Analysis of the actual shape of the ESD generator pulse in relation to the normative requirements

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Abstract. The article presents a new method of verification of ESD generators that meets the requirements of the standard. A new solution of dependent generators was taken into account on the basis of the obtained measurement result of the actual operation of the current generator at its output from the mathematical model. In the shaping created for the needs of simulation work integrated with the required reservations of the standard and the required errors counted and accuracy of operations.

1. Introduction
The contemporary natural environment struggles with the threats resulting from the development of technologies allowing for the gradual evolution of civilization at the same time generating undesirable electromagnetic interactions. Currently, the awareness of the society requires precise information on the above-mentioned threats and responsible actions to prevent adverse environmental and technological effects [1].

Hazards arising from electrical and electronic devices are most often caused by their excessive electromagnetic emissions and insufficient resistance to electromagnetic disturbances. One of the main challenges is to provide electromagnetic compatibility (KEM) in the workspace of devices, which relates to their satisfactory operation in the electromagnetic environment without causing electromagnetic disturbances unacceptable in the given environment. Parameterization of electromagnetic compatibility assessments consists in the assessment of the degree of compliance by the given devices with the requirements of the EMC Directive and harmonized standards by conducting specialized tests [2,3].

The scope of these studies, research methods, permissible levels and thresholds for specific KEM research into:
• electromagnetic emission measurements of devices,
• resistance tests of given devices to electromagnetic disturbances.

One of the particularly important resistance tests of devices to impulse disturbances are tests of electrostatic discharge (ESD). These tests are performed in order to check the resistance of devices to discharges whose source are the people operating the device and other devices operating nearby. In Poland, these tests are carried out in accordance with the PN-EN 61000-4-2 standard [4].

The tests of resistance to electrostatic discharge are carried out by exposing the tested devices to pulses generated by special simulators (generators) of electrostatic discharge. It is assumed that the
uncertainty of this test method is determined by the uncertainty with which the ESD simulator generates exposure pulses. [5,6]

The subject of the study was to present a new method for determining the accuracy of ESD generators verification. The method includes performing the measurements of the S matrix with the corresponding frequency step, and determination of the transfer impedance of the measurement path using the Fourier transform. The innovative solution also includes appropriate "gluing" of the characteristics of the S matrix with the results obtained in the measurements. An electrostatic discharge simulator produces pulsed current waveforms characterized by parameters specified in the time domain. When calibrating the simulator, the values of these parameters are measured and the measurement uncertainty is estimated. The shape of the generated current impulse is influenced by all elements of the measuring chain, from the discharge disc (the so-called target), through the attenuator the measuring cable, to the oscilloscope, which records the measured pulses. The parameters of this chain are characterized in the frequency domain. An important element of the method is therefore to determine the measurement uncertainty of the pulse time parameters based on the measurements of chain elements measured with a specific uncertainty in the frequency domain. The size of these distortions is expressed in the form of absolute errors in the measurement of individual parameters of the current waveform in relation to the parameters of the pattern waveform, and their value affects the measurement uncertainty when verifying simulators. In solving this problem, the discrete Fourier transform and the inverse transform are used.

A completely new approach to the presented issue is the calculation of the real current impulse at the generator output, all new solutions have been implemented in the proprietary simulation programme created for this work. The programme is based on the development of a measurement track model which is used to obtain the waveforms recommended in the standard. The measurement path model is created using measurement data and theoretical assumptions for determining the transfer impedance of the measurement path [7,8].

The programme's algorithm enables a detailed analysis of the obtained waveforms through any scaling and observation of selected sections of the characteristics. The programme also calculates the absolute errors of the obtained simulation runs by comparing them with the normative reference course.

2. Materials and methods

The ESD generator is calibrated in the measuring system, the view and a simplified diagram of such a solution are shown in Figure 1, while the view from the laboratory tests is shown in Figure 1.

![Figure 1. A simplified diagram of the ESD generator calibration system](image)

The electrostatic discharge is directed to the discharge disc. The discharge shield is connected with a coaxial cable through an attenuator to a wideband oscilloscope with an input impedance of 50 Ω [9,10].

