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EFFECTS OF INDEPENDENT MAGNETIC FIELDS IN THE VERY LOW FREQUENCY RANGE ELF GENERATED BY SELECTED ELEMENTS OF AN ELECTRIC TRACTION UNIT ON THE AMBIENT ENVIRONMENT AND ELECTRONIC SYSTEMS

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Abstract – The article presents research results and issues related to of magnetic component of electromagnetic field on the environment and electronic systems used in the electric traction unit. The electronic systems used and built into an electric power unit are operated in a wide variety of environmental conditions. Electrical and electronic systems with different purposes coexist on the vast railroad area, and an important operational problem, apart from environmental changes in which these technical objects are operated, is also the issue of external and internal electromagnetic compatibility. Depending on the extent of the railroad area, the intentional or unintentional emission of electromagnetic fields over a range of frequencies, the construction, technical configuration and method of ensuring electromagnetic compatibility for the electrical and electronic systems in use and electronic systems in use are different. It is necessary to skillfully and appropriately use all measures included in the electromagnetic compatibility pyramid to ensure the appropriate level of robustness, immunity and susceptibility of the above mentioned systems. Due to the impact and propagation of electromagnetic waves in the railroad environment, individual frequency bands of interfering signals should be considered separately for the whole spectrum of interfering signals. The article presents the results of research on the generated magnetic fields from the very low frequency (ELF) range by electric power units. Diagnosing the electromagnetic environment over the entire frequency range enables the realization and proper protection of the electrical and electronic systems used in an electric power train from the effects of unintended interference. Knowledge of the parameters of interfering signals - e.g. amplitude, frequency range, spectrum, etc. - will enable designers of electrical and electronic train systems to properly protect these facilities from adverse environmental conditions.

Key words – magnetic field, electric traction unit, frequency spectrum

INTRODUCTION

Diagnosis of electromagnetic fields in the workplace and public environment is essential for protection against adverse effects of electric and magnetic components on animate (human) and inanimate matter (e.g. systems: electronic, telematics, security, etc.) built in an electric multiple unit (EMU) [3,5,6,15]. The activities related to diagnosing electromagnetic fields include the following processes: identification of field source(s), determination of their parameter values – including spatial distributions and spectral characteristics. The definition of electromagnetic compatibility is the permissible conditions for the influence of external and internal electromagnetic fields on the operation of electronic devices and equipment containing electronic components or circuits. As defined in the international standard IEC 50 (161) z 1990 r., then included in the draft Polish Standard Pr. PN-T-01030 it is agreed that: *„Electromagnetic compatibility is the ability of a device or system to operate satisfactorily in a particular electromagnetic environment, including without introducing unacceptable electromagnetic disturbances into that environment".* The electronic systems and equipment (EES) used in electric multiple units operate under a wide range of operating conditions [7,12]. Their proper functioning in a given environment depends not only on the reliability of individual components that make up a given device or electronic system, but also on the level of electromagnetic interference across the electromagnetic wave spectrum. If the level of electromagnetic interference exceeds the permissible level of immunity, susceptibility or robustness to electromagnetic field effects, then the electronic devices and systems built in the EMU in a fully operational state can change to two technical states [8,14]:

A safety hazard condition (some functions of equipment or systems are performed inappropriately),

safety failure condition the occurrence of e.g. catastrophic failure - e.g. exceeded permissible voltage induced by a disturbance at the transistor terminal [9,10].

The mode of penetration of unintentional or intentional (stationary or mobile) sources of electromagnetic interference occurring in the EMU into the EES is shown in Figure 1 [12,13].

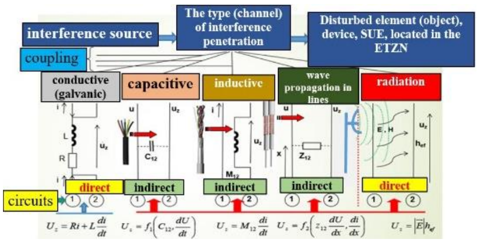

Fig. 1. Intrusion of electromagnetic interference from components, EES installed in an EMU generated intentionally or unintentionally

where: 1,2 circuits, i – current, U_z – disturbance voltage, C_{12} – coupling capacity, M_{12} – coupling factor, dU/dt, di/dt, itd. the rate of change of voltage, current in the circuit, z_{12} – coupling impedance, h_{ef} – Planck's constant.

