Features of Electromagnetic Compatibility in Railway Transport

Tetiana Serdiuk
Ukrainian State University of Science and Technologies
Dnipro, Ukraine
serducheckt@gmail.com

Serhii Buriak
Ukrainian State University of Science and Technologies
Dnipro, Ukraine
ser.buryak@gmail.com

Svitlana Serdiuk
Oles Honchar Dnipro National University,
Dnipro, Ukraine
semicvetik25@i.ua

Oksana Gololobova
Ukrainian State University of Science and Technologies
Dnipro, Ukraine
Gololobova_Oksana@i.ua

Kseniia Serdiuk
Ukrainian State University of Science and Technologies
Dnipro, Ukraine
Opasna28@gmail.com

Viktor Skalko
Ukrainian State University of Science and Technologies
Dnipro, Ukraine
viktorska66@ukr.net

Oleh Voznyak
Lviv Polytechnic National University,
Lviv, Ukraine
oleh.m.vozniak@lpnu.ua

***Abstract* – The paper is devoted to the study of the causes of electromagnetic interference on railways, methods for their determination and combating them. Various approaches to studying the influence of interfering influences in the operating conditions of railway transport are considered. The actual permissible values of the level of interference from various sources currently operating on the railways of Ukraine are given.**

Keywords – electromagnetic compatibility (EMC), track circuits (TC), electromagnetic interference (EMI), limit values for interferences, railway

I. Introduction

Every electronic device creates electric and magnetic fields, which are invisible areas of energy that propagate in space in the form of electromagnetic waves. If this radiation has sufficient power, then it can disrupt the operation of parts and other devices both in the same subsystem and in close proximity or having some kind of electrical connection. In this case, electromagnetic interference is divided into three types: radiated electromagnetic interference, coupled electromagnetic interference and conducted electromagnetic interference.

Railway engineering is a field associated with complex electromagnetic environments. Therefore, the development of electromagnetic compatibility is an important part of the development of rail transport. Traction currents and their harmonics are the main source of interference affecting railway automation and remote control devices on electrified sections of railways.

The interaction between sources and receivers of interference is considered as the connection of the source of interference with the receiver. The concept of EMC covers conductive (capacitive, inductive and wired) and radiate connections. To ensure EMC, it is necessary to regulate the interactions for all types of connections of the ground components of the "Signaling and Communication" subsystem with other components of the subsystems of the railway system.

To decide these issues it is needed: to evaluate the causes of EMC breakdowns in the TCs; to study the standards of permissible impact on railway transport and make experiments; to simulate of electromagnetic forces in locomotive ALS coils and make conclusions.

II. Causes of EMC breakdown

Consideration of the current state of research and developments in the field of EMC in railway transport in recent years has shown that the railway transport system is in a complex electromagnetic environment, which is also dynamically developing, therefore, in order to ensure normal and safe operation, EMC must be fully taken into account and must be adopted necessary measures. Therefore, the EMC design of railway transport is a very important work that goes through the entire process of railway transport, including its design, construction, installation, operation and maintenance.

Railway transport is directly in the environment of the influence of electromagnetic interference sources, but despite this, the trains themselves, through the operation of the installed equipment and control and traction systems, have a response electromagnetic influence, so the prevention of electromagnetic interference is an important task of railway transport. The system for closing traction electrical circuits by connecting a pantograph, as a special equipment for providing electricity to trains, is one of the most powerful interference sources that cannot be ignored. In addition, numerous measurements under operating conditions have shown that the asymmetry of the traction current in the rail threads of a rail line is always greater than the asymmetry of the resistances of these threads, and an increase in the magnitude of the alternating traction current in the rail line does not lead to a proportional increase in its asymmetry. In addition, the values of asymmetry change depending on the season of the year [1].

It should also be noted that when moving with a change in the traction mode, the impedance of the electric rolling stock and the reverse traction rail network changes, the resistance of the mechanical contacts of the "wheel-rail" and "contact network – pantograph" systems fluctuate, which leads to a change in the magnitude of the traction current and generation of interference. When crossing the border (junction) of two adjacent sections of the system for monitoring the vacancy of track sections based on the track circuit through the impedance of the electric rolling stock

979-8-3503-2400-6/23/$31.00 ©2023

and the contact network, they are closed (cross effect). The value of the minimum impedance of the electric rolling stock affects the level of harmonics of the traction current, the degree of influence of the cross effect, the magnitude and asymmetry of the reverse traction current, which affect the reliability of the system for monitoring the vacancy of track sections based on the track circuit (saturation of the choke-transformer core, etc.). The influence is enhanced when dual traction trains are used or when two or more units of electric rolling stock are powered within one traction section of a traction substation.

