Time-Domain Characterization of the Surge, EFT/Burst, and ESD Measurement Systems

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Abstract—A simple, well-established (although in applications different from electromagnetic compatibility), amenable to direct interpretation, and inexpensive method for the time-domain characterization of the measurement systems used for the calibration of the standard impulse generators for immunity tests is presented. The validity and general applicability of the method is demonstrated through an extensive experimental investigation.

Index Terms—Convolution integral, electromagnetic compatibility (EMC), immunity test, impulse measurement, measurement uncertainty.

I. INTRODUCTION

In the framework of the Electromagnetic Compatibility (EMC) standards issued by the International Electrotechnical Commission, immunity to impulse disturbances is tested against three fundamental phenomena having different physical origins: surge (SURGE), electrical fast transient (EFT), and electrostatic discharge (ESD). SURGE is a relatively low-frequency high-energy transient arising from lightning or switching of large capacitive loads in the ac power supply system. EFT is a high-frequency low-energy disturbance mainly arising from the disconnection of inductive loads from the mains network. ESD has the broadest frequency content, and it involves both the conducted and the radiated energy.

For immunity testing purposes, impulse disturbances are simulated by using special impulse generators capable of producing transient waveforms that should comply with the requirements defined by the relevant standards and reported in Table I. Compliance with the tolerances in Table I is assessed through calibration. Standards define also the method of calibration and the minimum performance requirements of the measurement system (MS) used for the calibration. It is important to observe that the performance requirement concerning the dynamic response of the MS is expressed in terms of frequency-domain parameters, namely, the bandwidth and flatness of the frequency response, while the tolerances in Table I are expressed in terms of time-domain parameters. Unfortunately, the correspondence between the frequency-domain behavior of the MS and the time-domain distortion that the same MS induces on the waveform generated by the generator under calibration is far from being evident. The lack of such correspondence becomes evident when attempting to evaluate measurement uncertainty or in developing specifications. In these cases, one is confronted with questions like “how much do the limited bandwidth and ripple of the frequency response of the MS affect the rise time and peak amplitude of the measured ESD impulse?”

The subject here is the time-domain analysis of the effect of the response of the MS on the rise time, peak amplitude, and duration of standard impulse disturbances. The phenomena considered are SURGE [1], EFT [2], and ESD [3]. The time-domain technique adopted is well known and extensively applied in the context of high-voltage measurements [4]–[7]. First, the step or impulse response of the MS is experimentally obtained; then, the distortion induced to the theoretical impulse waveform by the MS is evaluated through numerical computation (convolution integral). In annex C of [6] and [7], guidance is provided for the measurement of the step response, and requirements are set for the rise time of the applied step and also for the response parameters (overshoot, settling time, and flatness). Furthermore, in annex D of [6] and [7], a detailed procedure for performing the convolution calculation is provided, and some considerations about the calculated errors of the impulse parameters and uncertainty contributions are offered. The novel contribution here consists in the modification of the method [4]–[7], originally conceived for application to high-voltage and high-current test techniques, to the SURGE, EFT,
and ESD phenomena, which are peculiar to EMC immunity tests. It is important to observe that, according to [6] and [7], the method of the step-response and convolution integral is valid for obtaining traceable measurement results.

The MS usually consists of a transducer connected to a digital oscilloscope through a section of coaxial cable. The transducer is a voltage divider, current shunt, or transformer whose nominal input impedance is specified by the standards [1]–[3] and that provides adequate attenuation.

Sections III–V are devoted to the analysis of the issues relevant to the application of the method to the characterization of SURGE, EFT, and ESD MSs, respectively. The basic and general equations on which the method is based are presented in Section II. The validity of the method is demonstrated through experimental confirmation.

The present work is a special issue paper whose content is a technical extension of the corresponding conference paper [8].

