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Electromagnetic Compatibility and Radiation Analysis in Control Room

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The article presents a theoretical analysis of electromagnetic compatibility (EMC) and experimental measurement of effects of radiation and acoustic emission of high-voltage transformers for electronic equipment and working personnel in a control room. Electromagnetic compatibility and safety of equipment are not considered as two distinct areas of study in electric and electronic safety. Economic criteria cannot compromise safety but at the same time immunity levels must be relevant in order to establish a "Functional Safety". Introducing Special Immunity Levels in the level of equipment testing allows us to combine the two areas of EMC and safety. The measurement was carried out in high-current of very high-voltage distribution station. A real-life analysis of effects of electric and electromagnetic field was carried out. FFT was used for mathematical processing of data which were later presented in a graphical form of a spectrally analyzed area. In the last part of the paper we discuss the suitability of acoustic camera to perform contactless monitoring of the health and operation conditions of the power transformer by analyzing acoustic field generated by the transformer core and windings in near control room.

Keywords: Electromagnetic compatibility, spectral data processing, radiation frequency analysis, acoustic emission.

1. Introduction

Reliability and safety of communication devices are of paramount importance, regardless of the type of operation, their technology or conditions. Data transfer and handling is affected by numerous factors of various origins. Disturbances come in the form of signal distortion, undesired bonds, resonances, transient events, interference noises, and eventually possible destruction of equipment.

The limit of emittance resistance is defined as maximal permissible (permitted by, e.g., ISO or EN) limit of emittance for a particular electronic device [1], [2].

From the electromagnetic interference (EMI) viewpoint, the electromagnetic compatibility (EMC) reserve is defined as a range between Limit of resistance and Limit of emittance. Level of Resistance (Fig.1.) is the maximal level of disturbances affecting a particular piece of equipment at a point where operation is not made worse. Lowest Permissible Level of resistance of equipment is the level of resistance, and the range between them is the Reserve of Design of given equipment.

Similarly, a difference between emittance and resistance represents the EMC reserve of a given piece of equipment. International technical standards state that Compatible Levels are those that do not permit disturbances that may have detrimental effects on particular equipment in particular conditions. Reserve of Resistance and Reserve of Emittance are defined as differences between resistance and emittance towards compatible level.

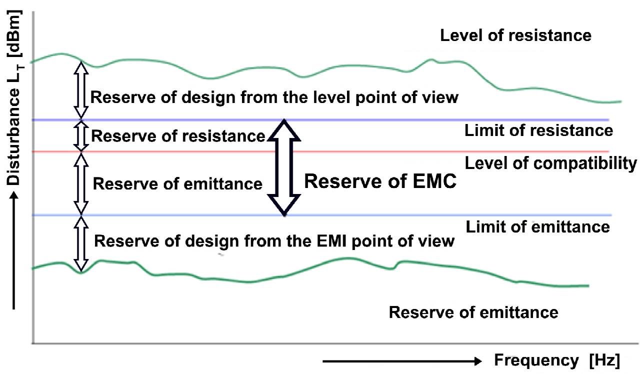

Fig.1. Compatible disturbance levels in relation to frequency.

If equipment is to pass the requirements of EMC, the level of its emittance must lie below the maximal permissible

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level, which means that limit of emittance must be below the limit of resistance, so a satisfactory Reserve of EMC is achieved. There is no defined numerical value of this reserve for EMI and EMC, and the value is set either by manufacturer themselves or by a customer specification.

Various EMC analyses prove that strong non-sinusoidal regimes occur, specifically for the currents in the transformer windings. Higher harmonic currents may cause new power quality and, respectively, EMC problems (including related Electromagnetic Interference problems), not addressed by existing standards [3].

2. INTERFERENCE BOND MECHANISM

Electromagnetic waves of desired frequency come from a source in the form of an oscillating circle. A charge emitting its electromagnetic energy to its ambient surroundings is the theory behind this phenomenon.

