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A REVIEW OF POWER QUALITY ISSUES IN ELECTRIFIED RAILS

Introduction

Electrified railways are among of the largest consumers of electric energy which is supplied from the AC power system to the electric supply station (ESS), where it is transformed to the required voltage level and, if necessary, rectified to DC voltage. Electricity is supplied from the ESS to vehicles via the traction network and also to additional consumers through the lines of longitudinal power supply. Traction current returns back from vehicles to ESS via rails and partly via earth that is electrically connected with rails through low value resistance of ballast [1]. It is a common design of directly supplied traction system but modern electrified rails have some variations in design. In general electrified rails forms multiconductor system with longitudinally distributed power supply stations and connected to lines moving loads (vehicles) and fixed (unmovable) electrical loads (consumers), which operate, in general case, in nonlinear pulse modes. Due to the electrical non-linear nature of power stations and loads, current and voltage distortions appear in system, which have a devastating effect on the entire power system and consumers. AC railway traction systems are high power single-phase loads for three-phase supply system and they cause a significant amount of Negative Sequence Current (NSC) into utility grid. Harmonics and consumption of reactive power are further power quality problems that the supply network is encountering.

The disturbances propagate in electrical supply system and affect both the external power lines that feed the ESSs, and its own traction and non-traction loads. Current harmonics arising in the traction network due to its nonlinearity, impact the train control systems, which ultimately have a direct effect on the safety of train traffic.

Electromagnetic compatibility (EMC) between various railway subsystems has been extensively studied in many aspects by many authors (see for example [1–3]), and also by author [4, 5]. The distribution of the harmonics of traction return current in rails for direct AC and DC supply systems and their influence on the track circuits were investigated also in many works [6–12].

The EMC issues are closely related to the electrical power quality (PQ), but they aren't fully similar terms [13–16]. Electromagnetic compatibility is defined in IEC 61000-1-1 as "the ability of a device, equipment or system to function satisfactorily in its electromagnetic compatibility without introducing intolerable electromagnetic disturbances to anything in that environment" [17]. The development of high-speed railways and the use of new types of rolling stock with power electrical equipment and pulse-width modulation lead to problems with EMC and power quality in feeding grids that can adversely impact on other consumers and equipment at points of common coupling [18–22]. Among these problems are the voltages and currents transients (impulsive and oscillatory), power and frequency variations, waveform distortions, unbalanced loading, and etc. These disturbances cause undesirable effects in utility power systems, such as strong shocks and noise in generators, increased heat and losses in transformers and transmission lines, bad impacts on protective systems. As a result of disturbances, adverse interference occurs, which can cause malfunctions in railway signaling systems.

The main task of PQ analysis involves detection, identification, recognition and classification of various types of PQ disturbances. The processes of classification of power quality disturbances include segmentation, feature extraction and classification itself [13]. With increasing requirements to PQ, it becomes necessary to monitor the power quality in an automatic mode. Recent digital signal processing technologies allows fulfill detection, identification, recognition and classification of various types of PQ disturbances automatically [16].

Aim of the article

The aim of this article is to give a brief overview of power quality issues in electrified railways and related standards. The main PQ disturbances are illustrated by using specially chosen fragments of the traction current and voltage dependences registered during tests of rolling stocks on electromagnetic compatibility with track circuits [22–24].

This paper is organized as follows. Section 2 describes the power quality definitions. In section 3 the results of measurements are presented. The power quality standards and power quality disturbances are considered in sections 4 and 5. Section 6 concludes the work.

Power quality definition

There is no universal agreement for the definition of power quality [13]. According to Standard IEEE1100 [25] power quality defines as “the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment”. This definition links the power quality problems with wrong design of the powering and grounding which not suitable for the used equipment.

The standard IEC 61000-4-30 defines power quality as “Characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters” [27]

In [16] the definition for PQ is used in next form. "Power quality is the combination of voltage quality and current quality. Voltage quality is concerned with deviations of the actual voltage from the ideal voltage. Current quality is the equivalent definition for the current". The ideal voltage is considered for simplicity "as a sinusoidal voltage waveform with constant amplitude and constant frequency, where both amplitude and frequency are equal to their nominal value. The ideal current is also of constant amplitude and frequency, but additionally the current frequency and phase are the same as the frequency and phase of the voltage. Any deviation of voltage or current from the ideal is a power quality disturbance" [16].

