Mathematical Model of the Susceptibility of an Electronic Element to a Standardised Type of Electromagnetic Disturbance

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Abstract: The problem of estimating the deterministic susceptibility coefficient of electronic components to standardised types of electromagnetic disturbance has been presented in this paper. From a theoretical point of view, the problem of damage to electronic elements is presented with the impact of disturbances of critical values on them and the potential impact of this effect on the reliability of the element and ultimately the system or electronic device. For a selected exemplary electronic component, a method for estimating the susceptibility coefficient according to the developed methodology is discussed. Experimental tests were carried out by exposing the test component to a standardised surge of 1.2/50 µs which was observed in an electrical grid. In order to illustrate the developed method, aimed at describing the immunity of an electronic component to a standardised type of disturbance, a signal diode was selected for testing. Using this element as an example, it is shown how, using statistical techniques, the coefficient of its susceptibility to a specific type of disturbance can be estimated.

Keywords: electromagnetic compatibility; susceptibility; immunity; EMC; EMS

1. Introduction

The immunity of a component of an electronic system is a property, a physical characteristic, that allows it to fulfil its assigned function. It is created by a number of factors. Building a generalised model of the susceptibility of electronic elements which would take into account the influence of electrical and environmental factors is still not an easy task in the current state of knowledge. At the current level of technical development, it is possible to determine whether the tested device is immune or sensitive to a specific type of electromagnetic disturbance during experimental tests. This condition can be confirmed for a strictly defined disturbance level for a specific coupling mode, with strictly imposed measurement conditions specified in the EMC standard.

An electronic element, in normal operation, is affected by a set of factors that create its environment. The temperature, humidity, pressure, atmospheric contaminants, mechanical exposures, and electromagnetic exposures under study are all factors that can, over time, cause changes in the molecular structure of a component and trigger specific damage mechanisms. A thorough understanding of these factors, their nature, and the way in which they interact with the device and its components is becoming indispensable with the current development of technology. The degradation processes that may occur in an object during its use lead to a reduction in its ability to perform its assigned function. In value terms, the ability of an object to perform established tasks is described by the probability of its fulfilment.

A measure of life of most components in an electronic device is the time for which the component retains certain characteristics within fixed limits and under fixed operating conditions. The end of “life” is defined by the moment it fails to meet the life criterion. Environmental factors can significantly modify the service life of electronic components. A
very good example of this are surges from lightning or from switching processes. In the absence of adequate protections and under adverse conditions, such disturbances can cause disruptions to the correct operation of an electronic circuit. An electronic system is made up of interconnected electronic components, which, according to their purpose, should fulfil a function strictly assigned to the system. The correct operation of any circuit is dependent on the correct operation of each of its components. Disturbances to which the systems are exposed during tests in the laboratory and during operation in the real environment can cause various unforeseen effects. The first range, determined by the susceptibility threshold, is the range within which the system can tolerate the disturbance. When the susceptibility threshold is exceeded, the system may go into a state of temporary inability to operate its assigned functions. Once the disturbance ceases, the system returns to normal operation. Another characteristic disturbance limit is the value for which there is a permanent change in the parameters of the elements of which the system is built, e.g., a permanent change in the resistance of a resistor, the capacitance of a capacitor, or the inductance of an inductor. In the case of semiconductor elements, e.g., diodes or transistors, a permanent change in their current–voltage characteristics can be observed. If the disturbance value from which permanent degradation changes occur in the element’s structure is exceeded, the element can be considered to be in good working order if its nominal parameters do not go beyond the tolerance limit. As long as the nominal value of the component does not exceed the tolerance limit, the component can be considered operational and capable of fulfilling its assigned function. For each component, a disturbance value that leads to permanent damage of the component can also be determined. In most cases, the permanent failure of an element in a system is synonymous with the failure of the entire system.

The basis for this conclusion is the results of our team’s research into the mechanisms by which electromagnetic disturbances affect the operation of electrical and electronic devices. The authors’ publication [1] presents how a 1.2/50 µs surge used in laboratory conditions to test the immunity of electrical and electronic devices can affect the operating state of LED lamps. This type of disturbance defined in the standard [2] is used to check how the tested device will react in real conditions to surges generated in the power grid during switching processes or lightning discharges. According to the requirements of standard [3], it allows one to check whether a device has the required level of immunity. The standard defines two immunity thresholds for LED lamps (0.5 kV for 5 W ÷ 25 W lamps and 1 kV for >25 W lamps).