Closing a circuit with a charge, oscillations of capacitor current are formed and defined as

$$I = I_0 \sin \omega t \quad . \tag{1}$$

Thompson equation defines the ω radial frequency

$$\omega = \left(\frac{1}{LC}\right)^{1/2} \tag{2}$$

Accelerated (a) charge (q) is emitting below defined intensity of electromagnetic energy

$$W = \frac{2}{3}\frac{\mu_0 q^2 a^2}{4\pi c} \tag{3}$$

Dipole momentum p emitted from an electric dipole creates electromagnetic radiation with intensity

$$W = \frac{2}{3}\cdot\frac{\mu_0 p^2}{4\pi c} \tag{4}$$

where $p = \frac{d^2 p}{dt^2}$ and after modification

$$\frac{d^2 I}{dt^2} + \omega^2 I = 0 \tag{5}$$

A solution of equation (5) is the following function

$$I = I_0 \sin(\omega t - \varphi) \tag{6}$$

Analyzing the EM field normally consists of determining a vector of magnetic and electric intensity in any point. [4]

To process a signal, communication devices use higher frequencies; their dimensions are lower and connections tighter.

Forms of interferences are: [5]

- galvanic (different electrode potential of conductors),
- capacity (conductive objects creating parasitical capacitance),
- inductive (transfer of magnetic inductance),
- wave (capacity interference in combination with interference inductive while in parallel).

Field bonding (with its three distinctive sources): [6]

- electrostatic field (lower frequencies),
- magnetic fields (lower frequencies),
- electro-magnetic fields (frequencies in the orders of in MHz).

3. STATISTICAL ANALYSIS OF EMC PROBABILITY

Precise analysis of probability curves of the EM phenomenon is currently being discovered and studied. However, few detailed examples, such as protection from lightning or surge impulses, are less known. [7]

For practical usage it is possible only to rely on measurable influences of these phenomena on electrical equipment, namely on safety and reliability.

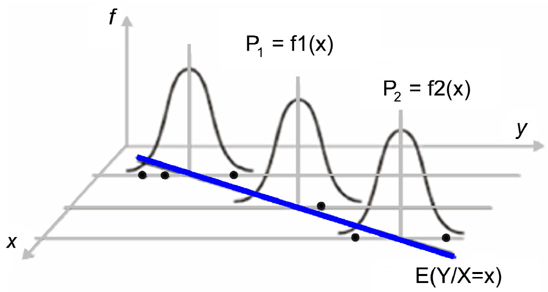

Fig.2. Relation Y and X: Variations around the regression line represented by the probability of a failure X as a result of disturbances.

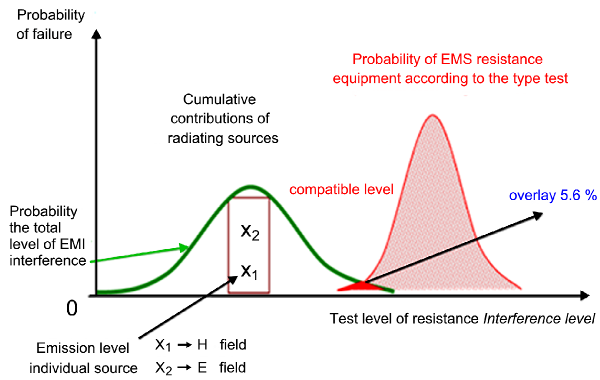

Fig.3. Relation of the probability of a failure as a result of disturbances.

Method of logical regression is particularly useful for statistical modelling of a probability of risk, what is an important procedure. Predicting the risk of an event (in our case possible failure) which depends on a known variable allows us to set disturbance signal as a variable while EMC reliability is being evaluated.

In Fig.2., there are indicated variations around the regression line, that are represented by the probability of a disturbance P1, P2 as a result of possible failures *x*.