Since the beginning of railway electrification, power quality and electromagnetic compatibility have been among the main problem in railway networks due to their special characteristics [1]. The increase in speed and weight of trains demands high electrical power. Converters-invertors that used in new types of rolling stock cause the harmonic distortion, sudden changes of loads cause voltage fluctuation and flicker, traction network that included in three-phase feeding system produces voltage and current imbalance. The interaction between the pantograph and catenary of overhead systems causes arcs [18,19].

Measurements

The voltage and current in the traction network were measured during the tests of the rolling stock on electromagnetic compatibility with track circuits [22]. The procedures for measuring, processing and obtained results were discussed in [22–24].

The traction current and voltage were measured in the power circuits of the on-board power equipment. Traction current was measured with using a current sensor (Rogowski coil) in the traction return circuit, where the total current flows to the wheel axes. Signal that is proportional to traction voltage was registered from measuring winding of locomotive transformer. Current and voltage signals were converted by analog-to-digital converter and recorded by PC.

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Traction current harmonics and interharmonics are calculated by means of the Fourier transform over a suitable time window, a tradeoff between frequency and time resolution.

The time dependences of the AC traction voltage and current when train was moved with acceleration have a characteristic form for non-stationary process. For analyzing power quality disturbances the recording signals were subdivided into segments. The purpose of the segmentation is to divide a data sequence into stationary and non-stationary parts. Some obtained traction current and voltage segments were chosen to visually explain the main types of the PQ disturbances in this article. Quasi-stationary fragments of voltage and current dependences during 0.8 s are shown in fig. 1.

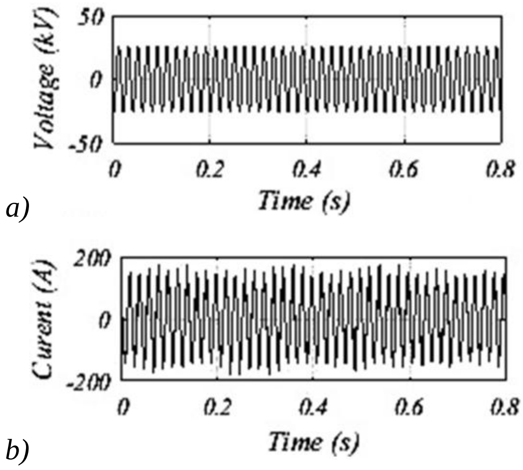

Fig. 1. Traction voltage *(a)* and current *(b)*

Voltage distortions that are known as sag and swell are illustrated by fragments of traction voltage in fig. 2.

Sine waveform distortions of current appear as harmonics (fig. 3).

The power quality standards described the main types of PQ disturbances are reviewed in next section.

Power quality standards

A set of standards in electrical branch connected with power quality have been developed by standardization organizations such as IEEE – Institute of Electrical and Electronics Engineers, IEC – International Electrotechnical Commission, ANSI – American National Standards Institute, NEMA – National Electrical Manufacturers Association, NFPA – National Fire Protection Association, NEC – National Electric Code, US Military.