Fig. 1 also shows the interference voltages Uz that are generated in the interference circuit (No. 2) [10,11]. The values of these voltages are proportional to: the different values of the components of the disturbed circuits, e.g. R,L,C; the rate of change of interfering signals in time, dU/dt, di/dt, coupling coefficients between circuits No. 1,2 (L_{12},C_{12},M_{12},Z_{12}), but are also dependent on the frequency range of the signals (relation 1) - Fig. 1. [4,8,10].

$$U_z = R \cdot i + L\frac{di}{dt} \tag{1}$$

$$U_z = |\overrightarrow{E}| \cdot h_{ef} \tag{2}$$

Very low frequency range (conducted interference) (1) High frequency range (radiated interference) (2). The adoption of a frequency range in which electromagnetic radiation is referred to as a "low (or extremely low) frequency wave" is always conventional. These include electromagnetic fields with frequencies less than several tens of kHz. These frequencies correspond to very long wavelengths - e.g., 50 Hz waveforms correspond to wavelengths of 6 000 km, and 10 kHz waveforms to wavelengths of 30 km [4,9,12]. When performing measurements of electromagnetic fields at low frequencies, in connection with such large wavelengths in relation to the distance from the sources of this radiation in which the field parameters are measured, the electric and magnetic components of the electromagnetic field are always considered separately [16,17]. In such cases, measurements of the electric and magnetic components of the electromagnetic field are usually carried out in two frequency ranges, depending on measurement considerations:

- from 5 Hz to 2 kHz – ELF (Extremely Low Frequencies),
- from 2 kHz to 100 kHz – VLF (Very Low Frequencies).

The research presented in this paper was carried out in laboratory and real-life conditions, i.e. during the EMU operation. The sources of disturbances that affect the EMU and the elements and EES built in this technical facility include:

- traction substations with installed converters (stationary or mobile sources while operating on the railroad line),
- Pulse-controlled traction vehicles - starting, driving, braking, etc.,
- all electrical and electronic equipment installed in buildings on the extensive railroad site, e.g. computer systems, internal power supply lines, electrical heating systems, electrical supply lines - indoor and outdoor lighting of the station or platforms, information boards, etc.,
- external electromagnetic interference, which is not located in the vast railroad area, but comes from e.g. transmitters of cell phone stations, high-voltage power supply line, transformer stations supplying a railroad station or railroad traction -Figure 2.

To determine the technical parameters of electromagnetic interference, which occurs in a large railroad area should be determined and located sources, and then the parameters of these circuits - as in Figure 1. The following circuits can be distinguished:

- circuits with very high current flow (e.g. traction substation supply lines, overhead power lines, traction vehicles, railroad and industrial traction power supply systems) [7,9,11],
- circuits with low current flow (e.g. railroad traffic control systems, wire, radio and public address communication systems, electronic safety systems responsible for traffic safety) wire, radio and public address systems, electronic safety systems responsible for traffic safety.

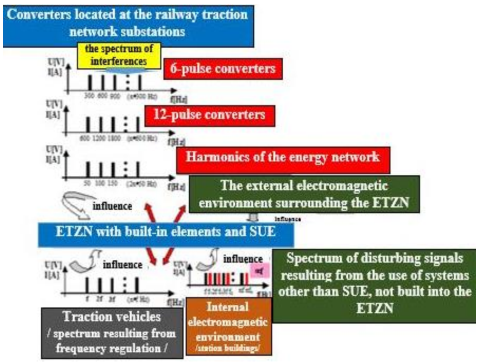

Fig. 2. Example of electromagnetic interference sources affecting EMU, embedded components and EES in a wide area or along a railroad route

I. TECHNICAL PARAMETERS OF MEASURING INSTRUMENTS, TEST STAND FOR TESTING THE MAGNETIC FIELD COMPONENT FOR A SELECTED ELECTRICAL EQUIPMENT LOCATED IN EMU

Measurement of the electromagnetic field - variable component of the magnetic field was carried out using a calibrated electromagnetic field meter EFA-300 with attached measuring probe 100 cm^2 companies Narda Safety Test Solution GmbH – Fig. 3. a), b).