In our scientific laboratory, influences of a failure unit to the point of terminal reliability have been studied. Mathematical formulations of a measured data file from a single unit with random X representing a random vector $X = (X_1, X_2, \ldots, X_p)$ are shown in Fig.3. as defined in [8]-[10].

4. EMI MEASUREMENTS BY SPECTRUM ANALYZER

In Fig.4., a sketch of a measuring apparatus in a control room in near high-voltage transformer is shown.

Technical specification of each component of equipment is in fact its own factor for a reliable operation without failure. Verification on a real component was carried out so the component that was designed on the basis of previous theoretical knowledge is in compliance with the technical standards.

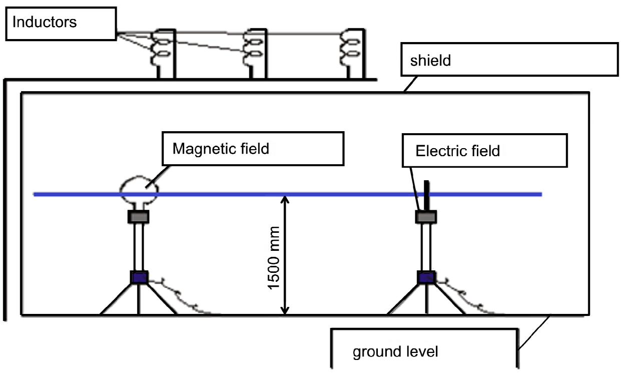

Fig.4. System layout for probes measuring magnetic field.

Experiments, as well as static and dynamic analysis of the system were carried out in both types of conditions: normal operating mode and non-liner load where transitions were present. To achieve such tests a careful selection of the measuring apparatus and probes is very important (Fig.5.).

The real measurement was performed by connecting output disturbance voltage and output of the probe, and furthers its quantitative evaluation and comparison with emission limits of a testing object – environment (Fig.6.). If the measured voltage waveform is harmonic, for this set-up we are able to connect low frequency meter to a receiver which works in linear regime.

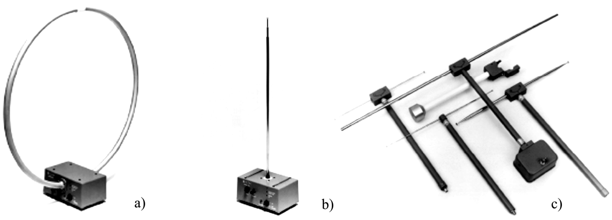

Fig.5. Measuring probes for: a) magnetic field, b) electric field, c) crow EM field.

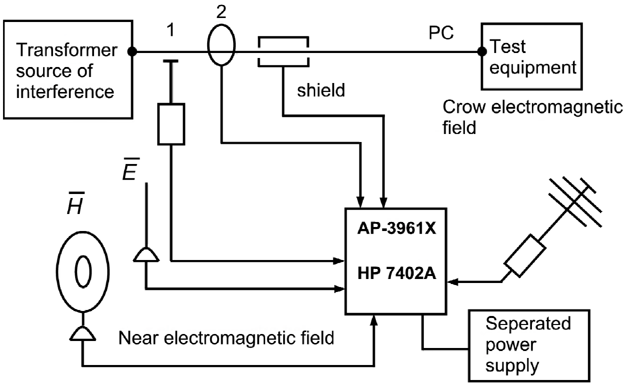

Fig.6. Layout of a testing plant equipped with measuring equipment.

In real life conditions, disturbance signals mostly come from waveforms which are not harmonic and have non-harmonic segments too. Limiting factors for a good quality measurement are: measuring system/apparatus specification, range, behavioral characteristics of modulus argument, and mutual inter-comparability. Our measuring equipment used for this experiment was a spectrum analyzer HP 7402A, RFI Meter with a special selective micro-voltmeter, which uses the superheterodyne principle (Fig.7.).