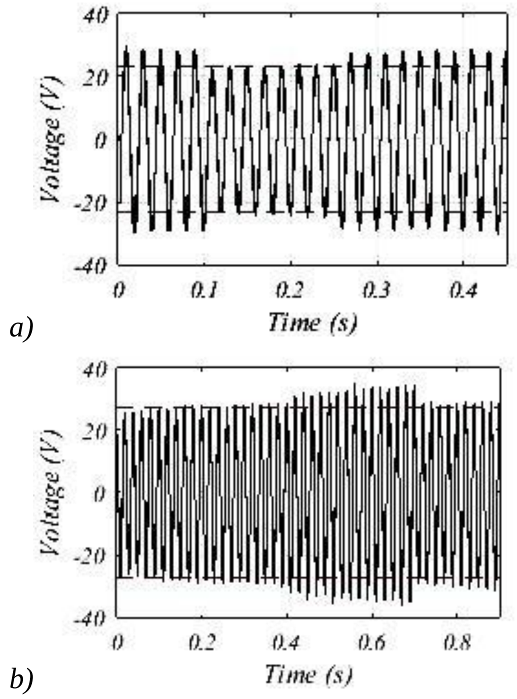

Fig. 2. Voltage sag *(a)* and swell *(b)*

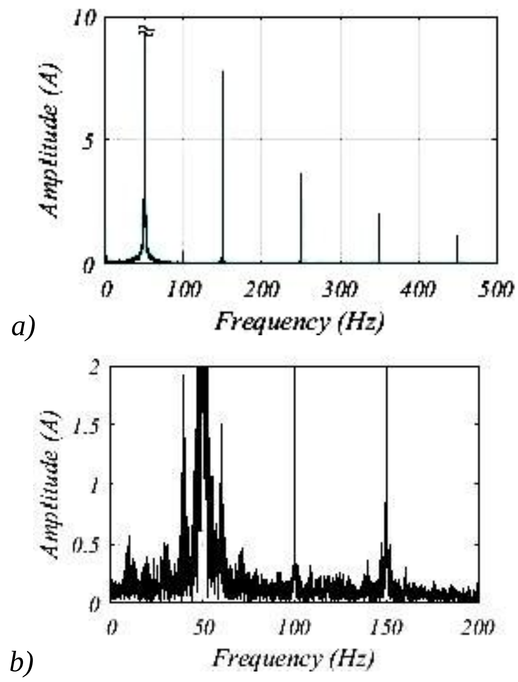

Fig. 3. Traction current spectrums

The IEEE standards consider practical and theoretical aspects of the electrical phenomena. Some of the IEEE power quality standards are listed below:

– IEEE Std 519-2014: IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems;

– IEEE Std 1159-2009: IEEE Recommended practice for monitoring electric power quality;

– IEEE Std 1159.3-2003: IEEE Recommended practice for the transfer of power quality data (PQDIF);

– IEEE Std 1250-2011: IEEE Guide for service to equipment sensitive to momentary voltage disturbances;

– IEEE Std 1409-2012: IEEE Guide for application of power electronics for power quality improvement on distribution systems rated 1 kV through 38 kV;

– IEEE Std 1453-2011: IEEE Recommended practice: adoption of iec 61000-4-15:2010, Electromagnetic compatibility (EMC). Testing and measurement techniques. Flickermeter. Functional and design specifications;

– IEEE Std 1453.1-2012: IEEE Guide: adoption of IEC/TR 61000-3-7:2008, Electromagnetic compatibility (EMC). Limits. Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems;

– IEEE Std 1564-2014: IEEE Guide for voltage sag indices.

The main set of international standards on power quality is contained in the IEC 61000 series on EMC. This large and considerably subdivided series will eventually consist of nine parts. Since the titles of parts 7 and 8 are still open, the present structure is as follows [27]:

Part 1. General.

– Basic concepts (fundamental principles, definitions, terminology) – interference model.

– Functional Safety (what a safety function does and approaches of its being performed satisfactorily).

– Measurement uncertainty.

Part 2. Environment.

– Description of the environment.

– Classification of the environment.

– Compatibility levels.

Part 3. Limits.

– Emission limits.

– Immunity limits (insofar as they do not fall under the responsibility of product committees).

Part 4. Testing and measurement techniques.

– Measurement techniques.

– Testing techniques.

Part 5. Installation and mitigation guidelines.

– Installation guidelines.

– Mitigation methods and devices.

Part 6. Generic Standards.

– Generic emission and immunity requirements in various environments.

Part 9: Miscellaneous.

The PQ standards applicable to the railway lines include EN 50507, EN 50238, EN 50160, EN 50163 [28–32]. The EN 50163 specifies the voltage characteristics of the supply voltages of traction systems in steady and transient conditions. The EN 50388 sets up the requirements for the acceptance of rolling stock on infrastructure and defines requirements of the power supply at the interface between traction unit and fixed installations. A brief review of the national standards on power quality is presented in [33, 34].

Power quality disturbances

Most of the PQ disturbances are connected with amplitude, frequency, phase or waveform variations. Based on the duration of PQ disturbances, they can be divided into short, medium or long type. The short duration voltage variations include: interruption, spike, sag and swell. Each type can be divided on instantaneous (0.01…0.5 sec), momentary (0.5…3 sec) and temporary (3…60 sec).

Voltage spikes. In electrical engineering, spikes are fast, short duration electrical transients in voltage (voltage spikes), current (current spikes), or transferred energy (energy spikes) in an electrical circuit (fig. 4). This is due to lightning, switching heavy loads and failures in the power system. Voltage changes can reach thousands of volts, even at low voltage circuits.