The results of tests that were carried out on two commercial LED lamps with similar luminous and design parameters that differed only in the warranty period declared by the manufacturer were presented in [1]. The warranty period depended on the quality of the components used in their construction. The tests carried out made it possible to determine the susceptibility coefficient of the tested lamps to a shock of 1.2/50 µs. The results of estimating the susceptibility coefficient for the tested LED lamps to a selected standardised type of disturbance and a methodology for modelling the susceptibility of an electronic component/system to a standardised type of electromagnetic disturbance were presented in [1]. During the testing of the lamps, it was noted that, despite the similar application circuits of lamps produced by the same manufacturer, each had a different level of immunity. It was interesting that the lamp with the longer warranty claim had a significantly lower immunity threshold. During testing of a series of 150 lamps from the same production batch divided into ten groups of 15 lamps, the level of disturbance was increased in each group and analysed to see how many lamps would fail permanently. The tests showed that the number of damaged lamps was subject to a certain statistical regularity. These observations formed the basis for further research leading to the development of a mathematical model for the damage process of electronic components, especially for the critical disturbance levels that lead to permanent component damage. The process of disturbance as well as damage to an electronic component is a stochastic process. It is never the case that a component from the same production batch made in the same regime will fail at exactly
the same disturbance value. Hence, in order to build a mathematical model for this process, statistical relationships must be used.

During testing, according to the procedure defined in [2], it can be verified whether the test object meets the requirements of the standard. By checking its level of immunity to a defined type of disturbance, it can be confirmed that a device is immune to standardised exposures. However, as a result of such a test, there is no way to know what the limit is for the disturbance value that can lead to permanent damage to the component/device and how the damage itself will occur when the critical disturbance value is approached. In [1], it is described how the impact immunity of a test item for an LED lamp can be described numerically. In publication [1], the problem of lamp failure was presented and, in the final part of the publication, the susceptibility coefficient was determined for each lamp. In that publication, the presentation of a method for the determination of this coefficient was abandoned. A methodology for the determination of the susceptibility coefficient is proposed in this publication. The technique of determining the susceptibility coefficient for an element rather than a system is deliberately shown in the experimental part.

Looking for hints on how to build a model of the susceptibility of an electronic component to a standardised type of disturbance, thematic textbooks and publications were analysed. Some information can be found in [4]. The author of this publication, in Chapter 10, entitled “Model for Immunity Testing”, presented the general assumptions of the theory of estimating the disturbance probability of the correct operation of a device subjected to a defined electromagnetic disturbance. Using a model microcontroller and PLC systems as examples, it was shown how ESD and BURST affect the operation of these systems and how, using probability calculus and statistics, the probability of disturbing the correct operation of an electronic system subjected to a disturbance of a critical value can be predicted. This paper presents the idea of a deterministic and behavioural model to estimate the robustness of an electronic system to a specific type of disturbance. The rationale for this item of literature provided the inspiration to conduct research in this aspect. Detailed information on the methodology for building the models is provided in [5–7].

Among a range of standardised disturbances, the most dangerous for electronic components/systems are surges and electrostatic discharges. As emphasised by the authors of [8,9], these types of disturbances can lead to permanent damage to components and, ultimately, to subsystems made of them. In publication [8], the authors presented a mathematical model allowing for the estimation of the batch size of tested elements so that the test result would be reliable. The general assumptions for the construction of models of the susceptibility of electronic components/systems to a specific type of disturbance are presented in [10,11]. As indicated by the authors, the construction of the model requires the consideration of a number of factors, i.e., the spectrum of disturbances, the bandwidth of the channel through which the disturbance is transmitted, and the threshold of the susceptibility of the electronic element/system to the energy carried by the disturbance. The complexity of the modelling process of EMC-related phenomena is illustrated in publications [12–22]. In order to obtain reliable results, a number of factors must be taken into account in the phenomena modelling process. In [14], the authors conducted an extensive analysis of electronic system modelling techniques and, using the example of an AC motor driver, showed how many factors should be taken into account in the modelling process in order to achieve the compatibility of simulation and measurement results. The effects of critical disturbances are presented in [12,13,15,19,21]. Publications [17,18,20,22] show the complexity of the modelling process in more complicated systems.

The technique presented in this paper for determining the susceptibility factor for an electronic component to a standardised type of disturbance has practical significance. In laboratory tests, when testing, e.g., the immunity of a system to a surge, there are strictly defined levels to which it is exposed. If the system is fail-safe, the question arises as to whether, by increasing the level of disturbance slightly, the susceptibility level will still be maintained and how far the distance from the susceptibility threshold is. It is very
common in tests to raise the level of disturbance by several per cent to check whether the susceptibility threshold is just beyond the threshold value. The technique proposed in this paper for determining the susceptibility coefficient for an element can be extended to a subsystem or the whole system.