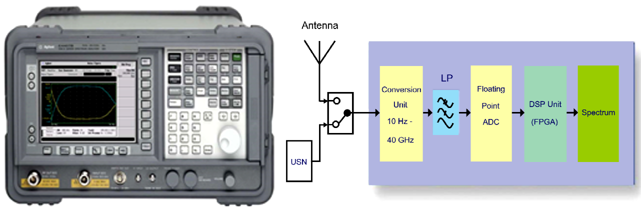

Fig.7. Measuring apparatus.

Comparing values of EMI measurement with the limiting values set by technical standards, frequency spectrum for each disturbance and their levels are absolutely necessary for each particular environment. The goal for these EMI measurements is to find a source for each disturbance, which eventually will result in elimination of undesired parasitic bonds of the source and receiver of disturbances.

To measure effects of disturbances it was necessary to divide them into groups of low and high frequency. For both groups, there is a separate methodology of measurement and separate measuring equipment. Disturbances produced by the source are transferred by in-line conduction and by radiation. Measuring conductive transfer was done by sensors of voltage and current with the supplement of artificial mains.

Radiation caused disturbances largely depend on homogeneity of electromagnetic fields (close and distant). Correlation of magnetic and electric part is the main characteristics of distant electromagnetic field which is measured at a distance $r > \lambda/2\pi$ from the dipole antenna – source of disturbance [11]-[13].

As for the closed electromagnetic field, the electric part was measured by anisotropic radiator and the magnetic part by a frame antenna.

Exact locations of measurements were pinpointed by the investor where experience suspected the presence of high intensity of electromagnetic field, and also in the control rooms from which operations were either monitored or controlled. Measuring was performed in high-current of very high-voltage distribution station.

Further measurements were carried out on all devices in control stations, measuring and control equipment responsible for reliable operation (Fig.8. and Fig.9.).

According to Fig.8. and Fig.9., maximal EMC values of electric and magnetic field were measured for the test control room: before screening 1.1 kV/m and 25 µT, and after screening 0.89 kV/m and 9.89 µT.

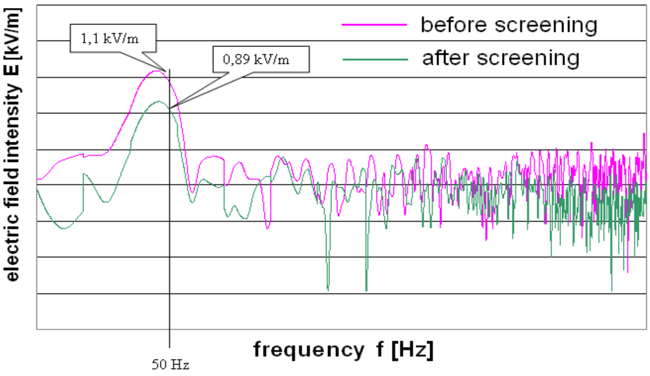

Fig.8. Electric part of electromagnetic field in a control room.

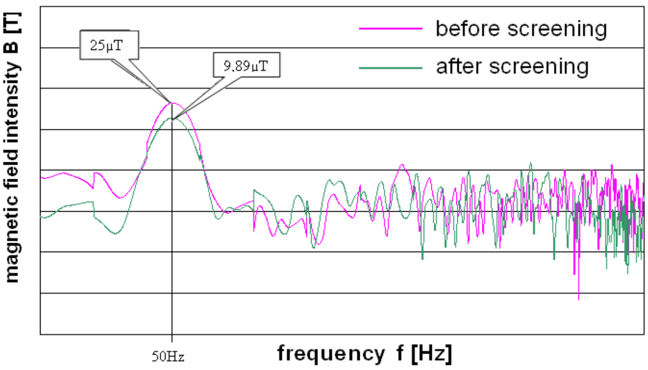

Fig.9. Magnetic part of electromagnetic field in a control room.

Concurrently, analysis of biocompatibility was carried out, with the viewpoint on how operating personnel was affected. FFT was used for processing of data which were later presented in a graphical form in the spectral domain. Measured values, which determine the behavior of electromagnetic field, were then compared to permissible values as set in ENV 50 166 – 1 (Fig.10.).

