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Effectiveness of filters in 3 kV DC railway traction substations supplied by distorted voltage–measurements and diagnostics

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ABSTRACT
Electric energy quality criteria relating to a DC supply system concern the circuits from the rectifiers installed in traction substations till the vehicle's current collector. Energy Law and related implementing provisions unequivocally state that an electrified transport system, as the energy recipient, shall fulfil energy consumption requirements that are defined in the agreement. It imposes certain conditions for the railway power supply company. Introduction into traffic of the traction vehicles that are equipped with converter power electronics drive systems increased requirements regarding voltage quality in a DC catenary. At the same time, increase in share of non-linear recipients causes the increase of distortions in AC voltage supplying traction substations, which also transfer to the DC side. In some cases, disturbances in operation of low power infrastructure, such as signaling and control circuits, were observed, although energy quality parameters at the AC side have been fulfilled. All these factors caused a change in operational conditions of the resonance smoothing filters hitherto used in the rectifier traction substations that are supplied by AC medium voltage power lines. This paper presents a research and a case study of the problem of effectiveness of functioning of the applied resonance filters, from measurements, allowing for problem identification, to the results of the studies of the proposed new solution of a filter and the results of the observed exploitation of a prototype with the application of a digital monitoring and diagnostics system.

Section: RESEARCH PAPER

Keywords: DC traction substation; Harmonics; Filters; Voltage distortion; Railway engineering; Measurements

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1. INTRODUCTION

Quality criteria for a DC traction supply system concern the circuits from the rectifiers installed in traction substations till the vehicle’s current collector. Technical effectiveness of the applied supply system as well as quality of the provided energy are assessed mainly by fulfilment of the following requirements [1], [3], [7]-[9], [12]-[16], [18]-[20], [22], [25], [26]:

a) required conditions for voltage of rolling stock supply (of values and quality of the provided voltage, including relations to the harmonics content) are fulfilled, and voltage drops in a supplying DC network are low enough not to significantly influence the speed of train traffic;

b) admissible levels of short- and long-term loads will not be exceeded in any element of the supply system (supply devices);

c) safety of passengers, personnel as well as other persons is provided;

d) short-circuit identification and reliability of switching-off (both on the DC and AC side of power supply);

e) the system remains open for the increase of traffic – possibility of expansion with further increase in transport demand by its modernisation, depending on a degree in traffic increase until achieving the target traffic anticipated in a forecast.

In the analysis of technical effectiveness of the examined load variants, one states conditions for fulfilling the assumed technical standards of a supply system – reliability and dependability of supply, admissible voltage drops and efficiency for the assumed circuits configurations [21]. Assumptions regarding train traffic and configuration of a supply system allow for assessment of a supply system functioning during peak traffic hours and correspond to the conditions assumed for dimensioning of system devices in a design process, including equipment on the side of DC voltage [2], [23].

DC output voltage of rectifier traction substations consists of AC components – harmonics, which could influence negatively the operation of various devices, e.g. a railway control and signalling system [3], [10], [23]-[26], and might disturb reception of broadcasting services in the areas close to the substation [22]. AC side current harmonics of rectifiers in traction substations cause distortion of voltage in supplying AC power lines and in a grid point, to which both a railway traction substation and other loads are connected [2], [4]-[6].

1.1. DC-side voltage harmonics

The variable component of the DC side voltage is composed of a set of harmonics [2], whose orders n equal:

$$n = c\,p \tag{1}$$

where c = 1, 2, 3, 4, ... and p=6, 12 (number of pulses of a traction rectifier).

Therefore, the content of higher harmonics in the rectified voltage will differ in various rectifier systems. For instance, in six-pulse systems the harmonics of the 6th, 12th, 18th and 24th order occur (harmonics of higher orders are usually omitted in technical considerations, due to their low values), whereas in 12-pulse systems only harmonics of the 12th and 24th order occur, thus the 12-pulse system has lower content of higher harmonics than the 6-pulse system. U_n rms of individual higher harmonics of voltage with a defined value of rectifier voltage is the lower, the higher n harmonics order is.

For an idle state of a rectifier operation state the following dependency for U_n is used [2], [6], [23]:

$$U_n = \frac{\sqrt{2}}{n^2 - 1} U_{doi} \,. \tag{2}$$

Knowing U_n, a total group variable component can be calculated:

$$U_c = \sqrt{\sum_{n_d}^{n_g} U_n^2} \tag{3}$$

where n_d, n_g – orders, respectively: lower and upper order of a sum of harmonics.