If a factor such as nominal voltage or power, etc., were determined for each component, the level of susceptibility could be estimated for the designed system. Currently, during engineering tests, it is checked whether the newly designed circuit has the required level of immunity. If not, based on the results, additional protection elements are introduced to guarantee the system the required immunity. Introducing spark gaps, varistors, or TVS diodes into a circuit undoubtedly increases the immunity level of the circuit, but the value of the susceptibility threshold is still unknown.

Another area where the proposed technique for estimating the susceptibility factor of an electronic component to a standardised type of disturbance can be used is in inter-laboratory immunity comparative tests. In the case of emission measurements, laboratories analyse reference standard sources. In the case of immunity, such sources are lacking. The method that is presented in this paper can be successfully used for this type of testing. If every laboratory involved in comparative tests receives a batch of components (it is important that they come from the same production series), the distributions they obtain using the method should be similar. This is possible if the test equipment used for the components is consistent.

2. Model of the Susceptibility of an Electronic System to Electromagnetic Disturbances

In EMC theory, a device is considered immune if it is able to perform its assigned function in the presence of electromagnetic disturbances. Susceptibility is defined as the state in which a device loses this ability. Determining the level of immunity involves observing the behaviour of the test object under the influence of a conventional disturbance signal with a value characteristic of the class of device. The highest level of this signal, at which no symptoms of disturbance are perceived, defines the immunity of the tested system. Susceptibility to disturbance, on the other hand, is defined by the smallest level of disturbance that causes a temporary or permanent loss of the ability to perform the assigned task. The reason for the failure of the electronic system is the failure of the weakest component.

Referring to the provisions of the EMC standards [2,3], immunity thresholds are defined for immunity tests. When testing a device according to the procedures defined in the standard, it is always checked if it can withstand the required level of disturbance. If, when tested according to the procedure, a device is found to be immune, then, without additional tests, it is not possible to determine how far away it is from the limit for which it will fail. If, on the other hand, the device under test fails, the test result will also not allow for a determination of how far it is from the disturbance value that would prevent it from failing. For this reason, it was decided to use statistical elements to solve this problem.

The immunity index \( R(z) \) of an element to a specific type of disturbance can be defined as the probability that the element will fulfil its assumed functions \( \Phi \) at a specific disturbance level \( z \), under specified operating conditions \( \chi \):

\[
R(z) = P\{z, \Phi, \chi, |0 \leq z \leq Z|\}
\]  

(1)

The event of an element failing at a certain level of disturbance \( z \) is a random event, and the characteristic values of voltage \( U \), current \( I \), and power \( P \) of disturbance signal \( z \) are random variables. Obtaining information about the distribution of a random variable in a given set of elements requires the examination of all the elements belonging to this set, i.e., a 100% test, which is generally difficult to achieve in practice and sometimes even impossible, e.g., when the tests are destructive. For this purpose, a representative group can be selected for the survey. To increase the reliability of the investigation, a sample from the set of elements is selected at random.
In the course of testing, depending on the specific nature of the components under investigation, their measurable (current, voltage, power, resistance, etc.) or non-measurable characteristics (short circuit, interruption, relay tripping or not tripping, etc.) are analysed. Statistical analysis of the empirical results obtained allows for the construction of theoretical reliability models. Knowing the results of a random sample, it is possible to infer the functional form and parameters of the distribution of a random variable that constitute a probabilistic model of the set represented by this sample. Statistical inference about a set of products on the basis of test results consists of the verification of a specific statistical hypothesis, or the estimation of unknown numerical values of specific probabilistic parameters of the considered set. Both in the verification of statistical hypotheses and in the estimation of probabilistic parameters of the considered set of objects, appropriate statistics are used, whose realisations are functions of observed test results of a random sample representing the set.

The immunity of an electronic component to a standardised type of disturbance is a function of the random variable \( z(U, I, P) \). The distribution of the variable \( z \) depends on the physical properties of the components, their conditions of use, and a fixed set of fitness states for the function that each component is expected to perform as intended. The random variable \( z \) is in the real world characterised by continuous (taking into account the level of disturbance) functions: the cumulative distribution function \( F(z) \), the probability distribution density \( f(z) \), the strength function \( R(z) \), the damage intensity function \( \lambda(z) \), the cumulative damage intensity function \( \Lambda(z) \) (resource function), and positional parameters such as the expected value and the variance of the random variable.

