

## Effectiveness of smoothing filters in the substations of 3kV DC railway traction - measurements and diagnostics

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**Abstract-** Electric energy quality criteria relating to a DC supply system concerns 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 the requirements regarding energy consumption, which are defined in the agreement. It imposes certain requirements for the Department of Electrical Power Rail. Introduction into traffic of the traction vehicles that are equipped with converter power electronics drive systems increased requirements regarding voltage quality in a DC traction network. At the same time, increase in share of non-linear recipients cause the increase of disturbances in voltage supplying traction substations, and they transfer also to the DC side. Both these factors caused a change in operational conditions of the resonance smoothing filters hitherto used in rectifier traction substations supplied by average voltage. This paper presents a case study of the problem of effectiveness of functioning of the hitherto used filters [1,3,4,5,8], from measurements allowing for problem identification to results of the studies of the proposed new solution of an aperiodic filter and the results of exploitation observed with the use of digital monitoring and diagnostics system.

### I. Introduction

Output voltage from rectifier traction substations consists of a changeable component, whose components influence negatively on operation of various devices, e.g. control system signalisation, and might disturb reception of broadcasting services in the areas close to the substation. Negative effects of harmonics occurrence also transfer to the side of supplying lines, i.e. to the side of power utility network. It causes deterioration in the quality of electric energy that is used not only by PKP but also by other recipients.

In order to decrease a changeable component on the side of rectified voltage, one uses smoothing devices, which aim at decreasing higher harmonics that are introduced to the traction network. It is performed by a serial branch and by forcing their flow in a low-impedance parallel branch that is shunting the traction network. Resonance and aperiodic filters are commonly used as smoothing devices.

In case of introduction into traffic of locomotives with a chopper drive and asynchronous motors, disturbances from higher harmonics in a traction network will increase, while additional harmonics occurring in the traction network might cause overload of filter's elements. Furthermore, what might occur is the phenomenon of transmission of higher harmonics by a traction network, and it might happen in case of cooperation of a substation with 6-and 12-pulse rectifiers. Locomotives equipped with converter drives, which generate higher harmonics of current usually have input low-pass filters of LC type.

Energy Law addresses, i.a. the problem of the quality of electric energy that is delivered to the recipients from the electricity grid. It imposes requirements so as operators supply the recipients with the energy of appropriate quality. The important quality parameters [1,3,4,6,7] include: i. a., the admissible level of non-linear distortions (THD - Total Harmonic Distortion) as well as admissible load fluctuations (due to the instability of receiver). One should pay particular attention to the criteria of energy quality, which are stated in the standard EN 50160, especially with supply of a traction substation with lines having various parameters.

### II. Measurements of the quality of voltage supplying a traction substation.

The studied traction substation, which is equipped with 12-pulse rectifiers and in which the phenomenon of deterioration of fuses occurred as well as the adjacent substations had smoothing devices of resonance type installed, which were adjusted for harmonics of 12<sup>th</sup> and 24<sup>th</sup> order, characteristic for the 12-pulse rectifiers [8]. Thus, in order to determine the cause of occurrence of such phenomena, it was important to conduct measurements of 15 kV 50 Hz voltage supplying substations.

Measurements of energy quality were performed in 3-phase 15 kV AC lines supplying a substation with the use of a specialised meter for measurement of the quality of electric energy that is consumed by a traction substation. Exemplary results - waveforms of averaged, 10-min. values of voltage harmonics in one of the phases (fig. 1a) and THD U values for all phases (fig. 1b) in an idle state of a supplying line (without the operating rectifier substation) are presented in fig. 1. One can observe a decisive role of the 5th harmonic in supplying

voltage (up to 5% at the admissible value of 6%), and this harmonic causes occurrence of a 300 Hz harmonic, which is not characteristic for a 12-pulse rectifier, on the DC side in a rectifier substation. The remaining harmonics had far lower values - below 1%. Global THD U coefficient exceeded 5% at the admissible value of 8%.