The relative value of a variable component of the rectified voltage in the δ_n idle state can also be determined according to:

$$\delta_n = \frac{U_c}{U_{doi}} \cdot 100\%. \tag{4}$$

Under conditions of an idle state, for p = 3 the δ_n coefficient is within 15.3 %, for p = 6 – 4.2 %, while for p = 12 the value is 1.04 %, hence the content of a variable component in the rectified voltage is evidently decreasing with an increase of the number of rectifier pulses. Voltage of individual higher harmonics U_n increases proportionally with the increase of the commutation angle u, thus their rms value $U_{n\%}(u)$ given in percentage of U_{doi} can be calculated as:

$$U_{n\%}(u) = \frac{U_{doi}}{(n^2-1)\sqrt{2}} \sqrt{2 + (n^2-1)\sin^2(u) + 2\cos(u)\cos(nu) + 2n\sin(u)\sin(nu)} \tag{5}$$

Harmonics values for declared operational overloads of rectifier units that are obtained from this dependency constitute a basis for calculations for smoothing devices installed in traction substations. Already at the stage of design, one should therefore determine the means that would enable decreasing disturbing voltages U_z to admissible levels, as stated in relevant regulations and recommendations. Currently in Poland, the admissible level of U_z equivalent voltage, taking into account the psophometric weight, is defined by equation (6)[8], [23]:

$$U_z = \sqrt{\sum (U_n\,\omega_n)^2} \tag{6}$$

where:

- U_n – rms of nth harmonic,
- ω_n – coefficient of a psophometric weight of the nth harmonic [8]

The value of this coefficient equals 16.5 V in Poland, while in Germany and in Italy it equals 10 V.

In some countries, the maximum admissible value of a single harmonic (e.g. 100 V) is determined as well, which in fact concerns the most significant non-characteristic harmonic of 100 Hz frequency. However, suitability for use of the psophometric weight criterion for the DC side voltage raises doubts, since in relation to track circuits the use of the current criterion is of more importance.

For instance, current limits given in [3] determine assessment of possible disturbances during introduction of a new rolling stock. This criterion does not have restrictions for the frequency range between 60÷1380 Hz, that is for a range including the harmonics with higher amplitudes (300, 600, 900, 1200 Hz) that are filtered through the resonance contours of DC side filters. Therefore, it can be difficult to fulfil current limits for 1500, 1800, 2100 and 2400 Hz [3], [26] harmonics (especially for filters with a small inductance), even though the voltage criterion (6) has been fulfilled.

1.2. DC side filters

In order to decrease an AC component on the DC voltage side, there are widely used filters that seek for decreasing higher harmonics that are introduced to a catenary. It is performed by introducing a serial branch and a low-impedance (for certain harmonics) parallel branch that is shunting the traction network. Resonance (Poland, Russia, Czech Republic, Slovakia, Spain, Slovenia, Croatia, Japan, Republic of South Africa, India, Algeria, Morocco) and aperiodic filters (Italy) are commonly used as smoothing devices [2], [23]. A typical scheme of resonance filters used on Polish State Railways is presented in Figure 1.

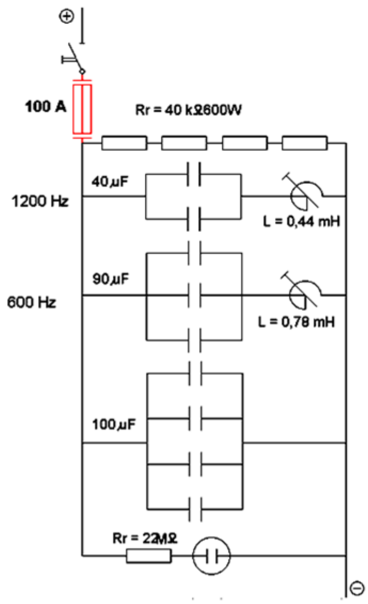


Figure 1. A simplified scheme of a filter with two resonance contours (600 and 1200 Hz) used in 12-pulse 3 kV DC traction substations.

The effectiveness of filters for each frequency is established using the w_n attenuation coefficient (smoothing), which is defined as a ratio of the rms value of voltage U_{on} of n^{th} higher order harmonic at the output of the filter to the rms value of the same voltage higher harmonic U_n at the output of a rectifier (at the input of the filter), this coefficient assumes the following value:

$$w_n = \frac{U_{on}}{U_n} \tag{7}$$

The basic disadvantages of resonance filters include:

- a low level of attenuation with fluctuation of the supplying voltage frequency,
- possibility of strengthening certain harmonics as a result of resonance phenomena (especially with supply of vehicles that are equipped with converter systems),
- low stability of characteristics in time and necessity of periodic tuning.

In case of introduction into traffic of locomotives with power electronic devices (a chopper drive or an inverter with an AC motor), disturbances from higher harmonics in a traction catenary will increase, while additional current harmonics might cause overload of filter elements. Furthermore, the phenomenon of transmission of higher harmonics by a traction catenary might happen in case of a substation cooperating with different types of rectifiers. Locomotives equipped with converter drives, which generate higher harmonics of current, usually have low-pass filters of LC type as an input.

Due to the distributed character of passive elements and current (vehicles) as well as voltage (substations) type of harmonics sources, a scheme of a power supply circuit of energy delivery from a 3-phase public network to the 3 kV DC catenary supplied electric vehicle (EV) is significantly complicated (Figure 2). So while designing solutions for the main circuit traction vehicles with asynchronous drive, it is necessary to take into consideration and analyse the mutual impact of a supply system (substations, substation's smoothing filters) on the circuits of signalling, control and communication systems. The frequency spectrum and impact of an AC component of the vehicle's current on other circuits depend on the method of control, an operating point and converter frequency as well as parameters of other circuits [3], [9], [12], [16], [22]-[24]. In some cases, a locomotive with a converter drive can constitute a lower impedance for harmonics occurring in the DC voltage of a traction substation (especially of lower orders and non-characteristic ones) than the conventional drive with DC motors and resistor start-up [24], [26].