## II. Convolution Integral Technique

The method consists of the following: 1) recording the step response \( w(t) \) of the MS; 2) scaling \( w(t) \) by using the scaling factor \( W_0 \), thus obtaining \( w_0(t) \); 3) numerically computing the output \( s_{\text{out}}(t) \) as (see [5])

\[
s_{\text{out}}(t) = \frac{d}{dt} \int_{0}^{t} s_{\text{in}}(\tau) \cdot w_0(t - \tau) \, d\tau
\]

where \( s_{\text{in}}(t) \) is the theoretical (ideal) standard impulse waveform applied at the input of the MS; and, finally, 4) comparing \( s_{\text{out}}(t) \) with \( s_{\text{in}}(t) \) in order to evaluate the distortion of the theoretical impulse due to the MS. The factor \( W_0 \) is defined as

\[
W_0 = \lim_{t \to \infty} w(t).
\]

Therefore, \( W_0 \) is the asymptotic value of the step response. The effect of scaling is to translate the actual input step into a unitary step (from 0 to 1). Since

\[
w(t) = \int_{0}^{t} \left( \frac{d}{d\tau} w(\tau) \right) \, d\tau
\]

then, substituting (2) into (3), we have \( W_0 = \int_{0}^{\infty} (d/d\tau) w(\tau) \, d\tau \). From (3), we conclude that \( W_0 \) can be obtained by integrating the time derivative of the step response.

In the case of the characterization of the SURGE MS (both open-circuit voltage and short-circuit current), it was found more convenient to apply an impulse (ideally a Dirac delta function), instead of a step, at the input of the MS. Therefore, the output is obtained as

\[
s_{\text{out}}(t) = \int_{0}^{t} s_{\text{in}}(\tau) \cdot i_0(t - \tau) \, d\tau
\]

where \( i(t) \) is the impulse response, \( i_0(t) = i(t)/W_0 \), and \( W_0 = \int_{0}^{\infty} i(\tau) \, d\tau \), since \( i(t) = dw(t)/dt \).

The effectiveness of the method is evident since it leads to the direct comparison between the distorted output \( s_{\text{out}}(t) \) and the ideal input \( s_{\text{in}}(t) \). It is important, however, also to point out its limitations. First, it is apparent from (1) and (4) that the unavoidable nonidealities of the input step \( w(t) \) or impulse \( i(t) \) propagate to the output \( s_{\text{out}}(t) \). As a consequence, a distortion may be attributed to the MS which does not actually originate from the MS itself but from the step or impulse source used to characterize it. A careful design of the input source is therefore needed in order to avoid an appreciable distortion of the output waveform due to the source itself. In particular, the rise time of the step (duration of the impulse) should be small with respect to the rise time of the standard waveform. Furthermore, the step should be monotonically increasing, i.e., with negligible overshoot, undershoot, or ringing. The waveform of the corresponding input impulse should be nearly unidirectional.

Another aspect of the method which deserves consideration is that the distortion of the output \( s_{\text{out}}(t) \) is evaluated assuming that the input to the MS is the ideal waveform \( s_{\text{in}}(t) \). How does the distortion evaluated assuming an ideal input relate to the distortion of the waveform provided by the generator under calibration? The rather obvious answer is that the waveform provided by the generator under calibration should not differ too much from the ideal waveform. The conversion of this qualitative consideration into a decision based on a quantitative criterion unavoidably relies upon some conventional threshold. We assume that the distortion evaluated through the proposed method is a valid estimate of the actual distortion provided that the generator complies with the requirements in Table I.

The mathematical expression of the input waveform \( s_{\text{in}}(t) \) for EFT and ESD is given by the relevant standards [2] and [3]. The input waveforms for the voltage and the current SURGE do not appear in the present standard [1], but they are available in the draft [9] of the future edition 3 of [1].

## III. Application of the Method: SURGE

The SURGE generator must be verified both in terms of the open-circuit voltage and the short-circuit current operation (see the second and the third row of Table I). This implies the use of two distinct MSs. Accordingly, two different impulse generators were designed and constructed. All the following experimental waveforms are represented by using dots. Dots correspond to the sample points acquired by the oscilloscope. Mathematical waveforms are plotted by using a continuous line.

### A. Open-Circuit Voltage MS

The equivalent circuit of the impulse source used to characterize the SURGE voltage MS is represented in Fig. 1. The use of two spark gaps (SGs) in series permits a relatively short rise time (about 12 ns).

\(^{1}\)The response of the MS produced by the application of a Dirac delta function to the input of the MS.
The impulse shown in Fig. 2 was measured using a high-impedance (100 MΩ in parallel with 6.5 pF) high-voltage (2 kV) 1:100 voltage probe having a bandwidth of 250 MHz and connected to a 400 MHz oscilloscope (sampling rate of 500 MS/s). The impulse source was loaded by two 50 W 10 kΩ resistors in series ([1] specifies a load of 10 kΩ impedance or greater). The amplitude of the impulse is 600 V. Its width within points at 10% of the peak voltage is 200 ns (short if compared with the 1.2 μs front time of the voltage SURGE). The waveform is unidirectional.

