determine the slope $dV/dt$ in the respective vicinities of $V_{10\%}$ and $V_{90\%}$.
\[ V_{\text{inc}} = V_{\text{measured}} + u_c \]  
\[ V_{\text{dec}} = V_{\text{measured}} - u_c \]  

The values found in Equations (5) and (6) are used to obtain the standard uncertainty in the X-axis which is related, through the slope \( dV/dt \), to the Y-axis uncertainty.

\[ dt = \frac{(V_{\text{inc}} - V_{\text{dec}})}{dV/dt} \]  

This whole process may be toilsome, but a software can be developed to automatically get the acquisitions, in accordance with the guidance presented in this paper. This solution has already been implemented for all the six parameters of IEC 61000-4-4 [5], by Inmetro’s Electromagnetic Compatibility Laboratory.

3. Uncertainty Components

In this work the measurement datasets were obtained by enabling and disabling the oscilloscope interpolation function (OIF). For both instances, the same uncertainty sources were considered and are described below. All values below were calculated according to the ISO GUM guidelines [10].

3.1. Time reading \((u_{t10\%} \text{ and } u_{t90\%})\)
The time reading is an uncertainty in time, determined by Equation 7. The estimate value is zero. The largest value obtained among ten different measurements, is divided by 2 to establish the standard uncertainty. The largest value is adopted, instead of an average, for a more conservative evaluation. It is considered a type B source of uncertainty and its PDF is normal.

3.2. Voltage measurement \((u_{V10\%} \text{ and } u_{V90\%})\)
The voltage measurement is an uncertainty in time, determined by Equation 7. The estimate value is zero. The largest value obtained among ten different measurements, is divided by 2 to establish the standard uncertainty. The largest value is adopted, instead of an average, for a more conservative evaluation. It is considered a type B source of uncertainty and its PDF is normal.

3.3. Horizontal accuracy \((u_{\text{acc10\%}} \text{ and } u_{\text{acc90\%}})\)
The horizontal accuracy is evaluated as type B. The expected value is zero. Its standard uncertainty is the value declared in the calibration certificate (0.010 ns) for the corresponding horizontal scale. The PDF is considered normal.

3.4. Repeatability \((u_R)\)
The repeatability is evaluated as type A. It is associated with ten rise time measurements, and its standard deviation is the standard uncertainty of this component. The expected value is zero and the PDF is considered normal.

3.5. Measuring System Bandwidth \((u_B)\)
The measuring system bandwidth is evaluated as type B and refers to the -3dB system bandwidth, which is calculated using Equation (8).

\[ B = \frac{1}{\sqrt{(1/B_{\text{osci}}) + (1/B_{\text{att}}) + (1/B_{\text{cable}})^2}} \]  

Where,
- \(B_{\text{osci}}\) – oscilloscope bandwidth (2000 MHz – from the calibration certificate)
- \(B_{\text{att}}\) – attenuator bandwidth (400 MHz)
- \(B_{\text{cable}}\) – coaxial cable bandwidth (5000 MHz)
The value found using Equation (8) is the system bandwidth expected value. The limit declared in Annex C of the IEC 61000-4-4 standard [5] was used to calculate the standard uncertainty of B. The PDF is considered rectangular.

3.6. Impulse Response Shape of the Measuring System (\(u_\alpha\))
This uncertainty component is evaluated as type B. It is a coefficient that expresses the rise time distortion due to the limited bandwidth of the measuring system. This coefficient range considers different mathematical models for the rise time calculation, and different frequency responses of the measuring system [11]. Its estimate (360 ns.MHz) and limit (40 ns.MHz) values come from the Annex C of the IEC 61000-4-4 standard [5], which also indicates a rectangular PDF. The \(\alpha\) standard uncertainty is calculated using the limit value above.

4. Results
Table 2 shows the results obtained when OIF was enabled. The results obtained by disabling the OIF are shown in Table 3.