The input filter of a vehicle is a damping circuit, which might cause occurrence of damped oscillations with a frequency corresponding to the frequency of own oscillations in the case of sudden changes of voltage in a traction catenary. When a drive is operating at constant power [12], the phenomenon of excitation of oscillations with a frequency equal to a traction vehicle input filter's own frequency is known.

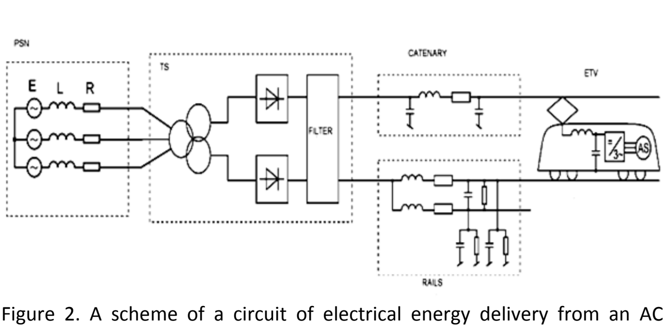


Figure 2. A scheme of a circuit of electrical energy delivery from an AC power supply network (PSN) to a rectifier traction substation with a DC side filter and via catenary to an electric vehicle (EV).

2. MEASUREMENTS OF THE QUALITY OF AC VOLTAGE SUPPLYING A TRACTION SUBSTATION

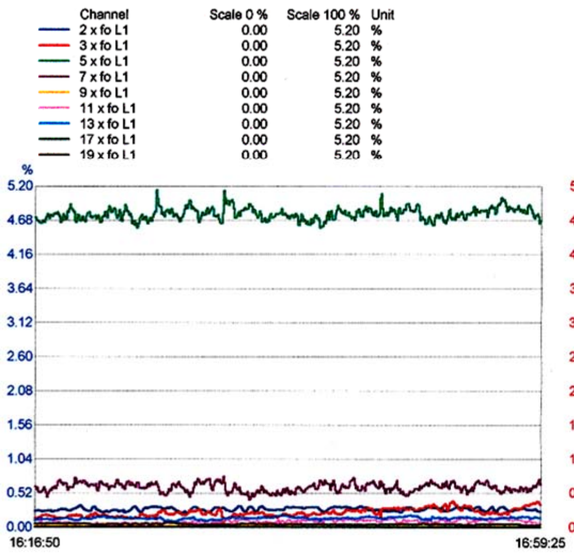
The problem of the quality of electric energy that is delivered to the consumers from the electricity grid concerns both suppliers and consumers of electrical energy. It imposes requirements so as operators of the power supply network supply the recipients with the energy of appropriate quality. The important quality parameters [1]-[7], [15], [25] include the admissible level of non-linear distortions (THD - Total Harmonic Distortion) as well as admissible load fluctuations (due to the instability of the receiver) and asymmetry. One should pay particular attention to the criteria of energy quality, which are stated in the standard EN 50160 [18], especially with supply of a traction substation with lines having various parameters.

Traction substation equipped with 12-pulse rectifiers served as an example of the negative influence of a distorted supply voltage on the operation of a 3 kV DC traction system, due to the fact that the phenomenon of fuses deterioration occurred in substation's resonance type filter. The adjacent substations had also smoothing devices of the resonance type installed, adjusted for harmonics of the 12^{th} and 24^{th} order, which are characteristic for the 12-pulse rectifiers. Thus, in order to determine the cause of occurrence of such phenomena, it was important to conduct measurements at 15 kV 50 Hz voltage supplying substations. Measurements of energy quality were performed in 3-phase 15 kV AC lines supplying a substation, using a specialised meter for measurement of the quality of electrical energy that is consumed by a traction substation. Exemplary results - waveforms of averaged, 10-min values of voltage harmonics in one of the phases (Figure 3a) and THD U values for all phases (Figure 3b) in an idle state of a supplying line (without the operating rectifier substation) are presented. One can observe the presence of the 5^{th} harmonic in the supply voltage (up to 5 % at the admissible value of 6 %). The remaining harmonics had far lower values - below 1 %. Global THD U coefficient exceeded 5 % at the admissible value of 8 %, so the limits imposed by [19] were not exceeded.

3. MEASUREMENT OF EFFECTIVENESS OF A DC SIDE RESONANCE FILTER WITH DISTORTED AC VOLTAGE SUPPLYING RECTIFIERS

Measurements of rms values of the filter's current on the 3 kV DC side were conducted at various configurations of operation of rectifier units and at different variants of operation of adjacent substations with the use of a specialised fibre optical measurement (Figure 4) system established at the Warsaw University of Technology. In this case, 12-pulse rectifiers were being exploited in the traction substation, thus a filter was devoted to attenuate 600 Hz and 1200 Hz harmonics (resonance contours) (Figure 1) and the harmonics of higher orders by a less significant element - an aperiodic element.