The impulse generated by the source in Fig. 1 was applied at the input of the MS that a testing laboratory uses for the internal calibration of its SURGE generator. The measured impulse \( i(t) \) is represented in Fig. 3. The MS consisted of a high-voltage (1.4 kV) 1:1000 differential probe having a bandwidth of 100 MHz (manufacturer PICO TECHNOLOGY, type TA042) connected to a 3 GHz bandwidth oscilloscope (sampling rate of 20 GS/s). No load was connected across the impulse source terminals except for that introduced by the voltage probe. The most evident alteration due to the MS is a damped oscillation at about 90 MHz, associated with an in-band resonance of the voltage probe. Despite the presence of this unwanted oscillation, the result of the comparison of \( s_{in}(t) \) and \( s_{out}(t) \) (see Fig. 4) does not show any appreciable distortion. This is evidently due to the fact that the oscillation frequency is well beyond the bandwidth of the standard 1.2/50 μs impulse.

**B. Short-Circuit Current MS**

The source of the current impulse used for the characterization of the current SURGE MS is shown in Fig. 5. It is essentially a series RLC circuit slightly below critical damping. The short-circuit impedance represented in Fig. 5 is the input impedance of the MS (current shunt or transformer impedance). The relatively large inductance present in the impulse source (450 nH) makes the waveform of the generated impulse fairly...
insensitive to the stray inductance inevitably present in the short-circuit impedance (a few tens of nanoheynries). The current impulse, as measured by a current probe, is shown in Fig. 6. It is unidirectional with a peak value of about 135 A and a duration of 0.85 μs (between the points at 10% of the peak current). The current probe [10] was obtained through winding 23 turns of 200 × 0.10 mm litz wire around a toroidal ferrite core (material 61, size 36 × 23 × 12.5 mm), thus obtaining a lower corner frequency of 2.8 kHz (1.2 Ω load resistance) and a transfer impedance of 52 mΩ. Care was taken to verify, by comparison with an independent measurement method,2 that the distortion due to the high-pass characteristics of the current probe was negligible and that saturation of the ferrite core did not occur.

The current impulse was applied at the input of a current SURGE MS which consisted of a triaxial shunt from the manufacturer LEM, type NORMA TRIAX 98.1 A/V, directly connected to a 500 MHz oscilloscope (sampling rate of 5 GS/s). The impulse response of the MS is shown in Fig. 7. In this case, the most evident distortion is a 500 kHz oscillation. The result of the convolution between the impulse response (see Fig. 7) and the ideal standard 8/20 μs waveform is shown in Fig. 8. The only effect is a barely visible increase of the current peak (1.8% increase, much less than the 10% tolerance specified; see the third row of Table I).

**IV. APPLICATION OF THE METHOD: EFT AND ESD**

The impulse source realized for the characterization of the MSs used for the calibration of both EFT and ESD generators is based on the equivalent circuit model shown in Fig. 9. The SWITCH adopted for the two applications is not the same: A self-constructed coaxial SG is used for EFT MSs, and a commercial shielded mercury-wetted relay is used for ESD MSs. The coaxial SG has the advantage of handling voltage impulses whose amplitude is several kilovolts, i.e., of the order of the peak voltage required by the standard severity levels, while the mercury-wetted relay cannot handle more than 200 V. At the same time, the coaxial SG is not able to produce steps whose rise time is much less than 1 ns, while the measured rise

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2Numerical integration of the electromotive force (EMF) induced in a loop in air, weakly coupled with the mesh where the current under measurement flows.
time of the step generated by using the mercury-wetted relay is about 135 ps (as measured through a 12 GHz 40 GS/s scope); see [11].

The distance between the tips of the coaxial SG can be adjusted with a precision of about 20 μm. In the experiments, the distance between the tips was set at about 100 μm. In order to produce steps with adequate speed of rise, the coaxial SG is pressurized at about 6 bar. With these settings (distance between electrodes and air pressure), the spark is initiated at about 3 kV. The dimensions of the coaxial conductors are such that a 50 Ω characteristic impedance transmission line (TL) in air is realized (16/7 ratio of the diameters of outer to inner conductor). The SG is equipped with N-type connectors (see Fig. 10).