Testing spatial distributions of alternating magnetic field in the vicinity of a transformer 400/230 V AC (3 kVA) was carried out with the use of an effective value meter (RMS). The measurement of the alternating component of magnetic induction was carried out using the instrument Narda EFA-300 (Narda Safety Test Solutions, Pfullingen, Niemcy), with isotropic probe 100 cm^2. The instrument's measuring range for the magnetic component is wide and amounts to from 100 nT to 32 mT. The magnetic field induction measurement can be performed in the frequency band from 5 Hz to 32 kHz. The correctness of the meter's readings is periodically checked in an accredited calibration laboratory. Technical parameters of the magnetic field induction meter and the measuring soda 100 cm2 are shown in Table 1.

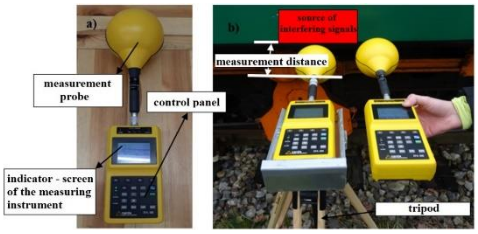

Fig. 3. Electromagnetic field meter EFA-300 with attached measuring probe, a) general view of instrument, b) instruments on measuring stand on railroad track

Table 1a. Technical parameters of the magnetic field meter

Parameter	Value
Frequency range	5 Hz - 2kHz; 40 Hz - 32 kHz
Resolution	range 2 kHz – 0.01 Hz; range 32 kHz – 0.1 Hz
Measurement range	100 nT ÷ 32 mT
Frequency scale	Logarithmic and linear
Detection	RMS, RMS Average, Peak Value and Vector Peak Value
Window length	range 2 kHz – 1 s; range 32 kHz – 0.1 s
Result averaging selectable	range 2 kHz – 1, 2, 4, and 8 s range 32 kHz – 4, 8, 16 and 32 s
Capacity, typical (dependent on setting)	3 600 single values or 22 spectral analyses
Display	LCD 128 × 64 with backlight
Interface	Optical, serial (RS-232)
Operating temperature range	0 °C to +50 °C
Humidity	< 95%
Dimensions	110 × 200 × 60 mm

Table 1b. Technical parameters of the probe 100 cm²:

Frequency range	Probe 100 cm²
5 Hz ÷ 2kHz	< 45 nT for ≤ 48 Hz; < 4 nT for > 48 Hz.
40 Hz ÷ 32 kHz	<0,3 nT for 200 Hz ÷ 20 kHz; <0,6 nT for >20 kHz

Investigations of the magnetic field induction in a selected frequency range have been carried out in a selected location of a three-member electric multiple unit (EMU), designation as shown in Fig. 4. During the measurements of time-varying magnetic field induction measurements in EMU turned on the following circuits and devices:

- Wagon heating and air conditioning circuit,
- Interior and exterior lighting of wagons,
- Passenger information system located inside and outside the carriages.

Near the place where magnetic field induction measurements were performed, there was a transformer 400/230 V AC (3 kVA). Fig. 5 shows the circuitry of the transformer.

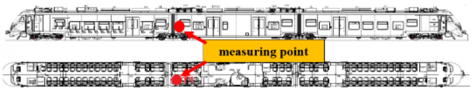

Fig. 4. Measurement of magnetic field induction in a selected frequency range - measurement location in a three-unit EMU

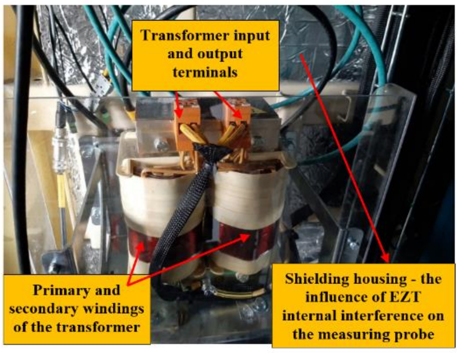

Fig. 5. Measurement of magnetic field induction in a selected frequency range - measurement location in a three-unit EMU

A schematic diagram of the test stand is shown in Fig. 6. Magnetic field tests are performed at three different heights from the ground surface - 0.9, 1.5 and 2.5 m. The measuring probe should be located in the area of the electromagnetic radiation source, and its dimensions and design should not distort the original measured signal. The geometric dimensions of the probe should be as small as possible. The measuring probe should be at least 30 cm from the signal source. The person carrying out the measurement should be at a distance of 1 m from the source, while bystanders should be at a distance of 1.5 m. Such distances do not disturb the distribution of the primary magnetic and electric fields. The measuring plane located at the bench should be free of metallic objects that disturb the primary distribution of the electromagnetic field, but can also be a source of secondary radiation induced by the primary source. Particularly sensitive during measurements is the electrical component. Non-compliance with the above mentioned distances causes very large errors during measurements. A human being, due to much higher conductivity than the surrounding environment, is treated as an antenna with an effective area of 5.5 m^2 which concentrates the electric field lines. Therefore, all electric field strength probes are on an insulated handle with a minimum length of 1.5 m. The authors of this paper did not perform measurements of the electric field strength due to the very low value of the field and the existence of a good shielding against the penetration of this component inside the EMU. Table 2 defines the location and spatial position of the measurement points on the test stand.