In practice, the asymmetry of currents in rail threads in sections with direct current electric traction can reach 10-12% (discrepancy in the resistance of rail threads due to a malfunction of the butt connectors, their increased resistance, and also due to poor electrical contact of one of the jumpers of the inductor-transformer).

III. EMC STUDIES ON RAILWAY TRANSPORT

In his work Zhao Renjie [2] carried out measurements and analysis of electromagnetic interference in the pantograph-contact circuit and improved test methods. Huang Jinlei in his work [3] analyzed in detail the causes, influence, features and harm of disconnecting the pantograph from the contact network. He presented a model for disconnecting a pantograph from a catenary using AC electromagnetic transfer software. Using the model, he performed an analysis and study of the features of electromagnetic interference in the electrical contact system of the current collector and the contact wire.

The train consumes a lot of power, which means several hundred or even over a thousand amperes. In work [4] Francesc Daura Luna claims that switching between power systems takes only a few nanoseconds (to limit energy losses during voltage and current transitions) and creates very significant levels of electromagnetic interference. This electromagnetic interference (EMI) is partly radiated directly by the wiring of the power converter, thereby causing voltages and currents in all adjacent wiring, but the worst effects can be due to interference conducted towards the power supply of the overhead line, i.e. the catenary. Since the level of this electromagnetic interference can be catastrophic, filters are added to all converters to attenuate them.

Since the contact network is a horizontal wire antenna, conducted electromagnetic interference inevitably propagates along its length and radiates electromagnetic fields. This can pose a serious threat to nearby telecommunications lines and can also pollute the frequency spectrum used by radio/TV channels. Ade Ogunsola and Andrea Mariscotti write about it too [5]. At the same time, the railway line can be considered as a multi-wire transmission line that allows the propagation of electromagnetic interference. Since other devices and equipment are connected to the same power line (depending on the system architecture), interference generated at one point can disrupt the normal operation of other devices even many kilometers away from the source of electromagnetic interference. A railway line may have only one track, or several parallel tracks (two, four or even more) located close to each other. This can cause interconnections between lines (crosstalk), thus providing another possible route for electromagnetic interference to interfere with other parts of the railway system, such as control signals along the tracks.

Any influence must be taken into account and requires some control and limitation for the level of electromagnetic interference generated by the train in order to ensure the correct operation of the railway system and nearby equipment. In fact, conducted electromagnetic interference can also disrupt electronic circuits for control and safety inside the train, as well as signal circuits connected to the rails, thus affecting the overall safety of the railway line. Failure to determine the position and condition of a train can lead to catastrophic consequences. These considerations are even more important for high speed lines.

At present, the rail is a guide system, a power return conductor in AC and DC railway electrification circuits, and is also often used as a conductor of low-level coded signals in the signaling system (in track circuits). The problem of electromagnetic interference is compounded by the use of AC traction motors with frequency converters, which must be compatible with the rest of the equipment and installations.

Liu Shaolin [6] introduced anti-interference measures for computer monitoring system in railway substations in order to suppress interference. Effective interference prevention measures have been put forward in terms of design, manufacture, assembly and installation location of equipment in substations.

It should also be borne in mind that the main connecting link of all types of electrical equipment on railways is the cable. Incorrect selection and connection will lead to deterioration of the electromagnetic environment of various systems and failure of the control device, which will also cause electromagnetic interference. This issue was addressed in their work [7] S. Brillante with a team of authors. They carried out testing and analysis of various types of cables and various ways of connecting the ground wire in the shielding layer respectively, so that conclusions were drawn about the noise immunity of various cables, which is necessary for the correct selection of locomotive cables. When designing, this issue also cannot be overlooked.

In the classical theory, the three main links for creating electromagnetic interference are the sources of interference, the propagation channel and the objects of interference. In works Rocco Dercosi Persichini [8], Wang Quandi [9] и Wan Yuanyuan [10] Based on the analysis of these three components and the basic principle of suppression of electromagnetic interference, widely used EMC design methods and measures to improve the performance of railway vehicles have been studied and implemented. This also includes reasonable equipment layout, cable type selection and installation standard, filtering technology, and the application of grounding and shielding technology, which is a useful benchmark for railway EMC.