Coming back to the circuit in Fig. 9, we observe that the length of the TL ensures a constant step level over a given time interval. With this in mind, a 10 m cable length was used with a propagation delay equal to 50 ns, which implies a step duration of 100 ns. The LOAD resistor at the right side of TL represents the input resistance of the transducer (50 or 1000 Ω for EFT and 2 Ω for ESD). When the SWITCH (SG or relay) is closed, the charged cable behaves as an equivalent 50 Ω source until the complete discharge takes place. During the first 100 ns after the closure of the SWITCH, the voltage step has a flat-top shape, irrespective of the LOAD resistance.

In the next two sections, we present some experimental results concerning the characterization of EFT and ESD MSs.

A. EFT

The step was applied at the input of a 50 Ω EFT transducer (manufacturer EM TEST, type KW 50, attenuation 1 : 100 from electromotive force to output voltage) connected to the oscilloscope input through a short section of coaxial cable. The step response \( w(t) \) of the 50 Ω input MS is shown in Fig. 11. TL (see Fig. 9) was precharged at about 3 kV, and therefore, the step amplitude is about one-half of this value. The oscilloscope bandwidth was 3 GHz, and the sampling rate was 20 GS/s. The result of the comparison between the input standard waveform and the corresponding output is represented in Fig. 12. No appreciable distortion is introduced by the MS.

The result of the application of the step to the 1 kΩ input MS (transducer EM test KW 1000, attenuation 1 : 500, the rest unchanged with respect to the 50 Ω input MS) is shown in Fig. 13. Some ripple is visible. The compression of the peak voltage is less than 3%, and the rise time is increased by about 0.5 ns, an acceptable distortion if compared with the corresponding tolerance (1.5 ns; see the fourth line in Table I).

B. ESD

The ESD MS consists of an ESD target (manufacturer EM TEST, type CTR 2) plus a 20 dB attenuator and a short section of coaxial cable for the connection to the oscilloscope (3 GHz bandwidth and sampling rate of 20 GS/s). The step generated by the source in Fig. 9 is applied to the input of an adapter line connected to the ESD target (both the adapter and target are described in Annex B of [3]). The input resistance of the MS is 2 Ω. The mercury-wetted relay switched its maximum
Fig. 13. Comparison between (continuous line) $s_{in}(t)$ and (dots) $s_{out}(t)$ as obtained from (4) when the standard input impulse $s_{in}(t)$ is the 5/50 ns EFT impulse. Case of the 1 kΩ input EFT MS coaxial SG.

Fig. 14. Step response $w(t)$ of the ESD MS. The SWITCH of the impulse source in Fig. 9 is a commercial mercury-wetted relay.

Fig. 15. Comparison between (continuous line) $s_{in}(t)$ and (dots) $s_{out}(t)$ as obtained from (4) when the standard input impulse $s_{in}(t)$ is the standard ESD impulse. The step response of the ESD MS is the one plotted in Fig. 14.

V. CONCLUSION

The method of the convolution integral permits the easy characterization of the distortion that the MS produces on the measured impulse waveform in terms of its time-domain parameters (rise time, duration, and peak amplitude). The sources used for the generation of the impulse and step excitations required for the application of the method are inexpensive and easily constructed. The MSs investigated, all compliant with the relevant standard requirements, produced a negligible or small distortion of the standard waveforms in the case of the MSs for SURGE (both open-circuit voltage and short-circuit current) and EFT with 50 Ω input. The most critical MSs appeared to be the one for EFT, with 1 kΩ input resistance, and that for ESD, with 2 Ω input resistance. The deviation from ideal is due to the relatively high-frequency content of the standard impulse (particularly for ESD) and the mismatch at the input of the MS. A careful design of the step source, capable of preserving the integrity of the stimulus over a wide frequency range, is essential in these cases.

Furthermore, in-depth investigation is needed for evaluating the quality (measurement uncertainty) of the results achieved through the application of the method. To this purpose, interlaboratory comparisons (among national metrological institutes, calibration and test laboratories) should be promoted in order to obtain quantitative information about the reproducibility of the method, e.g., in terms of the degree of equivalence.

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