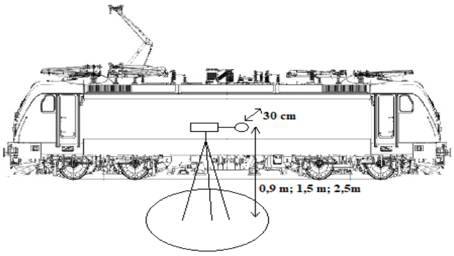

Fig. 6. Schematic of test stand for investigating magnetic field induction in the low frequency range

Table 2. Determination of location and spatial position of measurement points

Place / Distance	Height from floor/rail	Horizontal distance from walls	Notes
available for employees only	0,9 m 1,5 m	≥ 0,3 m	Measurement close to the source of equipment emissions where workers are present during normal operations and also where the driver of the is sitting.
publicly accessible, inside the vehicle	0,3 m 0,9 m 1,5 m	≥ 0,3 m	Measurement at the closest possible location from the emission source where passengers may be present.
publicly accessible, outside the vehicle	0,9 m 1,5 m 2,5 m	0,3	Measurement outside the vehicle near the inverter, traction inverters, power cables, and chokes of the.

II. Electromagnetic field test results - magnetic field component for a selected electrical device in EMU

Fig. 7 shows the classification of the electromagnetic interference produced in the extensive railroad area. The electromagnetic environment occurring in the railroad area is distorted due to the presence of various radiation sources in the low, medium and high frequency range. An additional source of interference that occurs in this area are non-stationary - mobile railroad vehicles supplied from the traction system drawing impulse inrush currents of several - a few thousand amperes. Such large currents create unintended magnetic fields that interact in undesirable ways with animate and inanimate matter (electronic devices and systems). The paper presents the results of investigations of the magnetic field B induction coming from the transformer supplying the power grid of an electric multiple unit (EMU). Electronic equipment installed in the EMU, which is responsible for the safety of passengers, is exposed to interference signals generated unintentionally by the transformer. This interference is generated in the low frequency range.

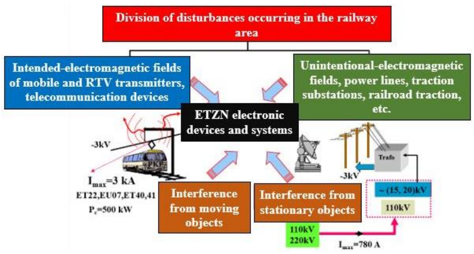

Fig. 7. Segregation of electromagnetic interference generated in the railroad wide area

The following criteria have to be considered when considering the influence of disturbances on the control systems of EMU:

- immunity of electronic systems built in EMU to disturbances - defined as the capacity to maintain proper operation of the system devices during disturbances,
- susceptibility of electronic systems built in EMU to disturbances - i.e. reaction of the working system to external or internal disturbances,
- immunity of the electronic systems built in EMU to disturbances - i.e. ability to retain the original properties of the system after the disturbance has passed.

The results of measurements of magnetic field induction B - spectrum distribution of undesired signals are shown in Figs. 8 and 9 in the frequency range up to 2000 Hz. Above this frequency range, the value of magnetic field interference is very small and constitutes the background of this field in the general environment - undistorted. The test results are presented at different rated load resistance of the power transformer. In fig. 8 the transformer was loaded with the adjusted resistance which value was R_{obc} = 100% R, while Fig. 9 shows an analogous spectrum but for a load of R_{obc} = 50% R. Changing the value of the load resistance causes a change in the value of the interference signals generated by the transformer for each stripe of the signal spectrum as shown in Figure 10.