When looking for an answer to the question of what the probability is that a system under the influence of a specific factor, in this case an electromagnetic disturbance, will fail at a specific value, it is necessary to know the distribution describing this process. The cumulative distribution function \( F(z) \) of the immunity of an electronic component is a function whose value for a fixed value of disturbance level \( z \) is the probability of failure of the component at that disturbance level:

\[
F(z) = P(Z < z) \text{ for } z \geq 0
\]  

(2)

Theoretically, \( F(0) = 0 \) means that the probability of a component failing at disturbance level \( z = 0 \) is equal to 0. The occurrence of the event \( Z < z \) means that a fit component at disturbance level \( z = 0 \) will fail in the interval \((0, z)\).

The cumulative distribution function \( F(z) \) is a non-decreasing function of argument \( z \), left continuous and always satisfies the condition:

\[
0 \leq F(z) \leq 1
\]  

(3)

The cumulative distribution function of immunity \( F^*(z_i) \) of the elements, for a specific random sample of \( n \) elements, can be determined from the relation:

\[
F^*(z_i) = \frac{m(z_i)}{n(z_i)} \text{ for } z_i \geq 0
\]  

(4)

where \( F^*(z_i) \) is the estimation of the cumulative distribution function for disturbance level \( z_i \), \( n(z_i) \) is the number of elements in the random sample for \( z = z_i \), and \( m(z_i) \) is the number of damaged elements for disturbance level \( z_i \).

The immunity function \( R(z) \) reflects the situation where a requirement is made of an element that its life be no less than \( z \). In this case, the strength of an element will be the probability that an element that is fit for disturbance level \( z = 0 \) will be useable in the interval \((0, z)\). Therefore, the strength of an element can be expressed as the probability of the event that durability \( Z \) takes a value greater than \( z \):

\[
R(z) = P(Z < z), \ z \geq 0
\]  

(5)
The empirical immunity function can be determined from the following equation:

$$R^*(z_i) = 1 - F^*(z_i) = \frac{n(z_i) - m(z_i)}{n(z_i)}$$  \hspace{1cm} (6)

Directly related to the immunity function is the susceptibility function $W(z)$. Susceptibility means the loss of a device’s ability to fulfil its assigned function. The susceptibility of an electronic system to a specific type of electromagnetic disturbance is directly described by the cumulative distribution function. Its value determines what the probability of the system failing is for the $z$-value of the disturbance:

$$W(Z < z) = 1 - R(z) = F(z) \text{ for } z \geq 0$$  \hspace{1cm} (7)

The empirical susceptibility function can be determined from the expression:

$$W^*(z_i) = F^*(z_i) = \frac{m(z_i)}{n(z_i)}$$  \hspace{1cm} (8)

If the cumulative distribution function $F(z)$ of strength is known, then, assuming it is continuous and differentiable, the probability density function $f(z)$ can be determined as a derivative of function $F(z)$:

$$f(z) = \frac{dF(z)}{dz} = -\frac{dR(z)}{dz}$$  \hspace{1cm} (9)

The empirical function of probability density can be estimated from the following relation:

$$f^*(z_i) = \frac{m(z_{i+1}) - m(z_i)}{n(z_i) \cdot \Delta z}$$  \hspace{1cm} (10)

The probability density function $f(z)$ describes the absolute deterioration of an object’s immunity per unit magnitude of disturbance signal. The waveform of this function will determine the damage dynamics of the elements in a given community with increasing levels of disturbance.

The damage intensity function $\lambda(z)$, important for building a reliability model, is a local durability characteristic. It is an indicator of the rate of damage to the parts of the community under analysis. If an item is fit for disturbance level $z$, then the probability of its failure in the interval of values $(z, z + \Delta z)$ is equal to:

$$\lambda(z) = \lim_{\Delta z \to 0} \frac{P(z < Z \leq z + \Delta z \mid Z > z)}{\Delta z}$$  \hspace{1cm} (11)

The value of this function can be determined using functions $f(t)$, $F(t)$, and $R(t)$:

$$\lambda(z) = \frac{f(z)}{1 - F(z)} \text{ or } \lambda(z) = -\frac{d \ln R(z)}{dz}$$  \hspace{1cm} (12)

The empirical local damage intensity function of the elements is determined from the relation:

$$\lambda^*(z_i) = \frac{m(z_{i+1}) - m(z_i)}{\Delta z \cdot (n(z_i) - m(z_i))}$$  \hspace{1cm} (13)

Damage intensity $\lambda(z)$ characterises the relative decrease of the object’s strength per unit of disturbance signal.

