**Electromagnetic Compatibility (EMC) Testing of Power Transformers**

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**Abstract.** The article covers the processes of determining and assessing the electromagnetic compatibility parameters of power transformers. The methodology for testing electromagnetic and induced effects, as well as the analysis of existing international standards and calculation methods, is discussed. Based on calculation results, mathematical models, and data from standards, spectral graphs are generated. Factors influencing the electromagnetic compatibility level of transformers and recommendations for their reduction are provided. Furthermore, based on the conducted research, it is concluded that ensuring the correct evaluation of electromagnetic compatibility of power transformers guarantees their safe and efficient operation throughout their service life.

**Keywords:** electromagnetic compatibility, field strength, resistance to electromagnetic interference, power transformers, spectral graph, mathematical model

**INTRODUCTION**

It is well known that power transformers play a crucial role in the transmission and distribution of electrical energy within the power supply system. During their operation, the electromagnetic field generated by transformers may adversely affect the performance of other devices. Therefore, testing transformers from the perspective of electromagnetic compatibility is of significant importance for modern power systems. Moreover, one of the key indicators of an electrotechnical device is its ability to operate efficiently throughout its service life within a defined area without causing electromagnetic interference to other equipment [1, 2, 3].

**METHODS**

When testing power transformers for electromagnetic compatibility (EMC), the following factors are taken into account: the level of electromagnetic field strength (Radiated Emission), electromagnetic disturbances transmitted through electrical conductors (Conducted Emission), and the degree of immunity to electromagnetic interference (Immunity) [2].

The testing process is carried out in accordance with IEC 61000-4-3, CISPR 11, and IEEE Std C57.12.90 standards, using instruments such as a spectrum analyzer, EMI antenna, and LISN (Line Impedance Stabilization Network) for measurement and signal reception.

**RESULTS AND DISCUSSION**

During the operation of power transformers, changes in the magnetic field generate electromagnetic waves that propagate into the surrounding environment. These waves can negatively affect radio communications, electronic equipment, and automated systems. Such influences determine the electromagnetic field strength levels within the systems. Therefore, identifying the level of electromagnetic field strength and verifying its compliance with regulatory standards are essential steps in ensuring electromagnetic compatibility [4, 5].

The measurement of electromagnetic field strength in power transformers is carried out within the frequency range of 30 MHz to 1000 MHz (in some cases up to 3 GHz). The measurement process is conducted using an EMI antenna positioned at distances of 3 meters and 10 meters. Measurements are performed either in an open area with minimal external interference or in a simulated enclosed environment.

Before starting the measurement process, the power transformer is brought into its operating state, and vertical and horizontal antennas are placed nearby at the required distance (3 meters or 10 meters). By rotating the transformer 360°, the maximum value of the magnetic field strength is determined within the frequency range of 30 MHz to 1000 MHz, and a spectral analysis graph is generated for this range [1].

According to CISPR 11 or IEC 61000-6-4 requirements, when the frequency is varied within the range of 30–230 MHz, a maximum magnetic field strength of 100 µV/m (40 dBµV/m) is allowed at a distance of 10 meters from the transformer. In the frequency range of 230–1000 MHz, the permitted maximum is 223.87 µV/m (47 dBµV/m).