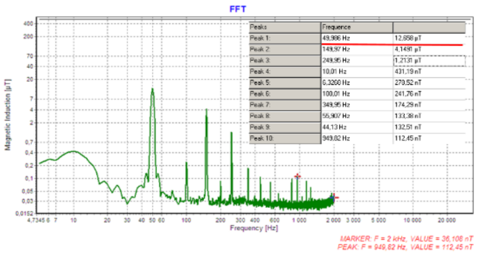

Fig. 8. Measurement results of magnetic field B induction - spectrum distribution of unwanted signals in the frequency range up to 2000 Hz for R_{obc} = 100% R.

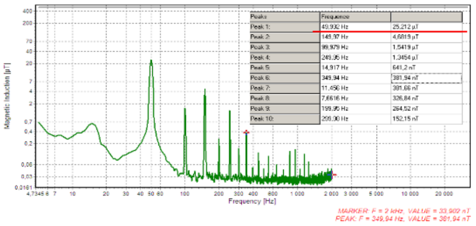

Fig. 9. Measurement results of magnetic field induction B - spectrum distribution of unwanted signals in the frequency range up to 2000 Hz for R_{obc} = 50% R.

The effect of load resistance on the spectrum of interference signals for the low frequency range is best traced in Fig. 10. Due to the large and very small values of magnetic field induction, the OY axis is shown on a logarithmic scale. For the basic component of the 50 Hz supply voltage, a 50 % change in the value of load resistance results in almost the same change in the value of the magnetic field induction B[µT] - a change from 25 to practically 12.7 µT. Also for the 100, 150 or 350 Hz spectral component (odd harmonics of the basic signal), a change in the resistance causes a decrease in the value of the magnetic field induction B - however, this change is most pronounced for the 50 Hz frequency. Changing the resistance R of the load also causes the appearance of additional components of the spectrum of unwanted signals at other frequencies - 10, 56 Hz in the absence of these striations for 100% load of the transformer. The spectrum of interference signals undesirably generated by the transformer includes various components of the magnetic field that affect the electronic equipment and systems built into the EMU. The appearance of harmonics - even and odd - in the spectrum of spurious signals is the source of spurious signals occurring in the confined space of the EMU [7,8]. These components may be the cause of introduction of electromagnetic disturbances into the environment and may affect in an undesirable way the living matter - train passengers. Therefore, the continuous diagnosis of the electromagnetic environment inside and outside the EMU is such an important problem. The spectral components of the unwanted signals also cause deterioration in the quality of power supplied to the on-board power grid of the EMU by increasing the h-value of the harmonic content [3,4]. This causes e.g. an increase of conductive losses in power cables (skin effect appears), but can also be the cause of interference with electronic devices or systems by changing e.g. static value of work points of active elements - transistors or digital circuits [5,6].

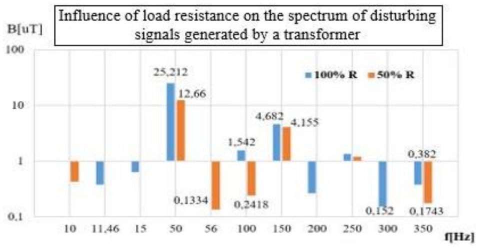

Fig. 10. Effect of changing the value of load resistance on the values of interference signals generated by the transformer for individual bars of the signal spectrum

III. Conclusions

The following sources of electromagnetic interference should be distinguished when defining the electromagnetic environment in the railroad wide area and in the EMU:

- stationary - coming from traction lines supplying EMUs, power lines supplying traction substations, lines supplying railroad traffic control systems and lines supplying transport safety systems (e.g. CCTV system, intrusion alarm system, fire alarm system),
- mobile - interference generated especially by traction vehicles (electric locomotives which have large starting engines, diesel-electric locomotives, electric power units),

The electromagnetic environment existing in the extensive railroad area is also significantly affected by interference:

- external sources of electromagnetic fields generated by power lines supplying electricity for the railroad station, wireless base stations, power lines supplying internal lighting of the railroad area, radio, television or radar transmitting stations located near the railroad area - the whole spectrum of interfering signals should be considered,
- Internal sources of electric and magnetic fields in the low-frequency range are usually devices powered by electricity, operated permanently or temporarily, and constituting equipment of the entire vast railroad area, or located (built) inside EMU. Also internal power lines supplying low-voltage receivers In EMU, electrical or electronic equipment of the station, railroad platform influence the distortion of the natural electromagnetic field of the Earth.