The fifth harmonic occurring in the supply voltage (Figure 3) [2], [20], [23] (although the limit imposed by [19] was not exceeded) causes occurrence, on the DC side, of a 6^{th} voltage harmonic (300 Hz), which is non-characteristic for a 12-pulse rectifier (1).



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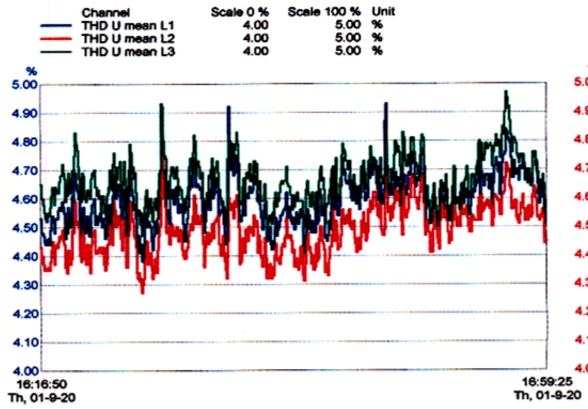


b)

Figure 3. The level of higher harmonics in a 15 kV line that operates in the idle state, participation (of individual voltage harmonics a) THD U in particular phases-b).

Therefore, a resonance filter lacks the resonance element for this frequency (this device was designed assuming that this harmonic does not occur in the rectified voltage), and thus it is not attenuated. While in case of operation of two rectifier units the 6th harmonic appeared to be additionally enhanced. This phenomenon causes current of this harmonics (300 Hz) in the smoothing devices to reach considerably large values (Figure 5a), while the main characteristic harmonic current (600 Hz) was much lower, and with the increase in load, the global current flowing was causing a filter fuse to blow.

Additionally, what appeared is the 2nd harmonic (100 Hz) – Figure 5, that is caused by supply voltage asymmetry and which is additionally enhanced by a filter.

The undertaken measurements showed:

- influence of a supply configuration of a traction substation and the level of distortions coefficient THD U on the energy quality on a DC side;
- significance of AC supply voltage asymmetry in the operation of the resonance filters;
- influence of the rectifiers configuration in a substation on the value of the filter current and the content of current harmonics of the resonance smoothing device (exemplary waveform of rms values of current harmonics in time is presented in Figure 3a).

Due to exploitation needs, in order to allow temporary operation of the filter, it was decided to increase the value of an aperiodic part (capacitance 100 μF – Figure 1) from 100 to 350 μF, and as a result the 300 Hz harmonic current value was reduced significantly (Figure 5).

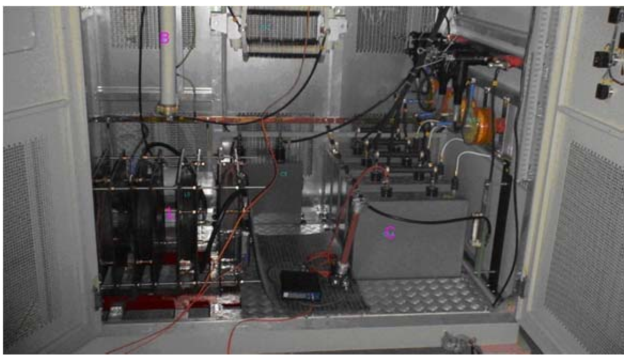
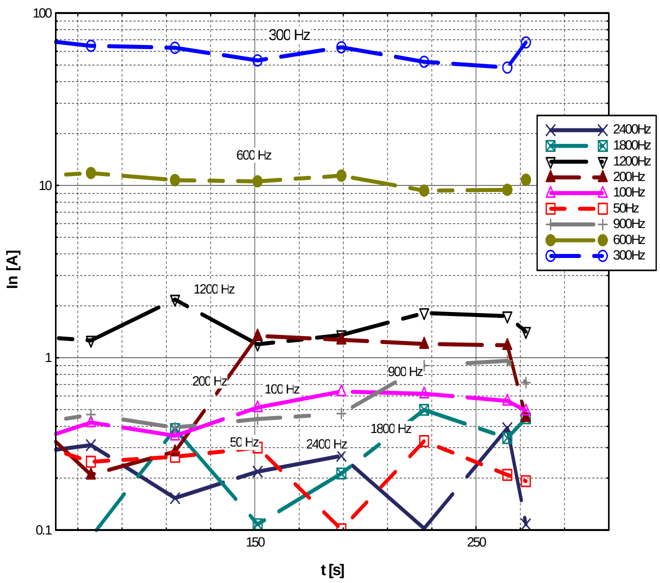


Figure 4. Measurement system in a DC side filter cabinet in a 3 kV DC traction substation (C- capacitance, B- fuse).