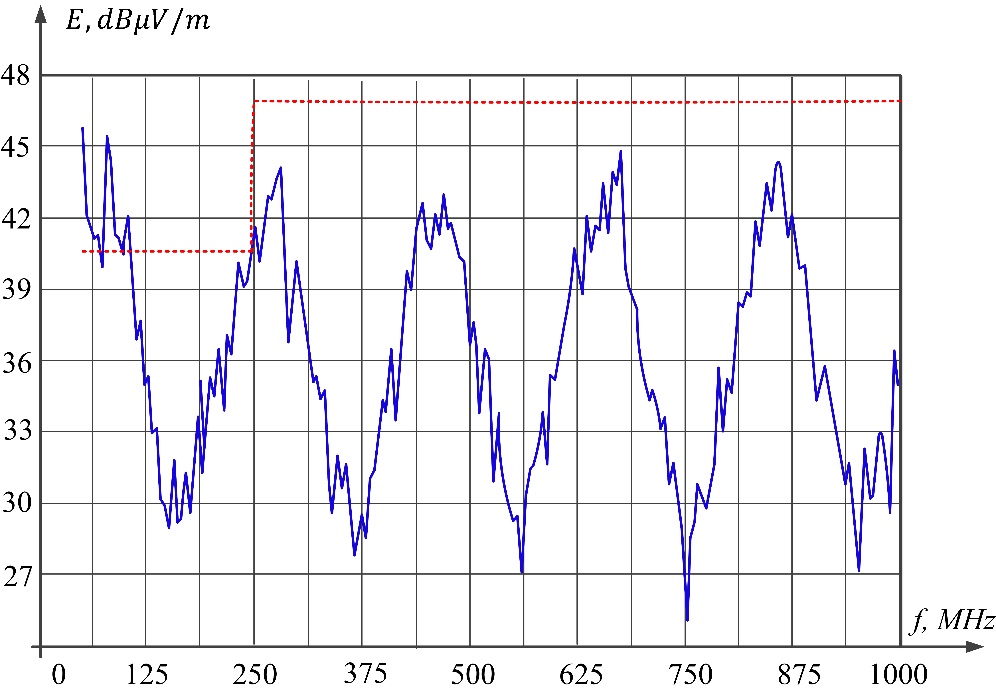
The results of the electromagnetic field strength of the power transformer are presented in the form of spectral graphs. These graphs make it possible to clearly identify the frequencies at which limit exceedances occur (Figure 1). The tests are conducted for all operating modes of the transformer, including short-circuit, rated load, overload, and no-load conditions. If any exceedances of permissible levels are detected, mitigation measures such as shielding, filtering, and grounding of the power transformer are applied. Furthermore, conclusions are drawn regarding whether or not the transformer meets EMC requirements.

To represent this process using mathematical models, we derive expression (1), which allows determining the dependence of the electromagnetic field strength of the power transformer on frequency. In doing so, the factors with the greatest impact on the accuracy of electromagnetic effect determination are taken into account.

(1)

here, – frequency-dependent electromagnetic field strength, in dBµV/m; – baseline electric field strength, approximately 35 dBµV/m; – amplitude of electric field strength fluctuations, approximately 7 dBµV/m; – frequency-dependent oscillation coefficient (≈ 0.01π); – random variation at each point, assumed to follow a normal distribution , where .

The graph obtained from expression (1) exhibits continuous sinusoidal oscillations. Additionally, this graph depicts a boundary line H (f) that corresponds to the permissible value of electric field strength. This boundary line varies within a certain range: H (f) = 40 for f ≤ 230 MHz, and H (f) = 47 for f > 230 MHz. If , the electric field strength is considered to be above the norm, and recommendations are provided for taking measures to reduce it.



**FIGURE 1. Spectral graph of electromagnetic field strength measurement in a power transformer:***dashed line – regulatory limit, solid line – measured actual values*

Electromagnetic disturbances transmitted through conductors primarily occur via power supply lines, neutral wires, and grounding conductors. These disturbances are typically observed within the frequency range of 150 kHz to 30 MHz.