Therefore, when determining the features of electromagnetic compatibility in railway transport, it is necessary first of all to take into account the specifics of building the electromagnetic compatibility of the train traction system and the signal system, the approach to the problem of reducing the effect of harmonics created by various sources of interference, including the reverse traction current line, as well as the current distribution parameters . At the same time, insulation, shielding, grounding and other measures must still be comprehensively observed to reduce the effect of harmonics in the reverse traction current in order to ensure the electromagnetic compatibility of the train and the signaling system.

A promising direction in the field of improving the state of EMC in railway transport is the introduction of a new approach to solving the issue based on such measures as suppressing sources of interference by transmitting mutually compensating electromagnetic signals. Also today, one of the most pronounced prospects for EMC in rail transport is the simulation and testing of electromagnetic compatibility, which in the future will provide a more reliable basis for the construction of rail transport.

IV. STANDARDS OF PERMISSIBLE IMPACT ON RAILWAY TRANSPORT OF UKRAINE AND EXPERIMENTS

Permissible levels of interfering effect of electric rolling stock traction current interference on track circuits and track signaling devices are regulated by establishing the maximum level of interfering effect of electric rolling stock electrical equipment on track circuits and track signaling devices (harmonic components of the input current).

Currently, there are more and more prerequisites for the unification of transport corridors of Ukraine with the countries of the European Union. In this regard, questions arise related to the technical implementation of the interaction. Coordination requires not only the legal aspects of cooperation, but also their practical implementation. In particular, if we talk about railway transport, then it is necessary to take into account a huge number of factors, ranging from the gauge, dimensions, principles of managing the transportation process and ending with the electromagnetic compatibility of devices.

All these and many unmentioned questions require detailed study. The levels of permission electromagnetic interferences in the track circuits, track signaling devices, automatic locomotive signaling system, locomotives and cars are given in the Table I – III [11].

Note for a Table II are follows. The limit values of the interference action time, when exceeded, a dangerous or interfering effect on the operation of the TC may occur, are: for the tone and code TCs with constant power supply– 0.1 sec; for code TCs is 0.3 sec.

The experimental research of receiving apparatuses of code track circuits at the 25 and 50 Hz were shown us:

- at the input voltages 10, 15, 18.5, 24 V of 50 Hz of receiving end of code TC the track relays switch on at the 2,6…2,8 V and 35…37 Hz and switch off at the 2.4 V 115 Hz;
- at the input voltages 10, 15, 20 V of 25 Hz of receiving end of code TC the track relays switch on at the 3.7 V and switch off at the 2.4 V 32…37 Hz; at the input voltage of station track circuits 10, 20, 50 V at the 25 Hz relay switch on at the range frequencies: 20…30 Hz and it is more reliability then other, because DSSh relay is electromechanical filter. Same we supervise for 50 Hz station TCs, but it works at the 45…55 Hz [12].

So, the most dangerous electromagnetic interferences are harmonics of 50, 75 and 100 Hz at the DC 3kV traction for a code TCs. It possible follows to the false switch on of track relay of 50 Hz. As for the 25 Hz TCs the harmonics, according on code frequency, is most dangerous. The station track circuits 25 and 50 Hz are protected well enough [12], [13].

But carried out experimental researches [13], [15] say us about needs to correct standards [14] – [16].

TABLE I. – THE MAXIMUM LEVEL OF INTERFERING INFLUENCE OF THE ERS ELECTRICAL EQUIPMENT ON TRACK CIRCUITS AND TRACK SIGNALING DEVICES (HARMONIC COMPONENTS OF THE INPUT CURRENT)

Power supply system	**Rated frequency of signal current, Hz**	**Permissible levels of interference in the traction current**	
		Frequency band, Hz	***Effective value of the harmonic current under continuous exposure (more than 0.3 sec), A, not more than***
DC electrified traction system 3 kV	50	46-54 40-46 54-60	1,3 5,0 5,0
	25	21-29 19-21 29-31	1,0(1,9)* 11,6 11,6
AC electrified traction system 25 kV 50 Hz	25	21-29 15-21 29-35	1,0 4,1 4,1
	75	65-85	4,1
	4500 5500	4462,5-4537,5 5462,5-5537,5	0,2 0,2
Both: DC electrified traction system 3 kV; AC electrified traction system 25 kV 50 Hz	175	167-184	0,4
	420 480 580 720 780	408-432 468-492 568-592 708-732 768-792	0,35 0,35 0,35 0,35 0,35
	4545** 5000 5555**	4507,5-4582,5 4962,5-5037,5 5517,5-5592,5	0,2 0,2 0,2

*) The value in brackets is for electric trains equipped with a device for monitoring the harmonic component with a frequency of 25 Hz, which have the function of uniformly reducing traction power when the limit value is exceeded.