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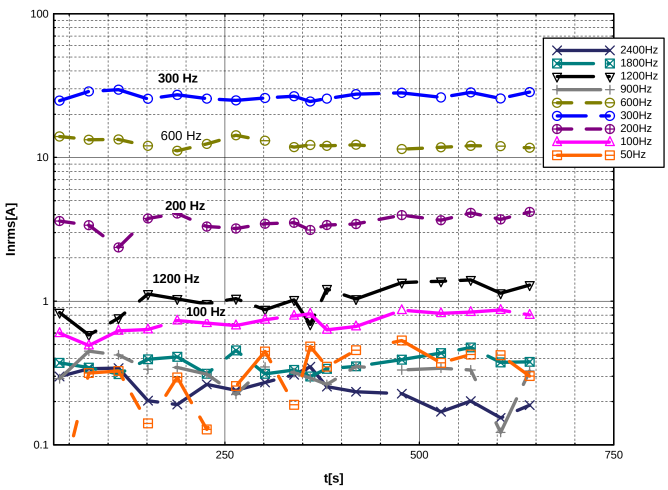


b)

Figure 5. Rms values of higher harmonics of substation's filter current a) with a resonance filter, b) with a resonance filter and an expanded aperiodic element from 100 to 350 μF.

4. MODIFICATION OF A SMOOTHING DC SIDE FILTER

Experience from exploitation of resonance filters and the introduction of a high-voltage supply of 3 kV DC traction substations on Polish railways required further analyses and study for several new phenomena that do not occur with substations equipped with previously used resonance filters [11], [17].

This concerned, among others, mutual cooperation (bilateral supply of the same catenary section) of a traction substation and a supply system both on AC and DC sides, taking into account:

- states of normal operation (including cooperation with high power vehicles equipped with drives with power electronic converters and adjacent substations with resonance filters);
- the most difficult operating and emergency state conditions so the degree of exposure of individual elements to overvoltage and excessive current, e.g. during short-circuit, had to be considered (Figure 6).

In developing the concept for solutions of a system filter based on the conducted analyses, preliminary work and measurements, the following requirements regarding a DC side filter have been formulated:

a) providing proper functioning under operating conditions of a traction substation, so as not to exceed admissible values of distortion;

b) limiting the influence of higher non-characteristic harmonics, caused by supply voltage asymmetry, on the value of interference voltage at the DC side;

c) limiting the impact of frequency fluctuations of supply voltage on the characteristics of a filter;

d) providing proper operation of a filter and limiting its interaction (coupling) with the filters of adjacent substations and input filters of locomotives equipped with converter drives;

e) limiting the generated switching overvoltages to the values lower than the withstanding overvoltage of a rectifier and DC circuit elements, e.g. high-speed circuit-breaker.

The source of overvoltages in the circuits of substations' filters is the inductance of a circuit during breaking the load or short-circuit currents by the high-speed circuit breakers of the feeders.

The values of overvoltages depend on the current derivative *di/dt* and the value of inductance in the circuit during short-circuit (including inductance of a choke and catenary).

The higher value of choke inductance decreases the steepness of current rising and subsequently the steepness of current decay with short-circuit breaking; however it linearly increases the value of the generated overvoltage on a choke.

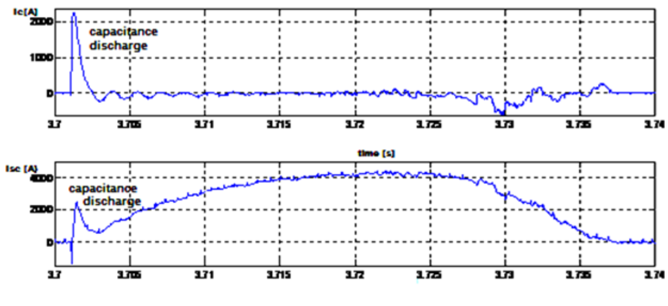


Figure 6. Short-circuit current I_{sc} at the output of a 3 kV DC traction substation (lower figure) and capacitance of a filter's current $-I_c$ (upper figure) – the observed peak current is caused by a sudden capacitance discharge.

Switching overvoltages occur in the circuits of a substation on the rectifiers terminals (Figure 7), irrespective of the type of the applied filter, while their values and duration depend on inductance of chokes and the values of capacitance (aperiodic branch) connected in parallel behind the choke.

Another important criterion is the overvoltage withstanding value of a rectifier as well as circuit elements to commutation and switching overvoltages in the circuit of a substation. For instance, in case of short-circuit breaking using the only operating feeder, the overvoltage will appear between the "+" and "–" rectifier terminals, and not in a catenary. Therefore, it is so important that the manufacturers define the actual withstanding voltage value of a rectifier, having regard to the transformer and high-speed circuit breaker. It concerned, among others, parameters such as: voltage connected to the "+" and "–" terminals from the side of a catenary; rectifier insulation; transformer insulation; overvoltage withstanding value of a chamber of a high-speed circuit breaker after breaking the short-circuit current.

The last one is of high importance, especially during possible occurrence of multiple short-circuits across a high-speed breaker chamber when its insulation parameters are lost.