The four-way diagram of the measurement path used for the calculations is presented in Fig. 2. The input data are measurements of the parameters of the scatter matrix S of the shield, the cable with an attenuator and the oscilloscope made with a vector network analyzer [11-13].
The measurement of the impedance matrix $S$ as a function of frequency enables unambiguous description of the electrical parameters of a device or system treating it as a multiport element. These types of measurements allow for the calibration of devices, measuring stands, or the assessment of the suitability of test stands. One of the areas in which the $S$ matrix measurements of devices and stations are commonly used is electromagnetic compatibility.

In the presented work the subject of actions were:

- analysis of high-frequency properties of the components of the measurement path,
- development of a simulation model of the entire measurement path,
- development of a measurement uncertainty assessment method based on frequency characteristics using the Fourier transform and its inverse transform,
- assessment of the impact of the uncertainty of measurements of the $S$ matrix parameters on the total uncertainty of the determined electrostatic discharge current.

Recreating the actual waveform of the power generator has improved the accuracy of verification of the required generator parameters. It might in the future result in narrowing the discrepancy of signals affecting the tests. This will improve the repeatability of tests as well as increase the accuracy and repeatability of current pulses created in generators, which will translate into increased precision of generators made by their manufacturers. It will also allow for the development (or the use of a higher accuracy class) of new elements of the measurement path, introducing less disturbances (cables, actuators, even textronics application [14]).

The presented method in the form of a programme (after its introduction as a proprietary procedure) can improve and accelerate the verification tests of ESD generators in Calibration Laboratories. It can also be used in other various solutions to create real mathematical models of measurement paths. It combines both the determination of the parameters of such a track from theoretical formulas and measurements of the physical parameters of the object.

The tests presented in the paper concerned ensuring the credibility of research on the resistance of electrical and electronic products to ESD by creating a software tool necessary to determine the balance of current uncertainty of an ESD generator. The method allows to get the real waveform at the generator output.

The programme also includes a proprietary solution consisting in obtaining the actual waveform at the generator output by simulating it. It supports calculations in research works related to the tests of resistance to electrostatic discharge. The programme is a set of scripts / functions written in the Scilab version 5.5.2. The programme is controlled by means of a graphical interface in the form of a graphic panel with control buttons Fig. 1 b. On the left side of the panel there are buttons that activate individual modules (functions) of the programme.

Pressing the button may display an auxiliary panel in which detailed parameters of the function to be started are selected. The results are displayed in the area to the right of the panel. Depending on the selected option, 1 to 4 charts are displayed. (Options A, B, C and 1, 2, 3, 4 in the lower left corner of the panel). Numbering of charts in C view (default) 1 - upper left area, 2-lower left area, 3- upper right area, 4- lower right area. Some functions generate additional graphical panels with results. The scilab console displays the results of the programme in the form of text Figures 3a and 3b.

The programme allows for analysis in two scenarios:

a) Scenario 1 - Checking the pulses in accordance with the standard without the filter activated.
b) Scenario no. 1+ Filter - Check the pulses in accordance with the standard with the filter activated. There are 4 types of filters. After selecting the option, you can decide on the filter type 1-Butt, 2-Cheb1, 3-Cheb2, 4-Ellip and enter the cut-off frequency in GHz (default is 4GHz, no filter)

c) Scenario No. 2 - Checking the pulses in accordance with the measured characteristics of the path as a function of frequency and recreating the pulse at the ESD generator output

The simulations were performed on the full scope of tests of the ESD generator, i.e. for the voltages of 2 kV, 4 kV, 8 kV and 15 kV. The waveforms were recorded by two different oscilloscopes, the Keysight MSOS804A with a bandwidth of up to 8 GHz and the Lecroy WP735Zi company with a bandwidth of up to 3.5 GHz, the error results of which were analysed in the Statistica programme.

*Sample simulations in the programme*

![Figure 3. View of the programme front panel](image1)

![Figure 4. The course of the spectral density of the calculated measurement system with the plotted graph specified by the standard](image2)
The simulation programme automatically calculates the errors obtained in the voltage shape at the generator output by comparing it with the values specified in the standard. The absolute errors of the rise time, the maximum value and the run value in 30 and 60 ns are determined. Examples of the results of such simulations for scenario no. 1, scenario no. 1 with filter and scenario no. 2 are shown in Table 1 and in Figures 1-4.