**) For AC electric trains, the compliance check in the frequency bands 4545, 5555 Hz is carried out if there are relevant records in the technical documentation and official confirmation from the operating organization about the presence of track circuits with the corresponding operating frequency bands at the operating site.

TABLE II. THE LEVEL OF INTERFERING INFLUENCE OF THE ELECTRICAL EQUIPMENT OF THE LOCOMOTIVE ON THE TRACK CIRCUITS, TRACK SIGNALING DEVICES

Signal current frequency, Hz	Bandwidth, Hz	Permissible interference level, A
25	19-21	4,1
	21-29	1,0 dangerous
	29-31	4,1
75	167-184	0,4

TABLE III. THE VALUES OF THE TOTAL COEFFICIENTS OF THE HARMONIC COMPONENTS OF THE VOLTAGE, IN PERCENT

Normal allowable value at Unom, kV				Limit value at Unom , kV			
0,38	6-25	35	110-220	0,38	6-25	35	110-220
8,0	5,0	4,0	2,0	12,0	8,0	6,0	3,0

The maximum allowable value of the coefficient of the n-the harmonic component of the voltage is calculated by the formula:

$$K_{U(n)} = 1{,}5 \cdot K_{U(n)\mathrm{norm}}$$

where $K_{U(n)\mathrm{norm}}$ is the normally permissible value of the coefficient of the n-th harmonic component of the voltage, determined according data given in the Table IV [11].

TABLE IV. PERMISSIBLE LEVEL OF INTERFERING INFLUENCE OF THE ELECTRICAL EQUIPMENT OF A PASSENGER CAR WITH A HIGH-VOLTAGE CONVERTER ON THE OPERATION OF TRACK CIRCUIT DEVICES AND AUTOMATIC LOCOMOTIVE SIGNALING

Signal current frequency, Hz	Bandwidth, Hz	Permissible noise level, mA
25	19 to 21	240
	21 to 29	60
	29 to 31	240
50	42 to 46	100
	46 to 54	24
	54 to 58	100
175	167 to 184	40
420	408 to 432	50
480	468 to 492	50
580	568 to 592	50
720	708 to 732	50
780	768 to 792	50
4545	4508 to 4583	30
5000	4963 to5038	30
5555	5518 to 5593	30

The values of the coefficient of the n-th harmonic component of the voltage, in percent are represented in the Table V. They are not multiples of 2 and 3. Such harmonics occur in the primary current of a transformer that feeds a three-phase six-pulse rectifier.

At the asymmetric non-sinusoidal primary voltages, in addition to canonical (even) harmonics, multiples of 300 Hz for six-pulse rectifiers, 600 Hz for twelve-pulse and 1200 Hz for twenty-four-pulse rectifiers, the rectified voltage time diagrams contains non-canonical (odd) multiples of 50 Hz (50, 100 , 150 Hz) also.

The values of non-canonical harmonic components depend on the switching angles and delay in case of asymmetry of the supply voltage of controlled rectifiers. So, with a delay angle of 60° and switching angles from 0 to 10°, they can reach 25 % of the rectified voltage for the sixth harmonic, 11.5 % for the twelfth, 6 % for the eighteenth and twenty-fourth, and for the fourteenth, sixteenth, twentieth and twenty-second harmonics it could be 1,5 %. At large switching angles, the amplitude of the harmonic decreases. The amplitudes of harmonics reduce with the exponential law [14].

Also the experimental research of spectrum of return traction current is demonstrated, that the most significant EMI are the harmonics 0…350 Hz and 850…1000 Hz, and the slot harmonics are 0…150 Hz, 400…500 Hz, 600…900 Hz.

Random impulse noise is also observed at the investigation of EMI in the return traction current. That occurs during switching processes in electrical devices, with a duration of up to 10 μs.