What also proved to be beneficial was equipping the filter with the elements limiting the overvoltage value (coordinated with overvoltage withstanding value of a rectifier) and (necessity) discharge resistors for discharging the energy accumulated in the capacitance of a filter as a result of overvoltage as well as discharging the capacitance after decay of rectifier (breaking) voltage [11], [17], [23].

Since the direct connection of a not charged set of capacitors to voltage will cause surge charging of a capacitor, hence charging current should be limited so to avoid damaging the capacitor. Similarly, high-current short-circuit in a catenary (with short-circuit resistance close to zero) will cause impulse and oscillation discharge of capacitor overload, which may result in its damage. Current impulses and oscillations in the circuit of a filter and DC switchgear cause excessive wear-out of contacts and circuit elements, so additional low-value power resistors in series with the filter's capacitance were added.

During trials, ongoing intermittently for a few years, the above mentioned assumed requirements towards the DC side filters were verified by performing the following studies:

- before including the filter in the operation:
  - measurements of filter's characteristics;
  - testing voltage insulation and resistance;
  - checking the correct functioning of the auxiliary circuits;
- while putting the filter into operation, checking the correct selection of a filter's protection fuse;
- the test under load was performed (heating of the elements, checking the transient states) and with connecting and switching-off the subsequent rectifier units;
- checking discharging time of capacitors with the filter off

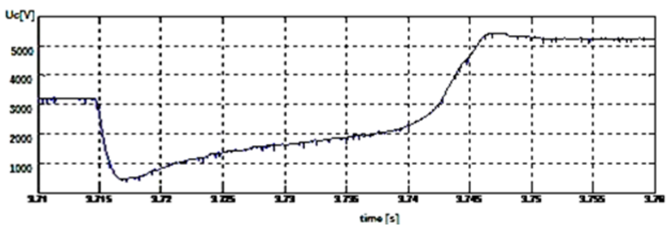


Figure 7. Voltage U_c at capacitance terminals during a short-circuit clearing.

as well as checking the proper selection of discharging resistors;

- checking the elements of a filter and the correct selection of a filter protection fuse with maximum value short-circuit in a 3 kV catenary, functional testing of a main circuit and auxiliary circuits (signalling of a fuse blow, capacitors damage etc.);
- measurements of the filter operation effectiveness (under conditions that were attained on a substation that has been selected for the test study purpose) with one and two rectifier units for existing quality conditions of 15 kV voltage that supplies the substation and with various schemes of bilateral supply of a substation on the 3 kV side with section cabins and adjacent substations operating or not.

The assumed specifications of a filter have been confirmed by in-situ measurements of:

- characteristics of a filter, before starting operation in the substation,
- characteristics of filter attenuation acc. to (4),
- harmonics voltages before and behind the filter,
- filter's current spectrum during normal operation,
- current of a filter during high-current short-circuit test in a catenary,
- calculated disturbing psophometric voltage U_z acc. to (6).

The presented measurements and theoretical analyses showed, in certain conditions, the increase of the 100 Hz harmonic that occurs at the DC side of the substation in case of AC supply voltage asymmetry. Filters with the resonance contours can efficiently attenuate the specific harmonic by parallel contours tuned to its frequency, but they may enhance (or do not attenuate) some harmonics (between the frequencies of resonance elements) and they require periodic tuning. Hence, what was proposed was a modified filter system according to the patents [11], [17]. LC filters have the appropriate low-pass characteristic of a better attenuation (4) coefficient (Figure 8) and they do not require tuning, but the necessary element is the high capacity of the 400÷800 μF range, in order to efficiently attenuate lower harmonics.

The disturbing voltage (3) for the analysed conditions with LC filters is considerably lower than the admissible value of 16.5 V and lower than for the substations operating with resonance filters thereto used (calculated disturbing voltage for a LC filter is 5 V, while for the thereto used resonance filter it is 17.1 V). LC filters are also efficient with the increase of distortions in the AC voltage supplying the substation [23].

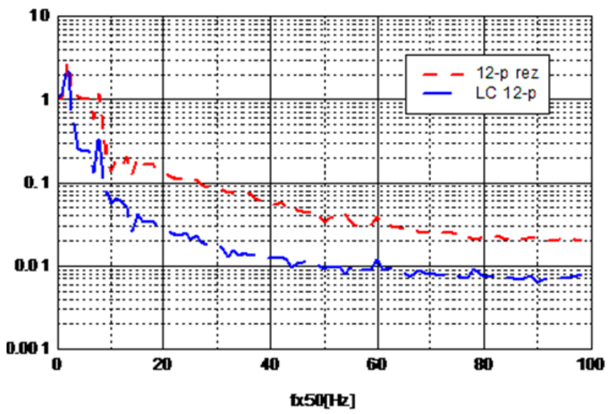


Figure 8. Comparison of attenuation characteristic (4) of a thereto used resonance filter (signed as: 12-p rez) with a 12-pulse unit and LC filter (LC 12-p), noticeably better attenuation of a LC filter with the supply of a substation with distorted and asymmetric voltage, when 300 Hz harmonic is present.

5. MONITORING AND DIAGNOSTICS OF FILTER'S OPERATION IN A TRACTION SUBSTATION

In order to monitor operating conditions of new filters, CZAT3000plus microprocessor controllers are used for traction substations; they were used in many automation systems developed by PKP-Elester [27].