From the experimentally obtained data, which were then analyzed and evaluated, we could give suggestions how to safely operate sensitive electronic equipment in an environment with known and defined detrimental effects from the EMC point of view.

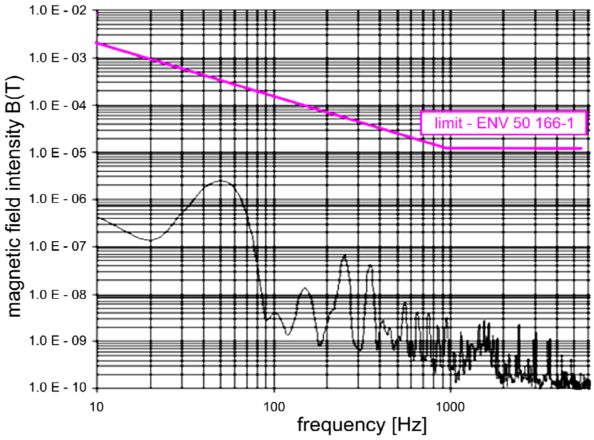

Fig.10. Magnetic part of electromagnetic field with limit ENV 50 166-1.

5. MEASUREMENT OF ACOUSTIC EMISSION BY ACOUSTIC CAMERA

An acoustic emission (AE) analysis was used to complement this measurement. Here we proposed the method of contactless measurement of AE by acoustic camera placed at a distance of several meters from the transformer in the direction of the control room (Fig.11.).

Fig.11. View for measured transformer with acoustic camera.

Such a measurement may be an additional analysis of the effect of an interfering electromagnetic field on a given object.

The vibrations in core and coil produce AE with maximal energy in the audible frequency range. Such AE has mainly tonal character with the fundamental frequency related to frequency of electrical current. Due to nonlinear dependence between electromagnetic forces and mechanical vibrations, fundamental frequency is usually twice the frequency of the current, i.e. 100 Hz, and spectrum of the AE is rich on higher harmonics. In addition, noise generated by magnetoacoustic emission causes random high-frequency fluctuations in the acoustic waveform [14], [15].

In [16], [17], and [18], there was proven that measurements of tank vibrations could be used for detecting deformations and monitoring of operational load of transformer windings.

Phased-array signal processing is one of the widely used techniques for acoustic emission (AE) remote sensing and measurements. Acoustic camera [19] is a modular system enabling such phased-array acoustic signal sensing and processing, and enables it to visualize acoustic field and localize acoustic emission sources. A basic configuration of acoustic camera is a microphone array, data recorder, and data processing software. Multi-channel processing of audio signals from a microphone array allows for 3D filtering of the acoustic field. Hence, such a system is able to focus on the particular point of a sound field and measure spectro-temporal variations of acoustic waves in any place of the space being monitored. Space / frequency resolution depends on the size of the microphone array.

Thus, the use of the camera in transformer diagnostics has two advantages: a) It allows the precise localization of the source of AE; b) It enables a detailed analysis of the sound field, allowing the microphone array to be directed and focused on, in particular, to eliminate interference from the surroundings.

Experiments with measurement of acoustic emission by acoustic camera and digital system for spatial and spectral analysis of acoustic field, and noise map generation have been carried out. The microphone field consisted of 128 microphones spread out on concentric circles on a circular disc with a diameter of 0.4 m. Such microphone field with a diameter of 0.4 m enables to locate acoustic sources and visualize the noise map in the frequency range from 316 Hz up to 15 kHz [20].

Fig.12. shows intensity of AE radiated by the transformer. From the figures it is clearly seen that the maximum intensity is located in different positions for different frequencies.