### Table 2 – Electrical transient rise time uncertainty budget (OIF enabled)

| Type | Symbol | PDF     | Standard Uncertainty | Relative Contribution |
|------|--------|---------|----------------------|-----------------------|
| B    | \(u_{10\%}\) | Triangular | 0.042 ns            | 38.89%                |
| B    | \(u_{90\%}\) | Triangular | 0.042 ns            | 38.89%                |
| B    | \(u_{V10\%}\) | Normal    | 0.0072 ns           | 1.17%                 |
| B    | \(u_{V90\%}\) | Normal    | 0.012 ns            | 3.26%                 |
| B    | \(u_{acc10\%}\) | Normal   | 0.01 ns             | 2.33%                 |
| B    | \(u_{acc90\%}\) | Normal   | 0.01 ns             | 2.33%                 |
| A    | \(u_A\) | Normal   | 0.02 ns             | 8.82%                 |
| B    | \(u_B\) | Rectangular | 0.011 ns          | 2.91%                 |
| B    | \(u_\alpha\) | Rectangular | 0.0078 ns       | 1.39%                 |
|      | Combined Standard Uncertainty |               | 0.067 ns          | 100%                  |

**Coverage Factor**
2.0000

**Expanded Uncertainty**
0.13 ns

**Rise time**
4.78 ns

**Expressed in % of 4.78 ns**
2.79 %
Table 3 – Electrical transient rise time uncertainty budget (OIF disabled)

| Type | Symbol | PDF | Standard Uncertainty | Relative Contribution |
|------|--------|-----|----------------------|-----------------------|
| B    | \(u_{10\%}\) | Rectangular | 0.059 ns | 41.57% |
| B    | \(u_{90\%}\) | Rectangular | 0.059 ns | 41.57% |
| B    | \(u_{V10\%}\) | Normal | 0.0080 ns | 0.77% |
| B    | \(u_{V90\%}\) | Normal | 0.012 ns | 1.74% |
| B    | \(u_{acc10\%}\) | Normal | 0.0045 ns | 0.24% |
| B    | \(u_{acc90\%}\) | Normal | 0.0045 ns | 0.24% |
| A    | \(u_R\) | Normal | 0.031 ns | 11.64% |
| B    | \(u_B\) | Rectangular | 0.011 ns | 1.51% |
| B    | \(u_{\alpha}\) | Rectangular | 0.0078 ns | 0.72% |
|      | Combined Standard Uncertainty | | 0.091 ns | 100% |
|      | Coverage Factor | | 2.0000 |
|      | Expanded Uncertainty | | 0.18 ns |
|      | Rise time | | 4.85 ns |
|      | Expressed in % of 4.85 ns | | 3.76 % |

As it can be observed in Tables (2) and (3), the time reading, the horizontal accuracy and the voltage measurement uncertainties are made of two components. For comparison purposes it was established for each one a combined standard uncertainty of both the 10% and 90% level components.

5. Conclusion

Analyzing the results, it is evident that the primary source of uncertainty is the time reading (\(u_{10\%}\) and \(u_{90\%}\)), no matter if the OIF is enabled or disabled. It also becomes evident that the repeatability uncertainty (\(u_R\)) component has the second largest relative contribution.

The differences between the results are highlighted in the following analysis. The change of the PDF of the time reading (\(u_{10\%}\) and \(u_{90\%}\)) from triangular to rectangular has a great impact on the standard uncertainty of this source. It rose 41% when the OIF was disabled. Additionally, it can be observed that almost all the other components experimented a decrease in their relative contribution. The exception is repeatability (\(u_R\)), whose relative contribution was raised by nearly 3 percentage points. This can be explained by the lower quantity of samples (bigger sample period), due to the disabling of the OIF. Also, the results show that the rise time expanded uncertainty is 27% lower when the OIF is enabled. This result suggests that, when available, this function should be enabled in order to obtain a lower measurement uncertainty.

Another difference between the results is shown in Table 4: the four least contributive components (Other components) become significant when enabling the OIF. The relative contribution of the “other components” is 4.6 percentage points larger than the “Repeatability (\(u_R\))” relative contribution.
Table 4 – Relative contribution comparison

| Uncertainty component | OIF enabled | OIF disabled |
|-----------------------|-------------|--------------|
| Time reading ($u_t$)  | 77.79%      | 83.13%       |
| Repeatability ($u_R$) | 8.82%       | 11.64%       |
| Other components      | 13.39%      | 5.23%        |

The Annex C of the IEC 61000-4-4 standard [5] points the vertical resolution and the time base error as further contributions to time measurement, but notifies that these components are, generally, negligible. However, the results presented in this paper suggest that such components shall be considered for a more conservative assessment. A thoughtful analysis should be carried on when building one’s own uncertainty budget, as the equipment calibration certificate data may change the real contribution of these uncertainty components.

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