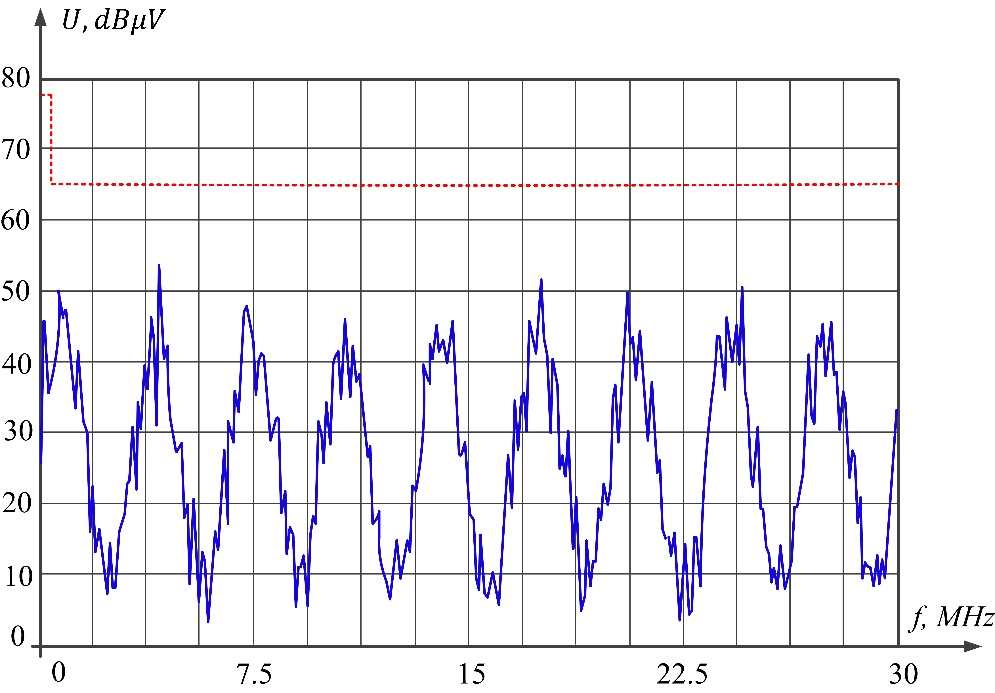
To detect conducted electromagnetic disturbances, the system is connected to the network via a LISN (Line Impedance Stabilization Network). The LISN device allows the power signal to pass through while isolating and filtering the interference signals, which are then measured using a spectrum analyzer [4]. Measurements are performed separately for each conductor (line and neutral). In most cases, significant interference is observed in the vicinity of the initial 5 MHz range.

According to the CISPR 11 standard, when changing the frequency in the range of 0.15 - 0.5 MHz, it is allowed to generate an electromagnetic signal of 79 dBμV (0.0089 μV), when changing the frequency in the range of   
0.5 - 5 MHz - 73 dBμV (0.0045 μV), when changing the frequency in the range of 5 - 30 MHz - 73 dBμV   
(0.0045 μV). The spectral graph of the detection of electromagnetic effects propagated through electrical conductors is presented in Figure 2.

To assess the electromagnetic effects propagating through an electrical conductor in accordance with established standards, we will develop its mathematical model. For this purpose, we will derive expression (2), taking into account the quantities and parameters that generate these electromagnetic influences.

(2)

here, – frequency dependence of electromagnetic voltage level, dBµV; – electromagnetic interference baseline level, approximately 55 dBµV; – electromagnetic interference amplitude, approximately 8 dBµV;  
 – frequency-dependent periodic oscillation coefficient (≈0.6π); – phase shift angle; – random variation at each point, , .



**FIGURE 2.** Spectral graph of electromagnetic effects propagating through electrical conductors:   
*dashed line – normative limit, solid line – measured actual values*

This mathematical expression makes it possible to analyze the frequency-dependent variations of electromagnetic effects in the device, taking into account the noise generated under normal operating conditions.

If the level of electromagnetic effects in the tested device is found to exceed the normative limits, measures are taken to reduce these electromagnetic effects. Such measures include the use of EMI filters (LC and π-filters), ferrite beads and chokes, grounding, shielding of wires and enclosures, as well as the optimization of PWM algorithms [7].

To ensure that electrical devices can operate without malfunction under external electromagnetic influences, their electromagnetic immunity characteristics are tested. Modern devices must demonstrate reliable, uninterrupted, and accurate performance even under exposure to external electromagnetic disturbances.

Electromagnetic immunity to external disturbances varies depending on the source of the interference. Electrotechnical devices are tested for resistance to airborne radio frequency waves (80 MHz÷1 GHz, 3÷10 V/m), conducted disturbances via power supply lines (150 kHz÷80 MHz, 3÷10 V), electrostatic discharges (±2÷±8 kV), high-frequency transients (1 kV ÷4 kV), short-duration voltage surges (1.2/50 µs, 2 kV÷6 kV), tested for resistance to magnetic field effects [6].

