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Filtration of harmonics in traction transformer substations, positive side effects on the additional harmonics

Abstract*. The article deals with harmonics filtration in railway traction transformer substations. In traction transforms substations in the Czech Republic there are filters of 3rd and 5th harmonics. The article discuses side effect of these filters – suppression of additional harmonics. The article is based on measurement and simulation results.*

Streszczenie. *Przedstawiono metodę filtracji harmonicznych w trakcyjnej podstacji transformatorowej. Przedfstawiono wyniki symulacji i pomiarów. (**Filtracja harmonicznych w trakcyjnej podstacji transformatorowej**).*

Keywords: traction, railway, harmonics, filtration
Słowa kluczowe: trakcja, filtracja harmonicznych.

Introduction

With their rated power within tens of MW, electric railway substations are one of the biggest appliances in the electrical network. At the same time, they represent a potential source of huge interferences that can be transmitted into feeding network and irradiate into their surroundings. These interferences can also have negative impact on railway safety devices, which is unacceptable. These interfering influences include harmonic current distortion and, consequently, voltage distortion, as well as irradiation of a high frequency field [1] and high, fast current changes. In the case of AC electric railways, another effect is also unbalance, because it is one phase appliance in three-phase network.

Of course, the electric railways have a number of advantages, and in the course of the 20th century, most of the important railways in Europe and elsewhere were electrified. As the importance of electric traction in the world is growing, it is also important to deal with the interferences that it brings.

The authors of this article have studied this problem for many years, and they have also carried out a number of measurements on different traction substations.

This article deals with harmonic distortion created by AC electric railways. Thanks to their high voltage (25kV) they allow relatively long distances between substations (40 km or more [2, 3]), and they have higher efficiency of energy transmission than DC traction. Energy recuperation is also possible in this system, almost without any adjustments in the substation. That is why this system is widely used and for example in Slovakia authorities are currently considering the possibility of applying this system to their whole railway network.

AC Electric Railways – Description of AC traction and its interferences

AC Electric railways are fed by traction transformer substations. These are one-phase, fed by high voltage network 110kV.

Electrical locomotives are usually designed in a way that alternate voltage 25kV is decreased by a transformer, to a value of about 1kV, and rectified. The rectifier can be controlled or not. The other circuits vary depending on whether the locomotive in question is equipped with DC series-wound motors, DC separately excited motors, AC asynchronous or synchronous motors. The most important thing from the perspective of current harmonic distortion is that current is rectified. All types of rectifiers draw harmonically distorted current.

Since the rectifier in question is one-phase, current harmonics spectrum includes all the odd harmonics, the most important ones being the low ones, i.e. 3rd, 5th and 7th (unlike 3-phase rectifiers, which do not have 3rd harmonic and its multiples). Harmonic distortion of current taken by traction vehicles is high. It is very common for *THD* (Total Harmonic Distortion) to reach 20-60%, or even more. To decrease current harmonic distortion, traction transformer substations are equipped with a filter-compensation unit (FCU).

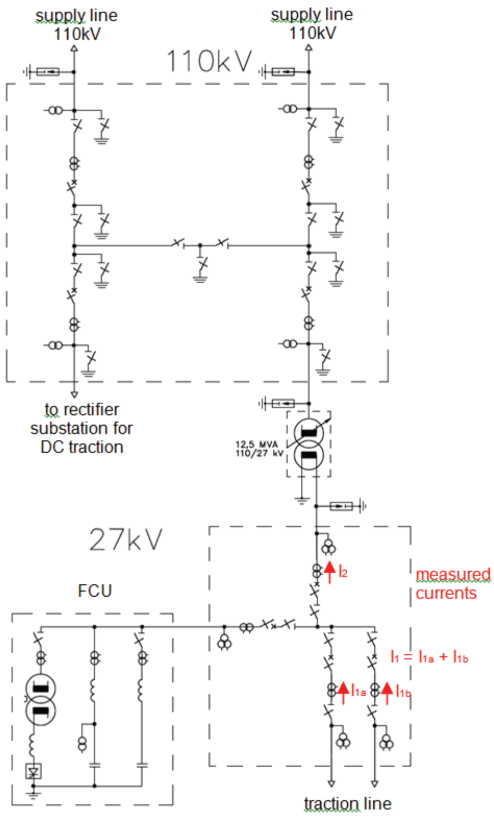

Fig. 1. Simplified diagram of a traction transformer substation

Each filter-compensation unit helps eliminate 3rd and 5th harmonics and compensates reactive power. The unit consists of two series resonance LC circuits. One has a resonant frequency of 150 Hz and the other one, 250 Hz. For first harmonic, both of these circuits have a capacitive character, and can thus be used to compensate reactive power. Because their capacitive reactive power is too high, a decompensation reactor is connected to the circuit. Power in the reactor is phase controlled by a thyristor controller,

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which makes it possible to set power factor to a desired value very quickly [4]. A simplified diagram of a traction transformer substation can be seen in Fig. 1. This is a transformer substation in Svitavy, CZ, where the authors carried out their measurements. Places where current was measured are indicated in the Fig. 1.