The course of each simulation is verified on an ongoing basis in accordance with the requirements of the standard, saved in a text file and a file for the Excel programme is created. The errors are determined in the simulation programme in one of the subroutines for each analysed course. An example of the obtained text file data is presented below:

Parameters of the reconstructed pulse:
Up=2.0kV, T=200.0ns, tp=6.250ps, n = 32000
Po=-11dBW/MHz, Et=0.702143uJ, Rin=0.913Ω

TEST OF CONFORMITY OF THE PULSE SHAPE WITH THE PN_EN_61000_4_2_2011 / (B.4.3)
[ 6.38 <= Ip <=  8.63]  Ip =  7.50 A   PASS
[ 2.80 <= I30 <=  5.20] I30 =  3.75 A   PASS
[ 1.40 <= I60 <=  2.60] I60 =  1.93 A   PASS
[ 0.60 <= tr <=  1.00]  tr =  1.02 ns  FAIL

TEST RESULT: FAIL
Pulse spectral density:
Up=2.0kV, fp=160GHz, df=5.00MHz, n=16000
Po=-11dBW/MHz, Ef=0.702165uJ, Rin=0.913Ω

For Excel:
delta_tr +25%; delta_lmax +15%; delta_I30 +30%; delta_I60 +30%
27,76; 0.04; 6.34; 3.49

Sample tables from the simulation programme are presented below:
Summary for measurements for the Keysight MSOS804A oscilloscope with a bandwidth of up to 8 GHz.

Table 1 Simulation error values for the MSOS804A oscilloscope; voltage 2 kV

| Scenario 1 | Scenario 1 + filter | Scenario 2 |
|------------|---------------------|------------|
| delta_tr+25%; delta_lmax+15%; delta_I30+30%; delta_I60+30% | delta_tr+25%; delta_lmax+15%; delta_I30+30%; delta_I60+30% | delta_tr+25%; delta_lmax+15%; delta_I30+30%; delta_I60+30% |
| 1 | 7,57; 0,83; 8,67; 8,43 | 12,87; 1,19; 8,62; 7,96 | 4,33; 2,17; 7,78; 8,10 |
| 2 | 21,76; 0,83; 4,73; 3,59 | 10,49; 1,96; 6,89; 1,46 | 3,28; 2,01; 7,00; 3,03 |
| 3 | 5,87; 2,32; 5,75; 1,57 | 7,31; 3,29; 6,60; 2,61 | 2,55; 0,26; 5,87; 1,11 |
| 4 | 3,35; 3,04; 7,38; 2,07 | 4,42; 3,54; 7,06; 2,89 | 0,39; 0,20; 6,72; 1,48 |
| 5 | 21,79; 3,13; 5,21; 4,22 | 15,04; 3,23; 4,35; 1,43 | 4,96; 6,28; 4,38; 2,55 |
| 6 | 27,76; 0,04; 6,34; 3,49 | 12,09; 1,56; 5,43; 4,28 | 4,19; 2,79; 4,85; 4,68 |
| 7 | 2,02; 1,76; 7,62; 3,10 | 4,92; 2,67; 6,42; 4,33 | 1,60; 1,95; 6,30; 4,49 |
| 8 | 2,40; 0,53; 5,90; 3,09 | 4,49; 0,66; 7,11; 5,93 | 1,62; 3,31; 5,92; 3,96 |
| 9 | 1,66; 0,32; 5,13; 4,40 | 1,21; 0,86; 6,84; 3,89 | 1,87; 3,46; 4,56; 3,32 |
| 10 | 15,07; 3,95; 6,05; 6,90 | 11,28; 5,01; 7,27; 7,75 | 9,01; 1,15; 6,54; 8,81 |
3. Results

Interpretation of the results in Statistica programme

In order to determine the variability of the obtained results, the coefficient of variation and the standard error of the mean were determined for a given research sample. For the purpose of achieving the predetermined accuracy of the results, the necessary number of repetitions of the measurement of a given parameter within a given sample was defined.