A measure of the depletion of an object’s ability to execute a task is function $\Lambda(z)$ of cumulative damage intensity, defined by the relation:

$$\Lambda(z) = \int_{0}^{z} \lambda(\zeta) \cdot d\zeta$$  \hspace{1cm} (14)
where $\zeta$ is an auxiliary variable. The empirical cumulative element damage intensity function is determined from the equation:

$$\Lambda^*(z_i) = \sum_{i=1}^{j} \lambda(z_i) \cdot \Delta z_i$$  \hspace{1cm} (15)$$

The depletion of an object’s ability to execute the tasks imposed on it follows the principle of increasing entropy in physical systems.

Often, in practical problems, the distribution of a random variable cannot be given for various reasons. The need then arises for at least an approximate description of the distribution by means of one or more numerical values “characteristic” of this distribution. The most common are the expected value $EZ$ and the variance $VZ$. If the object strength function $R(z)$ is known, the expected value of the disturbance level that leads to permanent damage to the object is determined according to the formula:

$$EZ = \int_0^\infty R(z)dz$$  \hspace{1cm} (16)$$

From the geometric interpretation of the integral and Equation (16), it follows that the expected value of the disturbance level that causes permanent damage to the object is equal to the area bounded by the graph of the strength function and the axes of the coordinate system. Equation (16) implies that a real electronic component with strength $R(z)$ is “equivalent” to an absolutely resistant component ($R(z) = 1$) to a disturbance of $EZ$.

The expected value of the immunity of the elements, based on the observed immunity of the individual elements in the random sample, is determined from the relationship:

$$E^*Z = \frac{1}{N} \sum_{j=1}^{N} z_j$$  \hspace{1cm} (17)$$

where $N$ is the sample size and $z_j$ is the observed life in the random sample. A measure of the spread of the values of a random variable around its expected value is described by the variance of the random variable:

$$VZ = E(z - EZ)^2 = \int_0^\infty (z - EZ)^2 f(z)dz$$  \hspace{1cm} (18)$$

3. Estimation of the Susceptibility Coefficient for an Example Electronic Component

In order to illustrate the course of action and application of the developed method, aimed at describing the susceptibility of an electronic component to a standardised type of disturbance, a signal diode was selected for testing. This element is an integral component of the circuit for which the immunity coefficient will be estimated. The component that was tested was a popular signal diode of the LL4148 series. The testing of this diode consisted of exposing it once to a 1.2/50 $\mu$s surge. After exposure in one shot, the threshold voltage of the diode was checked using a multimeter. A UCS500N5 generator from EMTest was used for surge generation. A CNV 504 coupling and decoupling network was used to inject the surges (Figure 1).

![Test circuit diagram for testing the LL4148 diode.](Figure 1)
The results of tests carried out on a representative sample of 1000 LL4148 diodes in a SOD80-C housing are presented in Table 1. During the tests, the sample was divided into ten random series of N = 100 diodes, in which, at disturbance levels close to the critical value (the value leading to permanent diode failure), the number of failed diodes was analysed using an alternative classification. In the alternative classification, the tested elements were divided into two sets, faulty and good elements. During the experiment, each series of 100 diodes was exposed once to a 1.2/50 μs surge. The tests carried out showed that 800 V is the threshold level of disturbance, at which no diodes undergo the process of permanent damage when a surge is applied to them. The diode damage process was analysed at the nominal allowable value of its current (IF(AV) = 150 mA). For successive runs, the surge level was raised by ∆u = 20 V and the number of damaged diodes was recorded within each run. The increase in surge level is related to the increase in the number of faulty elements in the series. Knowing the number of damaged elements allows the construction of an empirical cumulative distribution function, which is the starting point for the statistical analysis of the probabilistic properties of the population of elements represented by the tested sample. This course of action ultimately allows for the determination of a mathematical model for the population under test. The mathematical model of the population is the theoretical distribution of a random variable.

Table 1. Test results of the LL4148 diode on 1.2/50 μs surge.