### III Measurements of load currents of a resonance filter

Measurements of rms values of 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 of a measurement system developed at the Warsaw University of Technology [2]. 12-pulse converters are being exploited in the traction substation, thus a filter was devoted for attenuation of 600 Hz and 1200 Hz harmonics (resonance elements) and the harmonics of higher ranges by a less significant element - an aperiodic element [8]. Fifth harmonic occurring in the supplying voltage causes occurrence, on the DC side, of a 6th harmonic (300 Hz), non-characteristic for a 12-pulse rectifier. Resonance filter lacks the resonance element for this frequency (this devices 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 it is additionally enhanced. This phenomenon causes that current in the smoothing devices reaches considerable values causing blow of a filter's fuse when the load increases. Additionally, what appeared is the 2nd harmonic (100 Hz) that is caused by supply asymmetry, and which is additionally enhanced by a filter.

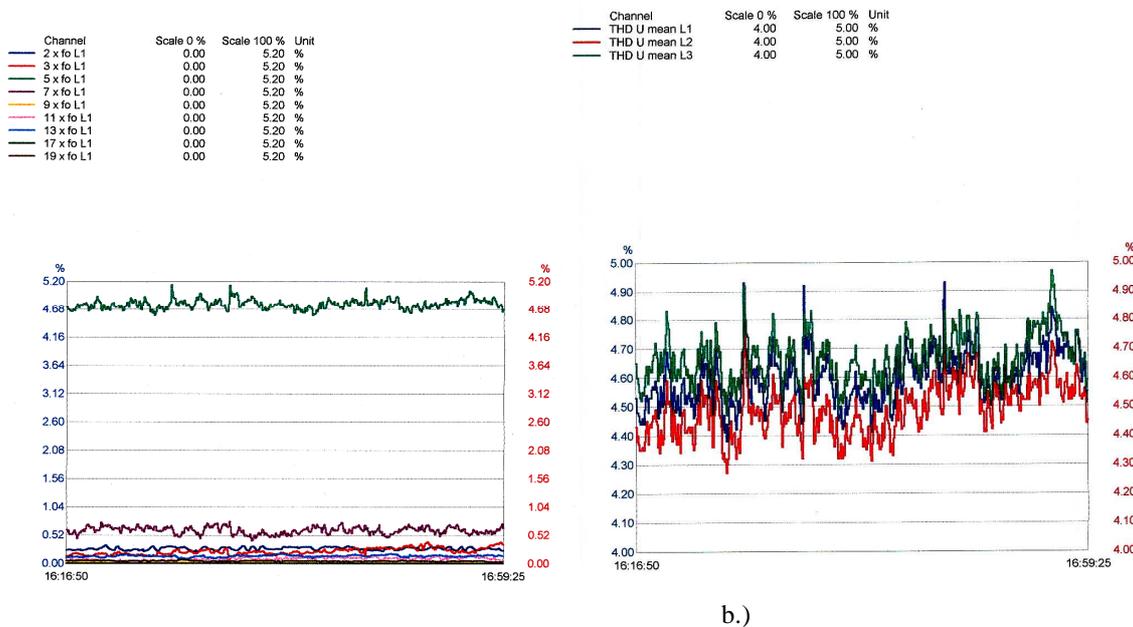


Fig.1. The level of higher harmonics in PKP 1 line that operates in the idle state, participation (of individual voltage harmonics a) THD U in particular phases-b)

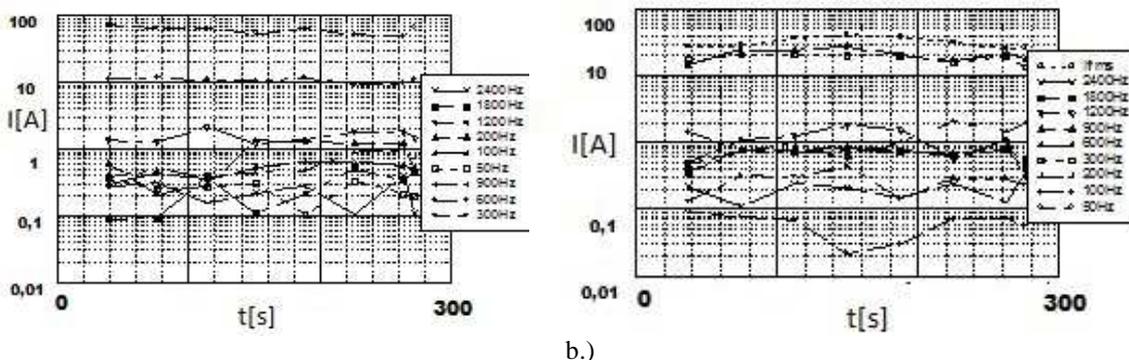


Fig. 2. Rms values of higher harmonics of substation's filter current a) with a resonance filter, b) with a resonance filter and an expanded aperiodic element.