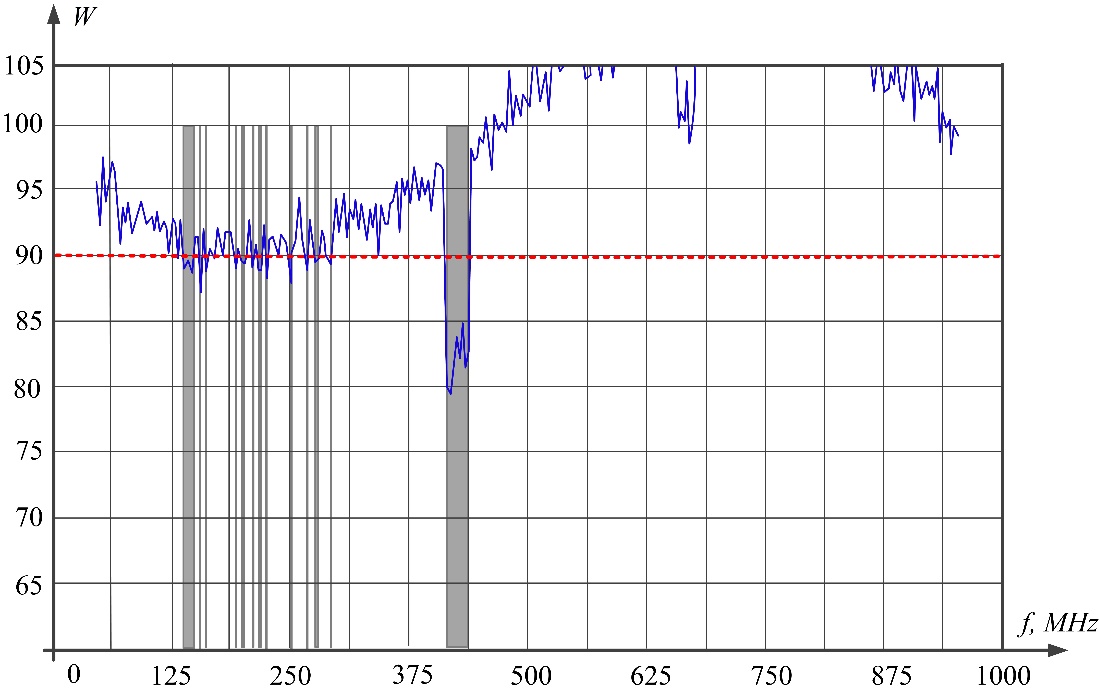
During testing for resistance to airborne radio frequency waves, the electrotechnical device is first placed inside a shielded chamber. Radio waves with an electric field strength of 3 to 10 V/m are transmitted using an antenna, and the frequency is gradually increased from 80 MHz to 1 GHz. Throughout the test, the device’s operation is monitored. If the LCD brightness changes, it indicates that the interference is within the acceptable limit. Conversely, if the device restarts, it means the tested device is not immune to the external radio frequency interference. The spectral graph for determining the resistance of electrotechnical devices to external electromagnetic influences is presented in Figure 3.

To mathematically assess the resistance of an electrotechnical device to external electromagnetic influences, we derive mathematical model (3), which represents the variation of the system frequency under the influence of these effects.

(3)

here, – the device’s operational capability at a specific frequency, %; – ideal operation of the device, %; – the device’s sensitivity level.

During the test, if , the device does not meet the requirements for this parameter; conversely, if  
, it is concluded that the device operates within the normative limits for this parameter. Additionally, using the developed mathematical model, it is possible to determine the frequency range in which the device exhibits increased sensitivity [8, 9, 10].



**FIGURE 3.** Spectral graph illustrating the electromagnetic immunity of electrotechnical devices:   
*red line represents the normative limit, solid line shows the measured actual values, and dashed lines indicate hazardous frequency ranges for device operation*

If the tested electrotechnical device is found to be non-resistant to external electromagnetic interference, measures to improve its electromagnetic immunity are implemented. These include shielding (covering the enclosure and conductors with a metal coating), filtering (using EMC filters and ferrite beads), and grounding through low-resistance grounding conductors.

**CONCLUSION**

According to the conducted research, it has been determined that the correct evaluation of the electromagnetic compatibility of power transformers (the degree of electromagnetic field intensity, electromagnetic effects spread through conductors, and the level of resistance to electromagnetic influences) ensures their safe and efficient operation.

Moreover, the calculation results presented in the article, mathematical models that allow determining the frequency range in which the device's sensitivity is highest, data obtained from standards, and the spectral graphs generated based on them, which indicate the electromagnetic field intensity, electromagnetic effects spread through conductors, and the resistance of electrical equipment to external electromagnetic influences, can be used by engineers in this field as a guideline [11, 12].

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