<table>
<thead>
<tr>
<th>z (V)</th>
<th>m(z)</th>
<th>n(z)</th>
<th>F*(z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>820</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>840</td>
<td>2</td>
<td>100</td>
<td>0.02</td>
</tr>
<tr>
<td>860</td>
<td>10</td>
<td>100</td>
<td>0.1</td>
</tr>
<tr>
<td>880</td>
<td>25</td>
<td>100</td>
<td>0.25</td>
</tr>
<tr>
<td>900</td>
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<td>100</td>
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<td>70</td>
<td>100</td>
<td>0.70</td>
</tr>
<tr>
<td>940</td>
<td>90</td>
<td>100</td>
<td>0.90</td>
</tr>
<tr>
<td>960</td>
<td>96</td>
<td>100</td>
<td>0.96</td>
</tr>
<tr>
<td>980</td>
<td>100</td>
<td>100</td>
<td>1.00</td>
</tr>
</tbody>
</table>

With the assumed definition of the cumulative distribution function \( F(z) = P(Z < z) \), its estimate is the empirical cumulative distribution function \( F^*(z) \), defined as the frequency of the event \( Z < z \), according to the formula:

\[
F^*(z) = \begin{cases} 
0 & \text{for } z \leq z_1 \\
m(z_i)/n(z_i) & \text{for } z_i < z \leq z_{i+1} \\
1 & \text{for } z > z_N 
\end{cases}
\]  

(19)

The results can be plotted in Cartesian coordinates or using a suitable function grid (Figure 2). A property of graphical methods for statistical inference, including function grids, is that they can be used to:

- test the validity of the hypothesis on the functional form of the distribution of a given trait;
- make a point estimate of one or two unknown distribution parameters.
for the is the expected value of the disturbance level for this distribution and \( \sigma \) is the
unknown parameters for an assumed significance level of 95%. For \( \alpha = 0.05 \) and \( n = 10 \), the tabulated critical value of the statistic was \( W(0.05; 10) = 0.842 \). Thus, there is an inequality \( W > W(0.05; 10) \), which means that there is no basis for rejecting the hypothesis of normal distribution of the analysed data. Also, the calculated \( p \)-value = 0.063 is greater than the accepted significance level \( \alpha = 0.05 \), \( (p > \alpha = 0.05) \), which means that the data have a normal distribution.

In order to confirm that the number of faulty diodes in the analysed disturbance level range is characterised by a normal distribution, the Shapiro–Wilk test was conducted. This test allowed us to conclude that the analysed community is characterised by a normal distribution. For \( m(z) \), included in Table 1, a statistical value of \( W = 0.853 \) was calculated for an assumed significance level of 95%. For \( \alpha = 0.05 \) and \( n = 10 \), the tabulated critical value of the statistic was \( W(0.05; 10) = 0.842 \). Thus, there is an inequality \( W > W(\alpha, n) \), which means that there is no basis for rejecting the hypothesis of normal distribution of the analysed data. Also, the calculated \( p \)-value = 0.063 is greater than the accepted significance level \( \alpha = 0.05 \), \( (p > \alpha = 0.05) \), which means that the data have a normal distribution.

If a given characteristic has a normal distribution, the course of its empirical distribution can be approximated by a function expressed by the relation:

\[
F(z) = \frac{1}{\sqrt{2\pi} \sigma} \int_{-\infty}^{u} \exp \left( -\frac{(z - \mu)^2}{2\sigma^2} \right) dz
\]

(20)

where \( \mu \) is the expected value of the disturbance level for this distribution and \( \sigma \) is the mean deviation of the expected value.

To avoid the problem of calculating an integral expression, very often the cumulative distribution function for a normal distribution is written using the tabulated Laplace integral \( \Phi(\tilde{z}) \) in the form:

\[
F(z) = 0.5 + \Phi \left( \frac{z - \mu}{\sigma} \right)
\]

(21)

To use relation (20) or (21) and determine the probability of failure of a component (system) for a certain level of disturbance, the unknown parameters \( \mu \) and \( \sigma \) for the theoretical distribution must be estimated based on the empirical distribution waveform. To estimate the values of parameters \( \mu \) and \( \sigma \), the waveform of the cumulative distribution

![Figure 2. The course of the empirical cumulative distribution function in Laplace regular grid coordinates.](image-url)
function plotted on a Laplace regular grid can be used. In such a grid, the distribution of the normal distribution is a straight line with the following equation:

\[ y = -\frac{Z - \mu}{\sigma} + \frac{1}{2} \]  \hspace{1cm} (22)

in which \( Z \) and \( \sigma \) are estimates of the unknown values of \( Z \) and \( \sigma \). The estimate \( Z \) of the unknown value of \( Z \) is the abscissa \( z \), corresponding to distribution \( F(z) = 0.5 \), and the estimate of the unknown value of \( Z \) is half the difference of the values of the argument \( z \), corresponding to the values of distributions \( F(z) = 0.84 \) and \( F(z) = 0.16 \).