Voltage Sags (or dips) are an RMS reductions in the AC voltage, at the power frequency, for durations from a half cycle to a (minute) (IEEE-1100, 2.2.67). During sag the voltage level decreases within a range of 10 and 90 % of the nominal RMS voltage (fig. 2 *a*).

According to IEEE 1159, Recommended Practice for Monitoring Electric Power Quality" sags can be classified as instantaneous (0.5 cycles to 30 cycles), momentary (30 cycles to 3 seconds), and temporary (more than 3 seconds to 1 minute).

Sags occur due to starting of heavy loads and power system faults and can cause malfunction of information technology equipment, namely microprocessor-based control systems that may lead to a process stoppage, tripping of contactors and electromechanical relays, disconnection and loss of efficiency in electric rotating machines.

Voltage swells are increasing in RMS voltage or current at the power frequency for durations from 0.5 cycle to 1.0 min (fig. 2 *b*), (IEEE 1100, 2.2.78).

Typical values are 1.1 p.u. to 1.8 p.u. (IEEE Std 1159). Swells occur due to faults and turning off heavy electrical equipment and can cause stoppage or damage of sensitive equipment. Solutions to voltage sag and swell problems include uninterruptible power supply (UPS), energy storage equipment, etc.

Interruption is a reduction in the supply voltage, or load current to a level less than 0.1 p.u. for a time less than 1 minute. It can be caused by the automatic reclosing of the protecting device, system equipment failures or control and protection malfunctions, etc.

Long-term voltage variations may last longer than 1min and include overvoltages, undervoltages, and sustained interruptions when voltage is 0 for duration more than 1 minute.

Overvoltages are increasing in the RMS AC voltage greater than 110 % at power frequency for a period of time greater than 1 minute (IEEE-1100,2.2.56).

Undervoltages are decreasing in RMS AC voltage to less than 90 % at the power frequency for a period of time greater than 1 minute (IEEE-1100,2.2.56).

Voltage imbalance (IEEE Std. 1159) or unbalance can be defined as the maximum deviation from the average of the three-phase voltages and expressed in percentage points (fig. 5).

The primary source of voltage imbalance (typically less than 2 %) is the distribution of single-phase loads in a three-phase circuit or faults in one phase. Voltage imbalance causes motors and transformers to overheat.

Voltage imbalance is characterized by the next value

$$V_{unb} = \frac{V_{\max deviation}}{V_{average}} 100 ,$$

where $V_{\max deviation}$ is a maximum voltage deviation from average value; $V_{average}$ is an average voltage.

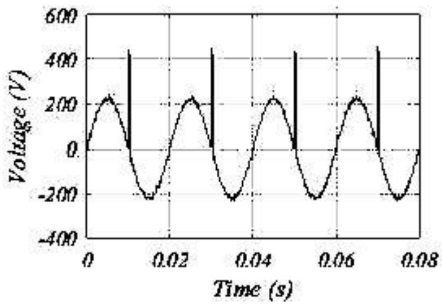

Fig. 4. Voltage spikes

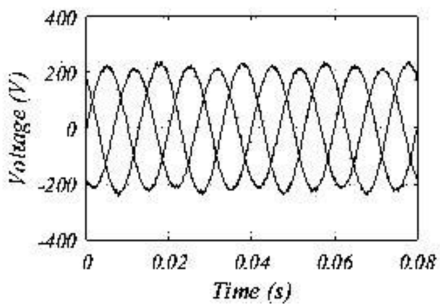

Fig.5. Voltage imbalance

Phase angle imbalance is the deviation from the normal 120 or 240 degree between phase of three-phase voltage. Phase angle imbalance can be caused by the uneven distribution of loads among the phases.

Voltage fluctuations are random or repetitive variations in the voltage RMS, whose magnitude does not normally exceed voltage ranges of 0.9 p.u. to 1.1 p.u. A visual effect of voltage fluctuations is the voltage flicker.

Flicker is defined as a variation of input voltage, either magnitude or frequency, sufficient in duration to allow visual observation of a change in electric light source intensity (as, for example, in fig. 1 *b*).

Power frequency variations are the deviations in the power system fundamental frequency from its normal value.

Waveform distortion is defined as a steady-state deviation of voltage or current time dependency from an ideal sinusoidal wave. Primary types of waveform distortion are harmonics, interharmonics, notching, DC offset and noise. For example, the distortion of the traction current waveform in locomotive during its operation in the recuperation mode, is shown in fig. 6.