The system of CZAT 3000plus controllers has a modular structure and is a part of a set with command and registration modules and measurement transducers HVM (High Voltage Measurement) or voltage transformers and temperature sensors. Individual CZAT3000plus controllers are connected with an object cabinet of remote control via the CAN-Bus/RS485, which eliminates the necessity of laying a large number of control cables from an object cabinet for controlled devices.

Waveforms of the filter current (Figure 9) and the DC voltage at the output of a substation as well as the temperature in a filter's chamber are measured on-line and are used in the automation and security systems, especially for undervoltage protection, overvoltage protection, overcurrent protection and temperature protection. Selected, measured values are registered in a memory card (maximum instantaneous values and averaged values per 1 s), and they are used for evaluation of the filter's operating conditions.

One might notice the increased load of a filter with the increased load of a substation (Figure 10a) and decrease of the filter's load in the occurrence of regenerative braking of vehicles (Figures 10b, 11b). Additionally one might observe the increase of the filter's load with decrease of capacitance voltage caused by the increase of the substation's load by the trains and decrease of current of the filter's load with decrease of the substation's load (Figures 10a, 11a). Also, the presence of a short term increase of capacitance voltage above the value of 3600 V under the conditions of occurrence of trains regenerative braking has been noted (Figures 10b, 11b). Figures 10a, 10b, 10c and d present the exemplary results of registration from the CZAT3000 controller waveforms of U voltage on a filter's capacitance (output voltage from a 3 kV DC substation) - upper figures and *I* current of filter's load (bottom figures).

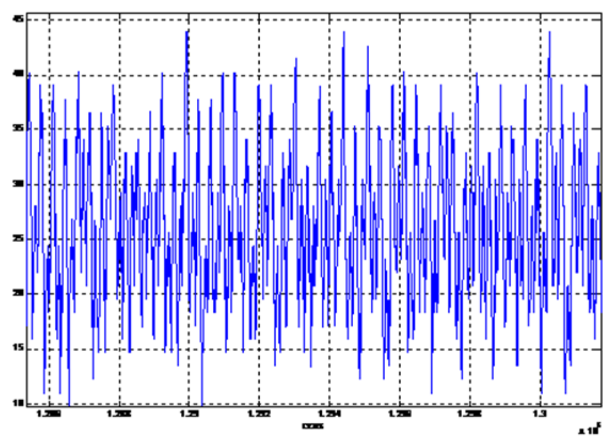
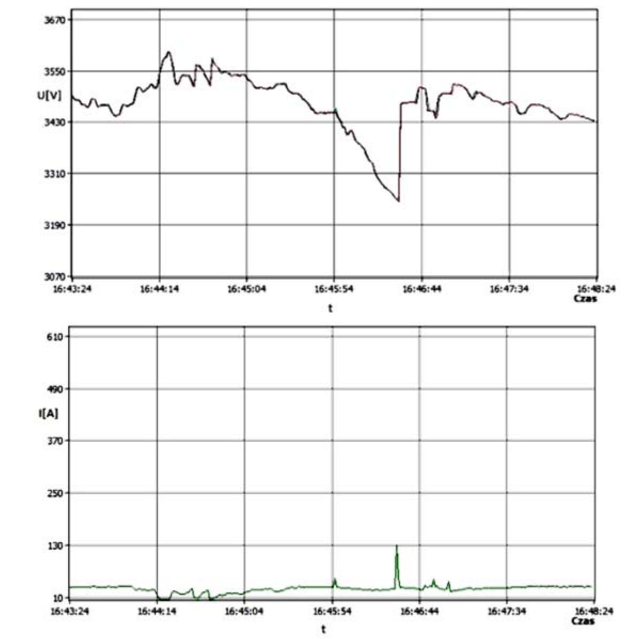


Figure 9. Exemplary time-curve of a filter current.