Figure 5. Graphical representation of the error values obtained in the simulation program with the requirements of the standard.

Figure 6. The structure of the variability of the error simulation values within the voltage of 2kV and all measurement scenarios used in the research (blue colour I oscilloscope, red colour II oscilloscope)
The sample variance was calculated from the obtained measurements, and the value of the normal variable was read from the tables for $\alpha = 0.05$. The correct results, as well as the results of the trial series, were subjected to the Kolmogorov-Smirnov test with the interpretation of Lilliefors probabilities in order to confirm or reject the hypothesis of a normal distribution of the parameter under study. Subsequently, basic statistics describing the correlation between the assessments of two scattering measures, i.e. the standard error of the mean and characterizing the variability in a given sample, i.e. the coefficient of variation, were calculated. Therefore, what appears to be methodically and statistically justified, a sample size of 10 in three replicates was adopted for each combination of measurements. In order to determine the statistical significance of the differences within the analysed values, an analysis of variance in multiple classification with Duncan's test was performed. Statistical inference was conducted at the significance level $\alpha = 0.05$. All data on the basis of which the presented charts were created are included in Appendix 2 of the paper.

Sample graphic interpretations and tables for 2kV voltage:

![Figure 7](image.png)

**Figure 7.** The structure of the variability of the error simulation values within the 2kV voltage and all measurement scenarios used in the research in the case of the oscilloscope

The detailed analyzes of the charts obtained from the simulation programme confirm the correctness of the applied solutions and analyses of the written computer programme. The analysis of the actual shape of the ESD current no longer requires a conditionally applied solution permitted by the standard in the form of an application for some filter cases.

The simulation programme is based on the use of the methods of analysis of the measurement path elements in the frequency domain to determine the uncertainty of the measurement of ESD discharge parameters, described in the time domain. Attempts are being made to use this method to verify the measuring instruments used in electromagnetic compatibility tests:

- coupling-decoupling systems used for resistance tests to conduct disturbances induced by radio frequency fields -standard EN 61000-4-6 - parameters S11, S21,
- artificial networks when measuring the emission of conducted disturbances according to EN 55016-2-1 parameters S11, S21,
- measurement antennas - parameters S11,
• usefulness of absorber anechoic chamber for disturbance emission measurements (NSA and VSWR measurements) - parameters S11 and S21

In the case of measurements and tests of devices in various laboratories, completed with an assessment, confirmation of compliance with the requirements by the measuring station is required.

4. Conclusion

The obtained test results confirmed that the developed method of evaluation of the electrostatic discharge current impulse verification is based on the actual current waveform at the ESD generator output, which was achieved thanks to the use of an original mathematical model built on the basis of measurements and the developed high-frequency characteristics of the measuring circuit.

In the developed method, the model of the measurement path was presented and the relationship describing its transfer impedance was determined. It became the basis for conducting simulations determining the values of individual parameters of the current pulse for specific input data and analysis parameters in the time and frequency domains. The programme enables setting various analysis parameters (frequency changes) as well as the use of various types of filters. The presented method has many advantageous features and allows for a more reliable assessment of the size of the ESD pulse distortion, thus more reliable verification of electrostatic discharge generators. It takes into account the errors caused by the main elements of the measurement path (discharge shield, cable with an attenuator and the oscilloscope input impedance), in a wide frequency range. Such an approach has not been presented in previous works in this field.

On the basis of the simulations performed and the error analysis, it can be concluded that due to the discrete signal processing of digital oscilloscopes and the use of the discrete Fourier transform, it is reasonable and justified to perform the verification of the registration waveform of ESD generators by means of oscilloscopes with a frequency range of up to 4 GHz, as a sufficient frequency range width. This is particularly important for the reliable recreation of that part of the current waveform, where its value rapidly increases, i.e. the rise time determination. The paper presents an innovative method of practical measurements of the S matrix parameters of the measurement path elements. Taking measurements by dividing the measuring range into intervals and then performing them with maximum accuracy for each vector interval of the network analyser and taking measurements of the entire assembled measuring system as a whole allowed to obtain an increase in the accuracy of the generator signal reproduction.

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