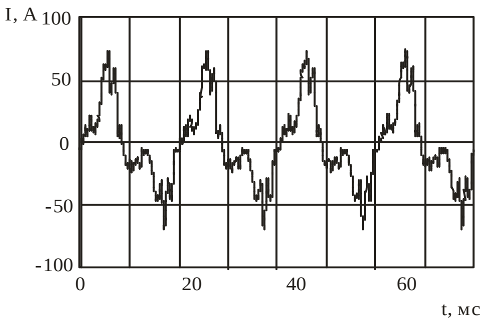

Fig. 6. Traction current waveform distortion [34]

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the fundamental frequency. Harmonics are a form of voltage or current waveform distortion that has a relatively steady-state condition, unlike momentary conditions such as sags or transients.

There are various reasons for harmonics generation like non-linear loads, power converters, etc. Harmonics have adverse effects on generation, transmission and distribution system.

Total harmonic distortion (THD) or distortion factor is defined as the ratio of the root mean square value of the sum all harmonic voltage (or currents) to the fundamental frequency voltage (or currents), and usually expressed in percent (IEEE Std 519)

$$THD_V = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1}, \quad THD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1},$$

where V_h, I_h are voltage and current of the individual harmonic of order h.

This index is used to measure the deviation of a periodic waveform containing harmonics from a perfect sine wave.

For a perfect sine wave at fundamental frequency, the THD is zero. IEEE 519 sets limits on total harmonic distortion (THD) for the utility side.

Harmonics in railway signalling circuits can cause dangerous or hinder failures overheating of all cables and equipment, loss of efficiency in electric machines, electromagnetic interference in communication lines, errors in measures when using average reading meters.

One of the major problems related to harmonic disturbances is harmonic resonance. Power factor correction capacitors in the distribution system are the main cause of harmonic resonance. Resonance can increase harmonic distortion to a level that can damage equipment or cause equipment malfunction.

Other effects of harmonics are equipment overload, increased losses, and sometimes equipment malfunction.

To reduce the influence of harmonics of the traction current, the rail lines are made symmetric for the flow of return traction current, use twisted pair and shielding in the automatic and telecommunication cable lines. Passive and active filters are used at the receiving end of the rail and cable lines to suppress harmonic frequencies.

To reduce the harmonic distortion at the DC power supply station rectifier with a higher pulse than 6 (usually 12) and active and passive filters are used.

Interharmonics are voltages or currents having frequency components that are not integer multiples of the fundamental frequency. They can appear as discrete frequencies or as narrow-band frequency components, produced by vehicle static converters.

The maximum permissible RMS values of the traction return current harmonic components generated by the electric rolling stock in rails, according national norms, are given in table 1, 2 [23].

The maximum permissible RMS values of the harmonics are calculated for all harmonics simultaneously present in a given frequency band with a time duration greater than 0.3 s.

Measurements of the traction current harmonics of the rolling stock during tests have to be carried out in all operational modes of electrical equipment, as provided by the technical documentation.

For passenger cars with high-voltage converter measurements have to be carried out for parked cars.

Transients are sub-cycle disturbances in the AC waveform that is evidenced by a sharp, brief discontinuity of the waveform. They may be of either polarity and may be additive to, or subtractive from, the nominal waveform.

Transients can be generated in the system itself or can come from the other system. There are two categories of transients: impulsive and oscillatory. Impulsive transients are a sudden, non-power frequency changes in the steady-state condition of voltage, current or both, that are unidirectional in polarity. Oscillatory transients have bidirectional in polarity Transients are classified into two categories: DC transient and ac transient. AC transients are further divided into two categories: single cycle and multiple cycles. This can result in a large amount of energy transfer with very short rise and decay times. IEEE 1159 “Recommended Practice for Monitoring Electric Power Quality” further categorizes impulsive transients by the speed at which they occur. “Fast” transients can have a 5 ns rise time and have duration of less than 50 ns. Oscillatory transients are classified by its frequency content, ranging from less than 5 kHz as low frequency and between 0.5 and 5 MHz as high frequency. Transients in electrified rails depend on the characteristics of the power supply system and the operational modes of rolling stock.

Power transients can be caused by transient processes in power traction system of rolling stock and by arc at the sliding contact of a pantograph and contact wire.

Notching is a switching (or other) disturbance of the normal power voltage waveform, lasting less than a half-cycle, which is initially of opposite polarity than the waveform, and is thus subtractive from the normal waveform in terms of the peak value of the disturbance voltage (fig. 7). This includes complete loss of voltage for up to a half-cycle.