This filter-compensation unit significantly suppresses 3rd and 5th current harmonics, and compensates power factor very well. In the Czech Republic, the required value of power factor is 0.95-1 (inductive). Traction transformer substations equipped with a filter-compensation unit have a power factor of about 0.98.

It is possible to also filter 7th harmonic, as it is also an important one. Many traction transformer stations in the Czech Republic have plenty of space ready for the installation of these filters. Our measurements from 2010, were focused on the question whether or not it is advisable to equip filter-compensation units with 7th harmonic filters. Our results suggest that overall current harmonic distortion would only decrease by approximately 1%. This is not a very significant decrease, and this filtration is thereby unnecessary. For more details, see the article in [5].

In the measurement evaluation process it was found out that filter-compensation units also had an influence on 7th harmonic. In another experiment in the traction transformer station in Svitavy the authors carried out simultaneous measurements before FCU and behind it, which makes it possible to accurately evaluate the influence of FCU on individual harmonics.

Influence of 3rd and 5th harmonics filters on other harmonic components

AC electric railways traction vehicles draw non-harmonic current, and thus behave like a source of current harmonics. These harmonics need to close up somewhere, and that is why they go through traction lines, traction transformer and feeding network, until they get to a place where they can close up. If there is no such place along the way, the harmonics only close up in power stations, causing non-harmonic voltage drop on feeding line impedance. This leads to harmonic distortion of voltage in network, which of course is not desirable.

In case that harmonic currents hit a place with a small enough impedance, they close up there and no longer continue in the network. That is the principle of filtration in a filter-compensation unit. The whole situation is shown in Fig. 2.

Series LC circuits in the filter-compensation unit have their resonant frequency set close to 3rd and 5th harmonics. For these frequencies, their impedance is close to zero and the harmonics are filtered away almost perfectly. However, impedance of this circuit is not infinite for other frequencies either, and so other harmonics can at least partly close up over them as well. This phenomenon is especially important for 7th and 9th harmonics, which are close to resonance frequencies of FCU filters. That is why FCU partly filter 7th and 9th harmonics too.

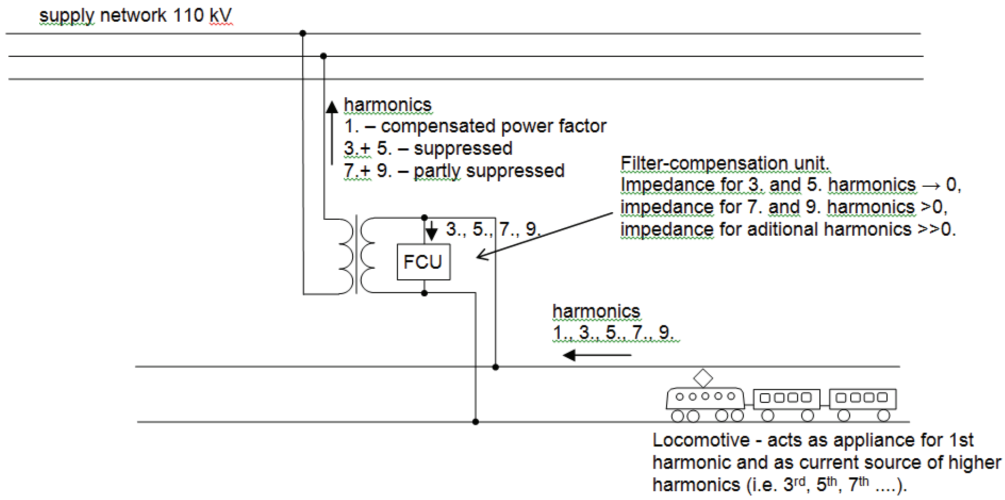

Fig. 2 Harmonics filtration principle in a filter-compensation unit located in a traction transformer substation

Measurements and measuring apparatus

The apparatus that was used to carry out measurements in the traction transformer substation in Blansko, CZ, consisted of a laptop, measuring converter USB6210, voltage and current converters and software created in the LabVIEW system. Measuring apparatus in the transformer substation was connected through the permanently installed current and voltage measuring transformers. Clip-on ammeters E3N were used to measure current.

Current on the secondary winding of the traction transformer (filtered out by FCU) as well as currents on the outlet into traction lines (not filtered) were measured simultaneously. By means of their harmonic analysis and comparison, it is possible to find out attenuation of the individual harmonics.

An important parameter for measurement evaluation is the accuracy of the measuring apparatus.

- Apparatus used in the traction transformer station was connected using instrument current transformers and instrument voltage transformers installed in the substation. Their accuracy class is 0.5%.
- Voltage LEM sensors LV 25 – P have error 0.5 %.
- Clip-on ammeters E3N (Chauvin Arnoux) have error 3%.
- Error of the data acquisition converter USB6210 for range ±5 V is ± 1,5 mV, i.e. ± 0,03 %.