Based on the results of the measurement, it can be concluded that there are the following impulse noises occur during the operation of the locomotive: 275 Hz and 320 Hz at the amplitudes up to 150 mV, 550 Hz is up to 250 mV, 650 Hz - 160 mV, 720 Hz - up to 250 mV. Harmonics with a frequency of 275, 550 and 720 Hz can be perceived by ALS devices and track circuits as a useful signal and have an interfering or dangerous effect on the operation of the automatic locomotive signaling system, depending on their duration and amplitude.

To study the signals taken from the ALS coils, a special program was developed in the Matlab environment, which makes it possible to determine the spectra, amplitudes and phases of frequencies.

V. SIMULATION OF EMF OF RECEIVING COILS OF LOCOMOTIVE

Based on the results of experimental investigation of values and spectrums and with the help of data given in Table I the EMFs of receiving coil of locomotive were simulated in the dependence on distance R between rail and coils. The minimum permissible amplitudes at the signal frequencies of code and tone TCs were chosen for simulation of EMI in the return traction current. The theory of calculation of EMF in dependence on frequencies and distance R was described in [15] in details.

Dependences EMF of receiving coils of locomotive on distance R at the DC 3kV electrified system are shown in the Fig.1. Dependences EMF of receiving coils of locomotive on distance R at the AC 25kV 50 Hz electrified system are represented in the Fig.2.

Dependences EMF of receiving coils of locomotive on distance R at the DC 3kV and AC 25kV 50 Hz traction systems for tonal track circuits are given in the Fig. 3, 4. Dependencies of the EMF on distances R between locomotive coils and rails at the current of current of EMI in 10 A and at the frequencies 100…1200 Hz are described in Fig.5.

These curves have hyperbolic characters (see it in Fig. 1- 5). And at the increase distance R between rails and receiving coils EMF decreases. Deviations of measurement data from the calculations of EMF did not exceed ± 3.5% [15].

TABLE V. – VALUES OF THE COEFFICIENT OF THE N-TH HARMONIC COMPONENT OF THE VOLTAGE, IN PERCENT

The odd harmonics not multiples of 3, at Unom , kV					**The odd harmonics multiples of 3*), at Unom , kV**					**Even harmonics at Unom , kV**				
n	***0,38***	***6-25***	***35***	***110-220***	***n***	***0,38***	***6-25***	***35***	***110-220***	***n***	***0,38***	***6-25***	***35***	***110-220***
5	6,0	4,0	3,0	1,5	3	5,0	3,0	3,0	1,5	2	2,0	1,5	1,0	0,5
7	5,0	3,0	2,5	1,0	9	1,5	1,0	1,0	0,4	4	1,0	0,7	0,5	0,3
11	3,5	2,0	2,0	1,0	15	0,3	0,3	0,3	0,2	6	0,5	0,3	0,3	0,2
13	3,0	2,0	1,5	0,7	21	0,2	0,2	0,2	0,2	8	0,5	0,3	0,3	0,2
17	2,0	1,5	1,0	0,5	>21	0,2	0,2	0,2	0,2	10	0,5	0,3	0,3	0,2
19	1,5	1,0	1,0	0,4						12	0,2	0,2	0,2	0,2
23	1,5	1,0	1,0	0,4						>12	0,2	0,2	0,2	0,2
25	1,5	1,0	1,0	0,4										
>25	1,5	1	1	0,4										

n is the number of the harmonic component of the voltage.

*) - Normally permissible values given for n equal to 3 and 9 refer to single-phase electrical networks. In three-phase three-wire electrical networks, these values are half those given in the table.

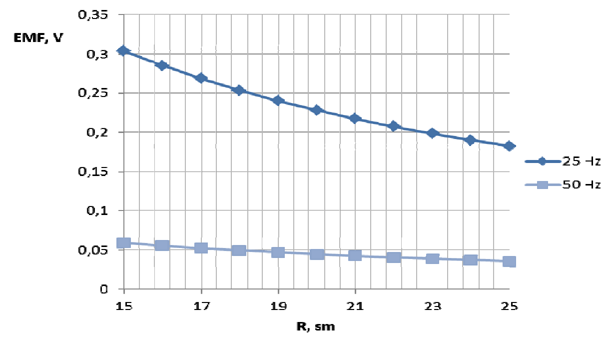

Fig. 1. Dependence EMF of receiving coils of locomotive on distance between them and rails R at the DC 3kV electrified system