The performed measurements showed:

- significance of the influence of supply asymmetry on the operation of the filters of the smoothing devices,
- influence of a supply configuration of a traction substation on the energy quality and level of non-linear distortions coefficient THD U,
- influence of rectifiers configuration in a substation on the value of filter's 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 fig. 2a) and after modification with an additional aperiodic element (fig. 2b).

#### IV. Modification of a smoothing DC side filter

The presented measurements and theoretical analyses showed, in certain conditions, the attenuation of 100 Hz harmonic that occurs in case of supply asymmetry. Filters with the resonance element can efficiently attenuate the harmonic of the frequencies of the resonance element, but they do not enhance (or do not attenuate) some harmonics (between the frequencies of resonance elements) and they require periodic tuning. Hence, one proposed a modified filter system according to the patent works. LC filters have the appropriate low-pass characteristic of a better attenuation coefficient (fig. 3) and they do not require tuning, but what is necessary is the high capacity of the 400-800  $\mu\text{F}$  range in order to efficiently attenuate lower harmonics.

Interference voltage for the analysed conditions with LC filters is considerably lower than the admissible value 16.5 V for a substation of both 6- and 12- pulse and lower than for the substations operating with resonance filters thereto used, both 6- (of about 7%) and but also considerably for 12-pulse (calculated interference voltage for a LC filter is 5 V, while for the thereto used resonance filter is 17.1 V LC filters are also efficient with the increase of disturbances in the supplying voltage [8].

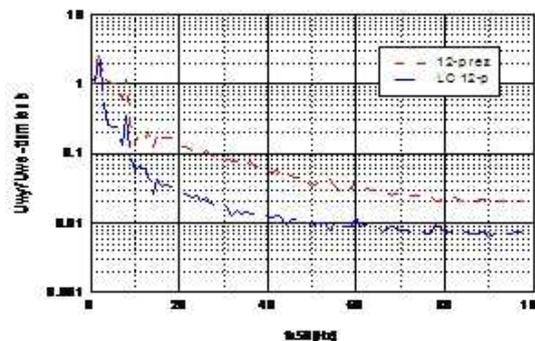


Fig. 3. Comparison of characteristic of thereto used resonance filter (12-res) with a 12-pulse unit and LC filter (LC 12-p), noticeably better attenuation of a LC filter with a supply of a substation with distorted and asymmetric voltage.

#### V. Monitoring and diagnostics of filter's operation in a traction substation

In order to monitor operation conditions of new filters, CZAT 300plus microprocessor controllers are used for traction substations, and they were used in many automation systems produced by PKP Elester [23].

System of CZAT 300plus controllers has a module 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 CZAT 300plus controllers are connected with an object cabinet of remote control via CAN-Bus/RS485, which eliminates the necessity of laying a large number of control cables from an object cabinet for controlled devices.

Waveforms of filter's current and voltage at the output of a substation and temperature in a chamber are measured on-line and are used in the automation and security systems, especially for: under-voltage protection, overvoltage protection, over-current protection (boundary characteristics  $i(t)$ ) and temperature protection. Selected, measured values are registered in a memory card (maximum instantaneous values and averaged values per 1s), and they are used for evaluation of filter's operational conditions. One might notice increased load of a filter with increased load of a substation (4a), and decrease of filter's load in the occurrence of regenerative braking of vehicles (4b).

Fig. 4a and 4b present the exemplary results of registration from the CZAT3000 controller presenting waveforms of U voltage on a filter's condenser (output voltage from a 3 kV DC substation)- upper figures and I current of filter's load (bottom figures). One might observe increase of filter's load with decrease of condenser's voltage caused by the increase of substation's load by the trains and decrease of current of filter's load with decrease of

substation's load (fig. 4a, c) Also, the presence of a short term increase of capacitance's voltage above the value of 3600 V in the conditions of occurrence of trains regenerative braking is noted (Fig. 4b,d).