Based on the values for the analysed example in Figure 2, the values \( Z = 904 \) V and \( \sigma = 25 \) V were obtained after calculations according to the described algorithm. The \( Z \) and \( \sigma \) estimators determined in this way fully allow for a mathematical notation of the course of the normal distribution for the strength function (in this case for a 1.2/50 \( \mu \)s surge):

\[ F(z) = 0.5 + \Phi \left( \frac{z - 904}{25} \right) \]  \hspace{1cm} (23)

The function thus written is an approximation function of the empirical distribution (Figure 3). Calculated for any value of \( z \), it expresses the probability of failure of an element for a given level of disturbance.

Using relation (23) for a known distribution, the immunity function (Figure 4) can be determined. For a normal distribution, it has the form:

\[ R(z) = 0.5 - \Phi \left( \frac{z - Z}{\sigma} \right) \]  \hspace{1cm} (24)

![Graphical illustration of the cumulative distribution functions of empirical R*(z) and theoretical F(z), and susceptibility function of empirical W*(z) and theoretical W(z) for the case of complete failure of the LL4148 diodes, with an increase of 1.2/50 \( \mu \)s surge.](image)

The strength function thus described is a measure of the component’s ability to operate correctly. In the case of electronic components, which are non-renewable objects, it expresses the probability of the component not failing, at least up to disturbance value \( z \).

The determined estimators of immunity distribution \( Z \) and \( \sigma \) may be parameters that describe the resistance of an electronic component to a defined type of disturbance, similarly to the rated current of a diode or transistor, resistance of a resistor, or capacitance of a capacitor. Including them in the catalogue data would allow the designer of an electronic circuit to properly select the components for the class of environment in which the circuit will operate and to predict its immunity.
On the basis of the analysis carried out, it can be proposed to describe the immunity of an electronic component using the $R_{NS}$ factor, described by parameters $Z$ and $\varphi$ and characteristic of normal distribution:

$$R_{NS,XXX} = (Z, \varphi)$$  \hspace{1cm} (25)

The subscript $N$ indicates that the given parameters refer to a normal distribution, while $S$ describes the immunity of the component to a surge of $1.2/50$ μs.

In the considered case, the factor for diode LL4148 is as follows:

$$R_{NS,LL4148} = (904 \text{ V}, 25 \text{ V})$$

Knowing the value of the $R_{NS}$ factor, it is possible to determine a number of other quantities that characterise the failure process of components when disturbances are applied to them.

The probability density function $f(z)$, which describes the instantaneous failure rate of the tested elements, can be determined from the defining relation by differentiating the strength function or the distribution. In the case of a normal distribution, it is as follows:

$$f(z) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{(z - \mu)^2}{2\sigma^2} \right]$$  \hspace{1cm} (26)

The graphical representation describes the instantaneous damage rate of the elements for continuous or discrete values of the disturbance (Figure 5).

In reliability theory, damage intensity $\Lambda(z)$ is a very important parameter. Using it, we can build reliability models that describe the probability that an object will operate with an assigned function in a set of external factors in time. In the case of the analysed disturbance immunity of electronic components, its meaning remains the same, only the argument changes. The argument is the level of disturbance, whereas in the case of reliability, it is time. An increasing level of disturbance leads to an increase in the probability of damage to an object, component, or system. The damage intensity function $\Lambda(z)$ is determined as the quotient of the probability density function and the strength function. For a normal distribution, it is as follows:
\[ \lambda(z) = \frac{f(t)}{R(t)} = \frac{\exp \left( -\frac{(z-U)^2}{2\sigma^2} \right)}{\int_{-\infty}^{\infty} \exp \left( -\frac{(z-U)^2}{2\sigma^2} \right) dz} \] (27)

![Graphical illustration of the empirical function f(z) and the theoretical function λ(z) of the probability density of complete failure of LL4148 diodes, with increasing surge level 1.2/50 µs.](image1)

Figure 5. Graphical illustration of the empirical function \( f'(z) \) and the theoretical function \( f(z) \) of the probability density of complete failure of LL4148 diodes, with increasing surge level 1.2/50 µs.

It describes the rate of damage to the components of a given set of elements with increasing levels of disturbance. Its empirical and theoretical course for the analysed example is presented in Figure 6.