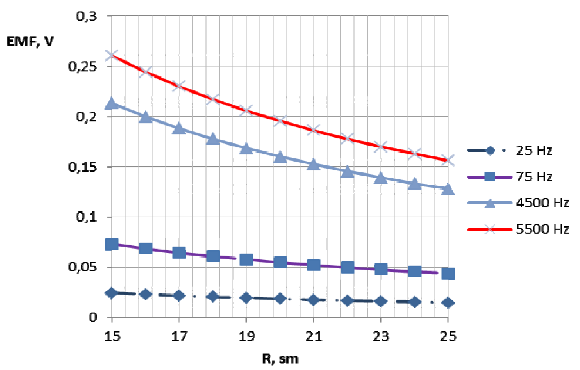

Fig. 2. Dependence EMF of receiving coils of locomotive on distance between them and rails R at the AC 25kV 50 Hz electrified system

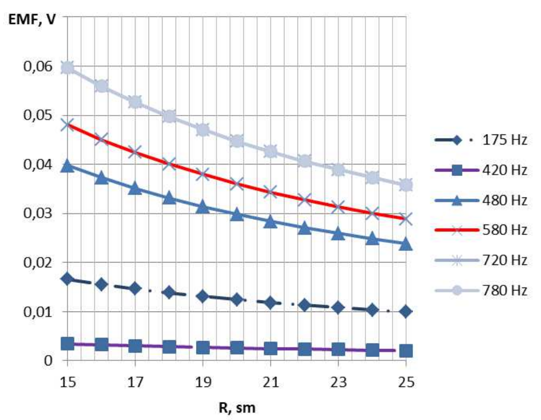

Fig. 3. Dependence EMF of receiving coils of locomotive on distance between them and rails R at the DC 3kV and AC 25kV 50 Hz electrified systems

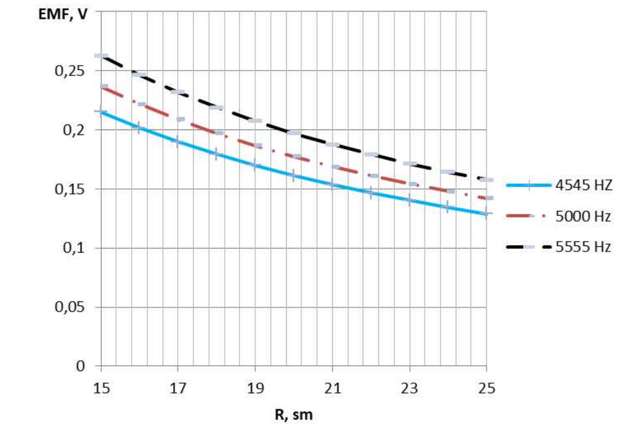

Fig. 4. Dependence EMF of receiving coils of locomotive on distance between them and rails R at the DC 3kV and AC 25kV 50 Hz electrified systems

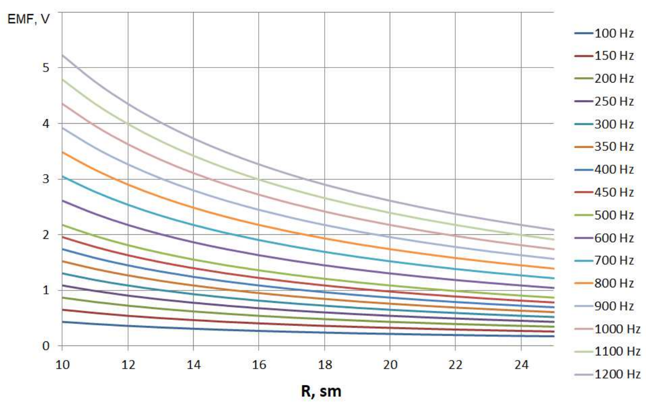

Fig. 5. Dependencies of the EMF on distances between locomotive coils and rails at the current of electromagnetic interferencies 10 A and frequencies 100…1200 Hz

VI. CONCLUSIONS

Thus, the chosen of new electric equipment for traction substations, interlocking systems, and modern rolling stock must be taken into account the evaluation on electromagnetic compatibility [16] – [18]. Only an integrated approach and unification in matters of EMC can prevent the inevitable effects of various systems operating according to different standards and consistent with the different parameters of the railway systems of Ukraine and the European Union.