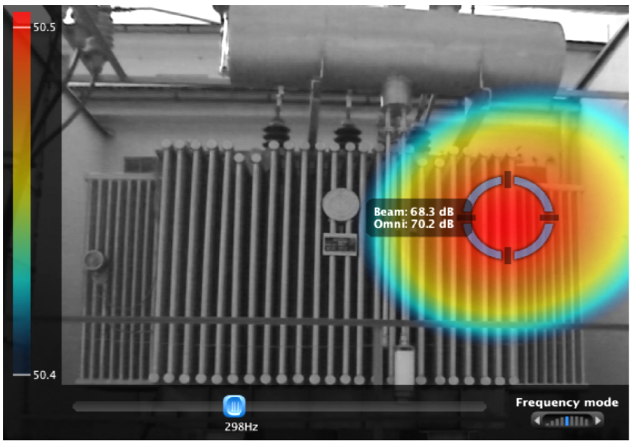

Fig.12. Visualization of acoustical intensity radiated by the transformer - an acoustic field of the 6th harmonic (300 Hz).

Fig.13. shows a graph of acoustic spectrum of the given acoustic field. From the graph, the fundamental frequency of 100 Hz and its higher harmonics are clearly visible. The spectral envelope has almost constant level up to 1200 Hz. Over this frequency, spectral level decreases by about 20 dB per octave. Note that the upper limit of the acoustic camera range is 20 kHz and is not able to measure AE from particle discharge.

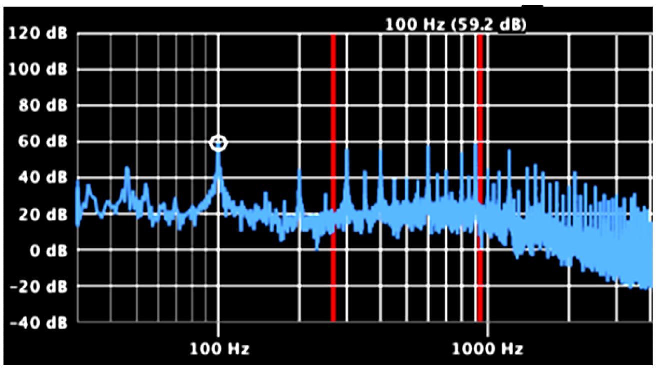

Fig.13. Spectrum of the acoustic emission source. Band-limited acoustic field and its spectrum at the cursor position. Spectral peaks represent higher harmonics of the power supply fundamental frequency of 50 Hz. The selected frequency band is marked by two red lines in the spectrum graph, and it covers a range from 6th harmonic (300 Hz) up to 18th harmonic (900 Hz).

6. Conclusion

A real-life analysis of effects of electric and electromagnetic field was carried out by a spectrum analyzer supplemented by the analysis of acoustic emission by acoustic camera.

Analysis and evaluation allowed us to set clear function criteria A, B, and C for a safe and failure-free operation of equipment.

Based on measurements it can define measures for proper operation of the equipment and their effects for electronic devices and operating personnel.

Additional analysis suggests that measures can in fact be taken to achieve near total functionality of a given piece of equipment for a dealt environment. Performing complex measuring of detrimental influences of electromagnetic field as per respective technical standards in the above-mentioned plant allowed us to design a set-up for safe working of equipment and a safe environment for operating personnel. Data and knowledge gained in these in-situ measurements open new horizons for further studies which eventually could result in a mathematical model that can be used in larger plants to establish immunity to detrimental effects.

Additional measurements by acoustic camera are advantageous for comparing the size of the acoustic signal with the EMC analysis signal and their interconnection in the subject matter.

During the measurement we found out, the localization of AE sources was very limited due to the placement of the transformer in the enclosed tank. But the acoustic camera seems to be able to localize the maximum of the individual frequency modes on the tank surface. So, such remote contactless sensing might replace the vibration sensors fixed to the tank surface. Thus, our future work will also be focused on examinations of connections between the distribution of the frequency modes on the tank surface and the operational conditions of the transformer. It is expected that the mechanical failure of the transformer would be possible to identify its locality and size.

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