Field measurements of the spectrum of disturbing signals and research work inform us what influence the individual components of the electromagnetic field - the magnetic and electric field components - have on equipment and human organisms. Requirements for magnetic induction levels for railroad vehicle workers exposed to such an environment. The requirements are enshrined in Directive 2013/35/EU of the European Parliament and of the Council on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) [1,2]. However, to estimate the levels of magnetic induction for the passenger compartment and outside the vehicle, the requirements of Council Recommendation 1999/519/EC Annex III [1] were adopted as the evaluation criterion. When interference effects on electronic systems are reduced, a comprehensive approach to EMC must always be taken - i.e., a synergistic approach must be used. EMC synergy is the use of all available technical, organizational, and legal means to limit the impact of electromagnetic interference on electronic systems of EMT. The cooperation of filtering elements (devices), the use of shielding elements, as well as the appropriate placement of interfering elements and elements sensitive to electromagnetic interference in the PCB circuit of electronic systems of EMU, including the above-mentioned standards and legislation gives a greater effect to ensure EMC than the sum of their separate operation - Fig. 11.

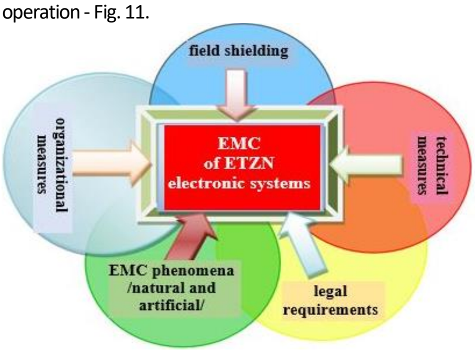

Fig. 11. EMC synergy effects for electronic devices or systems built into EMU

ODDZIAŁYWANIE NIEZAMIERZONEGO POLA MAGNETYCZNEGO Z ZAKRESU BARDZO MAŁYCH CZĘSTOTLIWOŚCI ELF GENEROWANEGO PRZEZ WYBRANE ELEMENTY ELEKTRYCZNEGO ZESPOŁU TRAKCYJNEGO NA OTACZAJĄCE ŚRODOWISKO I SYSTEMY ELEKTRONICZNE

W artykule przedstawiono wyniki badań i zagadnienia związane z oddziaływaniem składowej magnetycznej pola elektromagnetycznego na środowisko i systemy elektroniczne wykorzystywane w elektrycznym zespole trakcyjnym. Systemy elektroniczne użytkowane i zabudowane w elektrycznym zespole napędowym są eksploatowane w bardzo zróżnicowanych warunkach środowiskowych. Na rozległym terenie kolejowym współistnieją systemy elektryczne i elektroniczne o różnym przeznaczeniu, a istotnym problemem eksploatacyjnym oprócz zmian środowiskowych w którym eksploatowane są te obiekty techniczne jest także zagadnienie zewnętrznej i wewnętrznej kompatybilności elektromagnetycznej. W zależności od rozległości obszarowej terenu kolejowego, emisji zamierzonej lub niezamierzonej pola elektromagnetycznego w szerokim zakresie częstotliwości budowa, konfiguracja techniczna oraz sposób zapewnienia kompatybilności elektromagnetycznej dla użytkowanych systemów elektrycznych i elektronicznych są różne. Należy umiejętnie i we właściwy sposób wykorzystać wszystkie środki wchodzące w skład piramidy kompatybilności elektromagnetycznej dla zapewnienia odpowiedniego poziomu wytrzymałości, odporności i podatności w/w systemów. Ze względu na oddziaływanie i propagację fali elektromagnetycznej w środowisku kolejowym należy osobno rozpatrywać poszczególne pasma częstotliwości sygnałów zakłócających dla całego widma sygnałów zakłócających. W artykule przedstawiono wyniki badań generowanych pól magnetycznych z zakresu bardzo małych częstotliwości (ELF) przez elektryczne zespoły napędowe. Diagnozowanie środowiska elektromagnetycznego z całego zakresu częstotliwości umożliwia realizację i odpowiednie zabezpieczenie systemów elektrycznych i elektronicznych użytkowanych w elektrycznym zespole napędowym przed oddziaływaniem niezamierzonych zakłóceń. Znajomość parametrów sygnałów zakłócających – np. amplitudy, zakresu częstotliwości, widma, itd. umożliwi projektantom systemów kolejowych elektrycznych i elektronicznych właściwe zabezpieczenie tych obiektów przed niepożądanym wpływem warunków środowiskowych.

Słowa kluczowe: pole magnetyczne, elektryczny zespół trakcyjny, widmo częstotliwości

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