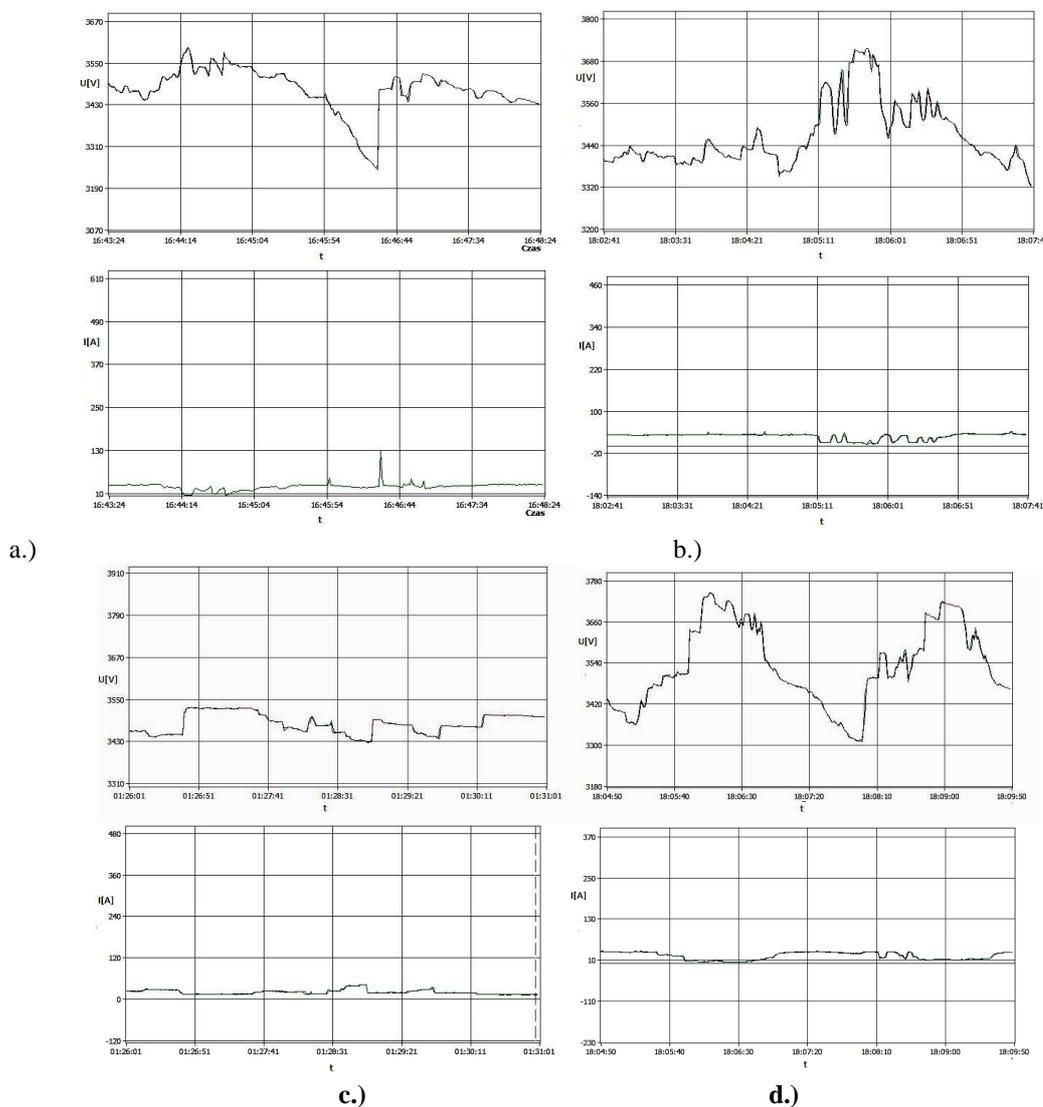


Fig. 4 Exemplary waveforms of U output voltage (upper figure) and I filter's current (bottom figure) from registration via CZAT controller in a traction substation.

### Conclusions

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

- a selection of the parameters of a smoothing filter for a traction substation should be performed with the measurement of the quality of energy supplied from a supplying line under conditions of supplying voltage distortions occurrence.
- the use in new supplied by 15 kV voltage traction substations of LC filters with higher inductance values than these hitherto used of value equal to 1.8 mH. LC filters do not require tuning and have higher effectiveness 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). 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 voltage (currently, these are extremely common phenomena),
- for few years now, in one of the 3 kV DC traction substations belonging to PKP Energetyka S.A. one conducts supervised exploitation of a prototype of a LC filter with use of monitoring and diagnostics with a digital CZAT

controller of PKP Elester, the exploitation has proven the feasibility of the changes and effectiveness as well as reliability of new solutions.

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