DC offset is a presence of a DC voltage or current in an AC system.

Table 1

The maximum permissible RMS values of the harmonic currents produced by the electric rolling stock

Electrical supply system	Frequency band, Hz	Rated frequency, Hz	Permissible RMS current, A
DC, 3 kV	19-21	25	11,6
	21-29		1,0
	29-31		11,6
	40-46	50	5,0
	46-54		1,3
	54-60		5,0
AC 50 Hz, 25 kV	15-21	25	4,1
	21-29		1,0
	29-35		4,1
	65-85	75	4,1
DC, 3 kV and AC 50 Hz, 25 kV	167-184	175	0,4
	408-432	420	0,35
	468-492	480	0,35
	568-592	580	0,35
	708-732	720	0,35
	768-792	780	0,35

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Noise is unwanted electrical signal that produce undesirable effects in the circuits of the control systems in which they occur (IEEE 1100, 2.2.49).

Power electronic devices and arcing equipment can cause noise in control circuits. Basically, noise consists of some unwanted distortion of the power signal that cannot be classified as harmonic distortion or a transient.

In according to [13], the power quality disturbances can be divided into variations and events. Variations are stationary or quasi-stationary disturbances, which proceed continuously.

Events are steady-state or quasi-steady-state disturbances having a beginning and an ending. In classical power engineering, the control of variations is analogous to the measurement of energy consumption (i.e., it occurs continuously), whereas event control is analogous to the functioning of a protective relay (i.e., triggering).

The events considered are short and long interruptions, voltage dips and swells, and (long-duration) overvoltages and undervoltages.

Some typical thresholds of RMS voltage and duration values of events are given in fig. 8.

Conclusion

A brief overview of power quality issues in electrified railways and related PQ standards are considered. Main power quality disturbances are illustrated by using fragments of the traction current and voltage time-dependences measured during tests of the rolling stocks on electromagnetic compatibility with rail circuits.

The traction current and voltage were registered in vehicle power equipment circuits, using a current and voltage probes, which signals were converted by analog-to-digital converter and recorded by PC. Using characteristic fragments of recorded traction current, the main power quality disturbances were illustrated.

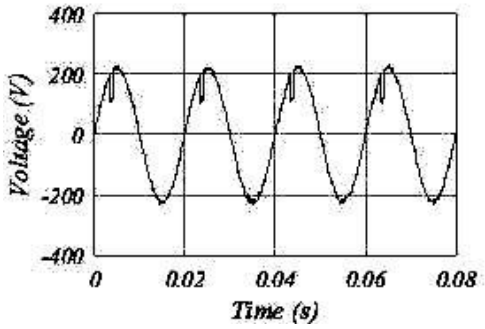

Fig. 7. Notchings

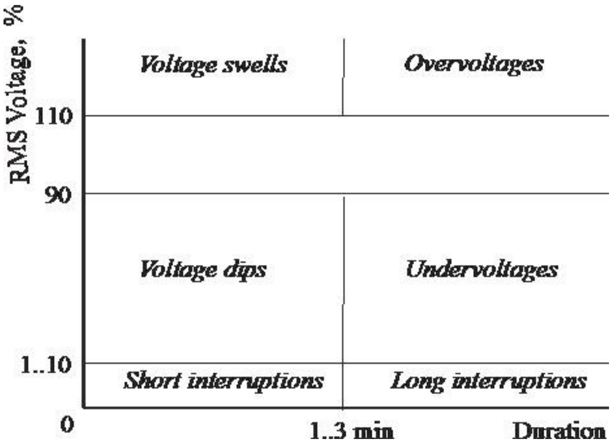

Fig. 8. Some typical thresholds of rms voltage and duration values of events

Table 2

The permissible effective values of the harmonic currents produced by the rail car's electrical equipment

Signal current frequency, Hz	Frequency band, Hz	Permissible RMS current, mA
25	19-21	240
	21-29	60
	29-31	240
50	42-46	100
	46-54	24
	54-58	100
175	167-184	40
420	408-432	50
480	468-492	50
580	568-592	50
720	708-732	50
780	768-792	50

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Ключові слова: якість електроенергії, електрифіковані залізниці. показники якості, стандарти та норми.

Ключевые слова: качество электроэнергии, электрифицированные железные дороги. показателям качества, стандарты и нормы.

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