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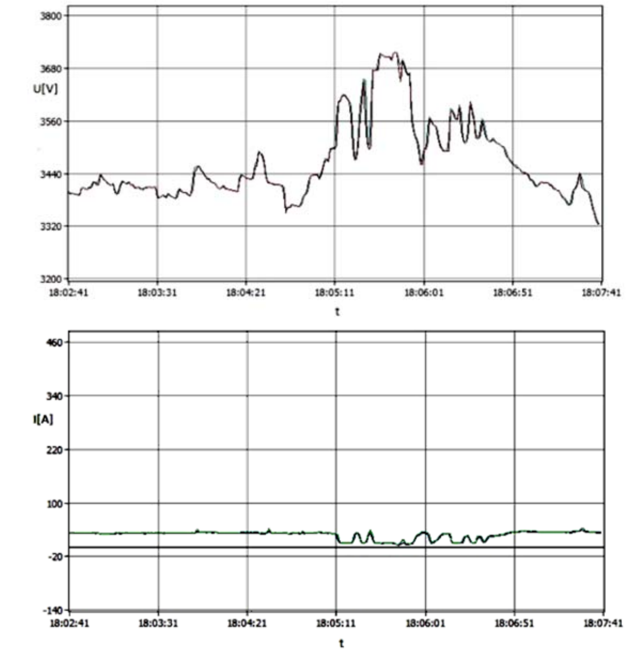
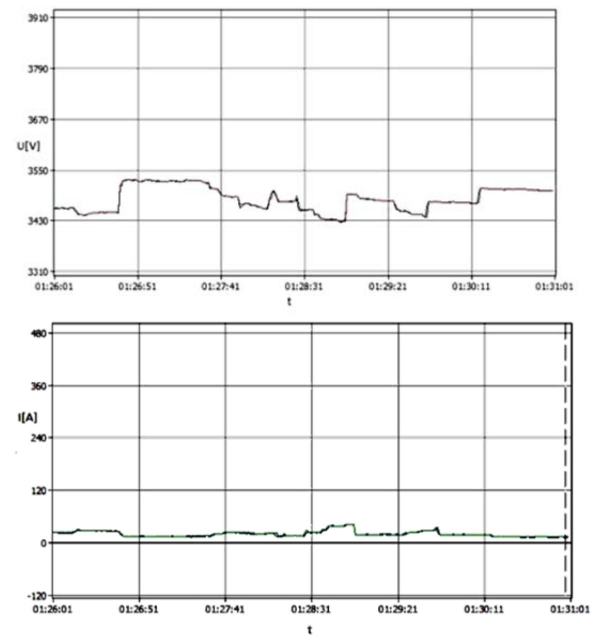


b)

Figure 10 a, b. Exemplary waveforms of *U* output voltage (upper figure) and *I* filter's current (bottom figure) from registration via CZAT controller in a traction substation.



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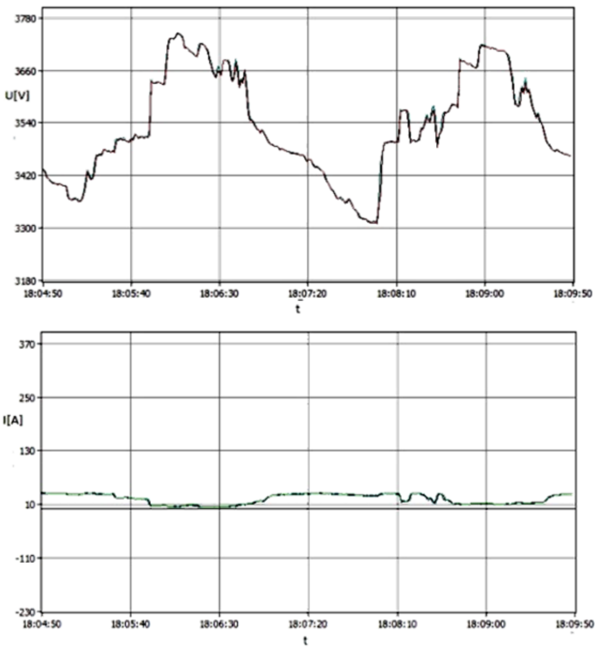

b)

Figure 11. a, b. Exemplary waveforms of *U* output voltage (upper figure) and *I* filter's current (bottom figure) from registration via CZAT controller in a traction substation.

6. CONCLUSIONS

The paper focuses on the analysis, based on measurements and monitoring of the effectiveness of applying DC side filters in 3 kV traction substations supplied by a 3-phase AC medium voltage line with distorted and asymmetrical voltage, but still having energy quality standards [19] fulfilled.

Using the results of the conducted analyses, studies and measurements as well as experience in filters' exploitation, it can be stated that:

- upon measuring the quality of energy supplied from a supplying AC line a selection of the scheme and parameters of a smoothing filter for a DC traction substation should be performed to assess the level of voltage distortions. It is worth underlining that even in case the energy quality standards [19] are fulfilled, it is not enough to ensure proper operation and effectiveness of operating resonance DC side filters and compatibility of track circuits and rolling stock equipped with power electronic converters;
- the use in new traction substations supplied by 15 kV voltage of LC filters with higher inductance values than these hitherto used, improved the filters' efficiency and eliminated problems of fuse burn-out, even in case of distorted AC voltage supplying a traction substation. LC filters do not require tuning and have higher effectiveness (Figure 8) than resonance filters in the range of frequencies above the last resonance element

(1.3÷2.4 kHz), a range significant due to the accuracy of operation of track circuits and cooperation with modern traction vehicles equipped with converter drive systems) [3], [16], [23], [26]. Furthermore, in the ranges between the frequencies of resonance elements, in resonance filters there occur strengthening (or considerable weakening of attenuation) of certain harmonics, which is unfavourable, especially in case of substation supply by distorted and asymmetric AC voltage (currently, these are extremely common phenomena);

- for a few years now, in one of the 3 kV DC traction substations operated by PKP Energetyka S.A., the supervised exploitation of a prototype of a LC filter with the use of monitoring and diagnostics with a digital CZAT controller constructed by Elester-PKP has been conducted. The exploitation has proved the feasibility of the changes and effectiveness as well as reliability of new solutions.

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