But at the same time, one cannot lose sight of the fact that due to the continuous development of electronic technologies and changes in the type and magnitude of interference from the electromagnetic environment in various industries, including railway transport, EMC design principles also need to be gradually improved in the process of design and application. Based on a detailed analysis of the current state of the issue and the basic principles and methods of EMC design in terms of developing systems to improve noise immunity, it can be said with confidence that the approach should be comprehensive, taking into account various influencing factors. It must take into account shielding and grounding measures, and can isolate or reduce the electromagnetic field generated by interference sources, so that exposure to sensitive equipment from interference sources can be reduced. It is also considered effective to use methods to reduce the level of interference during their inception, which requires a deeper study of the processes of formation of interference.

REFERENCES

[1] Ade Ogunsola, Andrea Mariscotti. Electromagnetic Compatibility in Railways. Analysis and Management. Lecture Notes in Electrical Engineering. Springer-Verlag Berlin Heidelberg. 2013, 523 p.

[2] Zhao Renjie, EMI testing of neighbourhood region of CRH3 railway [J]. Urban Mass Transmit, 2015(1): 39-42.

[3] Huang Jinlei, EMI study of bow net system of high- speed EMU [D]. Lan Zhou Jiao Tong University, 2013, 4: 1-53.

[4] Francesc Daura Luna. La compatibilidad electromagnética y la seguridad en los ferrocarriles Desarrollo electrónico. Mayo 2015. P. 80-86.

[5] Ade Ogunsola and Andrea Mariscotti Electromagnetic Compatibility in Railways Springer-Verlag Berlin Heidelberg 2013.

[6] Liu Shaolin, EMC protection of substation of urban rail transit [J]. Urban Mass Transmit, 2008(7): 58-60.

[7] S. Brillante, R. J. Hill, A. Pozzobon, P. Pozzobon and G. Sciutto. Modelling for electromagnetic interference assessment in electric railway traction systems. Int. Conf. Electr. Railways United Eur. 2005.

[8] Rocco Dercosi Persichini; Danilo Di Febo; Vincenzo Calà;EMC Analysis of Axle Counters in the Italian Railway Network[D]. IEEE Transactions on Electromagnetic Compatibility. 2015:44-51

[9] Wang Quandi, EMC design for electric car switch [J]. Transactions of China Electrotechnical Society, 2014, 29(9): 225-231.

[10] Wan Yuanyuan, EMC study of railway signal systems [J]. Railway Signaling and Communication, 2007, 43(8): 14-16.

[11] List of problems and open points of the “Analysis of the basic parameters for maintaining the technical and operational compatibility of the 1520 mm and 1435 mm gauge rail systems at the CIS-EU border. Subsystem: Control, Command and Signaling (version 1.03 of 31.08.2012) requiring additional decisions or study.

[12] Serdiuk T., V. Kuznetsov, Ye. Kuznetsova. About Electromagnetic Compatibility of Rail Circuits With the Traction Supply System of Railway / Conference proceedings of 2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS) (September 10 - 14, 2018, Kharkiv, Ukraine). – Institute of Power Engineering, Electronics and Electromechanics, National Technical University “Kharkiv Polytechnic Institute”, Kharkiv, Ukraine. – 2018.– P.59-63.

[13] Serdiuk T., Feliziani M., Serdiuk K. “About electromagnetic compatibility of track circuits with the traction supply system of railway”, Proc. of the 2018 International Symposium on Electromagnetic Compatibility -EMC EUROPE 2018. – Amsterdam, Nehterlands. - 27-30 Aug. 2018. – p. 242 – 247.

[14] Havrilyuk V.I., Sychenko V. H., Serdiuk T.M. “Power supply of railway automatics, telemechanics and communication systems”. Dnipropetrovsk national Railway University transp. named after Acad. V. Lazaryan: Dnipropetrovsk, 2016. – 193 p.

[15] Serdiuk T., Feliziani M., Serdiuk K. “About electromagnetic compatibility of track circuits with the traction supply system of railway”, Proc. of the 2018 International Symposium on Electromagnetic Compatibility -EMC EUROPE 2018. – Amsterdam, Nehterlands. - 27-30 Aug. 2018. – p. 242 – 247.

[16] DSTU EN 50163:2016 Railway. Supply voltage of traction systems (EN 50163:2004, IDT)

[17] IEC 60850:2014. Railway applications - Supply voltages of traction system.

[18] DSTU EN 50121-1:2019 Railway transport. Electromagnetic compatibility. Part 1: General provisions (EN 50121-1:2017, IDT)