![Graphical illustration of the empirical function \( \lambda'(z) \) and the theoretical function \( \lambda(z) \) of the damage density of complete failure of LL4148 diodes, with increasing surge level 1.2/50 µs.](image2)

Figure 6. Graphical illustration of the empirical function \( \lambda'(z) \) and the theoretical function \( \lambda(z) \) of the damage density of complete failure of LL4148 diodes, with increasing surge level 1.2/50 µs.

By integrating the course of the damage intensity function over a given interval of disturbance level \( z \), the course of the cumulative damage intensity function is determined.

\[ \Lambda(z) = \int_{0}^{z} \lambda(\xi) \cdot d\xi \] (28)

This is known as the stock function. It describes the depletion of an object’s ability to operate with the tasks imposed on it.

The presented procedure for determining the susceptibility coefficient of an electronic component can also be used directly to determine the immunity and susceptibility of the component to a defined type of disturbance. By adopting the appropriate criteria...
to identify reversible and irreversible changes in the parameters of electronic objects, the corresponding distributions can be determined and their parameters can be used to describe the immunity and susceptibility of a system component to a defined type of disturbance.

4. Conclusions

Electromagnetic compatibility regulations in the European Union require manufacturers and exporters of electrical and electronic equipment to ensure and confirm the immunity of finished electrical and electronic equipment to defined types of disturbances. The type of standardised disturbance is chosen according to the target environment of the device. Very often in laboratory practice, when checking the immunity of electronic devices to standardised types of disturbance, we encounter the problem of determining how far the exposure value is from the permissible value specified in the standard which can lead to a disruption of the proper operation of the device or to its permanent damage. The technique presented in this paper for determining the immunity factor of an electronic component or system allows us to obtain such an answer.

Knowing the values of immunity coefficients for a given class of components, it is possible to compare them qualitatively and to theoretically estimate such coefficients for the systems from which they will be made.

The results of tests for one component, which was a popular LL4148 signal diode, have been presented in this paper. Using the proposed course of action, parameters were determined for the tested diode which allowed one to determine the probability of its failure in the presence of an electromagnetic disturbance and, finally, the damage intensity function important for reliability analyses. The determined immunity factor describes the characteristics of the element in this range, but also allows for a comparison of elements made by different manufacturers.

As indicated by the results of the current research on basic electronic components, for each type of component, it is possible to define a threshold disturbance value that causes no change in their parameters, a disturbance value that leads to parametric changes, and a threshold value that leads to catastrophic damage. These values depend on the type of component, its implementation technology, its place in the application or the loading condition of the components. For the first range of disturbance values, the energy is so small that it does not lead to any changes in the structure of the materials of which they are made. For the parametric change range, a change can be observed, e.g., in the threshold voltage for the PN junction or in a permanent change in the static and dynamic characteristics of the active elements. In the case of resistors, there is a permanent change in their characteristic resistance, and in the case of capacitors, in their capacitance. If a characteristic parameter of an element goes out of tolerance, the element can be considered damaged.

The proposed concept of building a model for the susceptibility of an electronic component, presented on the example of the LL4148 signal diode, can be generalised for any electronic component and ultimately for a whole system. By introducing the susceptibility factor into the set of parameters characterising the properties of electronic components, it would be possible to predict and also model the strength of a system according to the requirements set by its environmental class. By selecting all components with known strength factor values for the designed system, it would be possible to determine this factor for the entire system and then the probability of system failure for any value of disturbance level.

Extending the group of reliability indicators for components to include quantities characterising their resistance to defined types of electromagnetic disturbances would make it possible to significantly shorten the design and design verification cycle. Such an indicator, like the voltage, rated current, or admissible power of an element, would be a determinant in the selection of components, according to the class of environment in which the designed device will operate.

The presented method of determining the susceptibility of an electronic component to a defined type of disturbance has an innovative character. Using the proposed technique, it
is possible to determine a parameter that determines the susceptibility/immunity of an element to a defined type of electromagnetic disturbance. The proposed technique can be used to predict the susceptibility of components, circuits and systems. This method can be used to compare components from different manufacturers, with different technologies, performing, for example, the same function in a system. Knowledge of these coefficients can be helpful in designing, for example, a system with increased immunity. In addition, this technique can be used in comparative tests to establish an agreement between laboratories in resistance tests for a standardised type of disturbance, for example, in ESD immunity tests according to IEC 61000-4-2 or shock immunity tests according to IEC 61000-4-5. As the results of these tests show, by selecting components from the same production run, it is possible to achieve consistency in the susceptibility/immunity functions of components tested in different laboratories.

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**References**


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