Total error for voltage measurement:

$\delta_U = 0{,}5 + 0{,}5 + 0{,}03 = 1{,}33\%$,

and for current measurement:

$\delta_I = 0{,}5 + 3 + 0{,}03 = 3{,}53\%$. [6]

Simulation Description

Parameters of FCU reactors and capacitors and the traction transformer impedance are known, as well as feeding network impedance. Thus it is possible to simulate

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the circuit and find out attenuation of the FCU for individual harmonics. Fig. 3 shows a diagram of the circuit and its parameters. All values are recalculated to voltage level of 27kV. Impedance of the transformer 400/110kV and network 400kV is insignificant, that is why in the simulation it is replaced by short connection. The simulation was carried out in the Micro-Cap software.

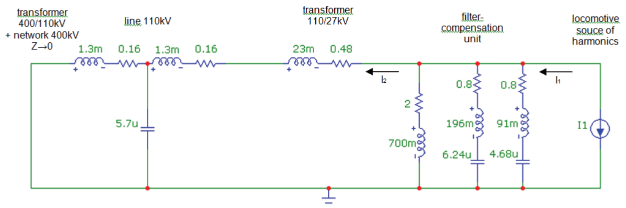

Fig. 3 Circuit diagram created by Micro-Cap simulation software

The result of the simulation was FCU attenuation as a function of frequency. This attenuation in is expressed as I_1/I_2 and can be seen in Fig. 4.

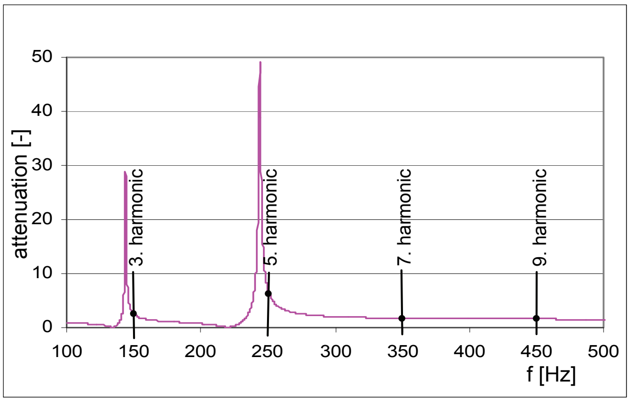

Fig. 4. Frequency characteristics – attenuation as a function of frequency (from simulation).

Table 1. FCU attenuation - measurement and simulation results

	3^{rd} harmonic	5^{th} harmonic	7^{th} harmonic	9^{th} harmonic
Most frequent measurement result (mode)	1,6 - 1,8	6 - 8	1,4 - 1,6	1,4 - 1,6
Simulation results	2,49	7,04	1,74	1,58

Measurement and simulation results

Currents harmonics I_1 and I_2 were measured (see Fig. 1 and 3), and based on these values, attenuation was calculated. To evaluate harmonics and attenuation, it was necessary to use sections with high load, because when the load is low, measurements tend to be less accurate. Thus only sections where current was higher than 100A were evaluated.

Table 1 sums up measurement and simulation results. Attenuation obtained by measurement was evaluated statistically. The mode, i.e. most frequently encountered result, was chosen as a statistical parameter.

Both measurement and simulation results show that FCU decreases the values of current harmonics, specifically 3^{rd} and 5^{th} harmonics, for which FCU is designed, and also further harmonics (7^{th} and 9^{th}). However, the degree to which the individual harmonics were suppressed varies greatly. The highest attenuation is for 5^{th} harmonic, 5^{th} harmonic filter is tuned very close to 5^{th} harmonic frequency. Attenuation for 3^{rd} harmonic is less significant because 3^{rd} harmonic filter is not tuned so accurately.

The attenuation is even less significant for 7^{th} and 9^{th} harmonics (approx. 1.5), which means that current of each of these harmonics is decreased by approx. 1/3. Given the fact that this is only a side effect of 3^{rd} and 5^{th} harmonic filters, it can be considered a relatively good result.

As far as the differences between measurement results and simulation results, the most significant ones are for 3^{rd} and 7^{th} harmonics (simulation was more favorable than reality). These differences can be caused by a number of factors:

- measurement error,
- influence of thyristor regulation of current in the decompensation reactor (not taken into account in the simulation),
- voltage distortion in the feeding network.

Conclusion

Measurements and simulation were carried out at a traction transformer substation that feeds 25kV/50Hz railway traction. This transformer station contains a filter-compensation unit filtering 3^{rd} and 5^{th} harmonics and compensating the power factor of 1st harmonic. The goal of the measurement was to find out more about the influence of the FCU on the other harmonics. Both measurements and simulation proved that the FCU has a positive influence on additional harmonics, i.e. 7^{th} and 9^{th} harmonics. FCU suppresses these harmonics by approximately 30%. This positive side effect of the FCU is caused by the fact that even though its filters are tuned to (approximately) 3^{rd} and 5^{th} harmonics, the other harmonics still partly close up through them and do not continue further into the network.

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