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Influence of AC Electric Traction on Harmonic Distortion in 110 kV Supply Voltage Network: Measurement and Simulation

***Abstract**. This paper deals with reverse effects of AC electric traction operation on 110kV supply system, from the point of view of spreading of harmonics. Investigation results for standard operation conditions are presented. The graphic part of this paper shows measurement results obtained by means of virtual instrumentation, with the use of LabVIEW software. In the next part is presented a model of the system on which the measurements were carried out, i.e. overhead lines, 110/27kV traction transformer substation and part of the power supply system. With the help of this model, an investigation of the spreading of harmonics in the power supply system was carried out. The conclusion of the paper includes a comparison between simulation and measurement results*

***Streszczenie.** W artykule zaprezentowano analizę zakłóceń wprowadzanych do sieci zasilającej przez trakcję AC. Przedstawiono wyniki pomiarów wykonanych z układem wykorzystującym oprogramowanie LabView. Przedstawiono także model systemu. (**Wpływ trakcji AC na zniekształcenia harmoniczne w sieci 110 kV**)*

Keywords: Electric railways, supply voltage, harmonic distortion.
Słowa kluczowe: trakcja, zakłócenia harmoniczne, trakcja AC

Introduction

When analyzing the influence of electrified railways on power network, special attention must be paid to the system by which these railways are supplied [1]. Traction current systems can be divided into three large groups:

- Direct current (DC) traction systems
- Alternating current (AC) 50 (60) Hz industrial frequency traction systems
- Alternating current 16.7 (25) Hz lower frequency traction systems

While traction transformer substations feeding 25 kV AC traction system are supplied by 110 kV power lines, traction rectifier substations feeding CD 3 kV traction system are fed by 22 kV lines, or by 110 kV lines, with a subsequent transformation to 22 kV.

In recent years, an ever increasing attention has been paid to harmonic distortion in railway traction systems. The analysis of harmonic distortion in railway systems is essential in assessing its effects on the adjacent distribution power network. Many of the locomotives operated on single phase 25 kV, 50 Hz electric railway systems are conventional diode based locomotives. They become the main source of harmonics, seriously threatening power quality [2]. Therefore, efficient measures need to be taken to suppress harmonics caused by the electric railway load. The generated harmonics are significant and line current is distorted.

Harmonic distortion

Harmonics are steady-state components of periodical alternating voltage or current. They should not be confused with inter-harmonics or transients. Magnitudes of the individual harmonics are often expressed as a percentage of the fundamental component, or of the Root Mean Squared (RMS) magnitude of the overall voltage or current. Due to its negative influence on electrical appliances, harmonic distortion in supply network has become of increasing concern. A non-sinusoidal waveform can always be represented as a sum of a certain number of sinusoidal components with multiple frequencies [3]. Harmonic frequencies are integral multiples of the fundamental supply frequency.

Any periodic signal (waveform) can be described by a series of sine and cosine functions, also called Fourier series.

$$u(t) = U_{dc} + \sum_{n=1}^{\infty} \left(U_{(n)s} \sin(n\omega t) + U_{(n)c} \cos(n\omega t) \right) \tag{1}$$

The coefficients are obtained as follows:

$$U_{(n)s} = \frac{1}{\pi} \int_0^{2\pi} u(t) \sin(n\omega t) d\omega t \tag{2}$$

$$U_{(n)c} = \frac{1}{\pi} \int_0^{2\pi} u(t) \cos(n\omega t) d\omega t \tag{3}$$

Where n - an integer, $\omega = 2\pi / T$, T - the fundamental period time.

Total Harmonic Distortion (THD) is often used as an overall measure of harmonic distortion. THD calculation equation is presented below:

$$THD_U = \frac{\sqrt{\sum_{n=2}^{n=40} U_{(n)}^2}}{U_{(1)}} \tag{4}$$

Where $U_{(1)}/U_{(n)}$ - the RMS of the first harmonic or the n^th^ harmonic component of voltage.

Effective value

$$U_{RMS} = \sqrt{\frac{1}{T} \int_0^T u(t)^2 \, dt} = U_{(1)} \sqrt{1 + THD_U^2} \tag{5}$$

For low distortion levels, e.g. for voltage, $U_{RMS} \approx U_{(1)}$.

Measurements at traction transformer substations

The apparatus used to measure instantaneous values of voltage and current was designed for long term monitoring. The whole equipment consisted of an industrial computer, data acquisition converter card, input transducers, cables, and special software.

Fig.1. Measuring apparatus

Fig. 2 shows a block diagram of the measuring process in the traction transformer substation.

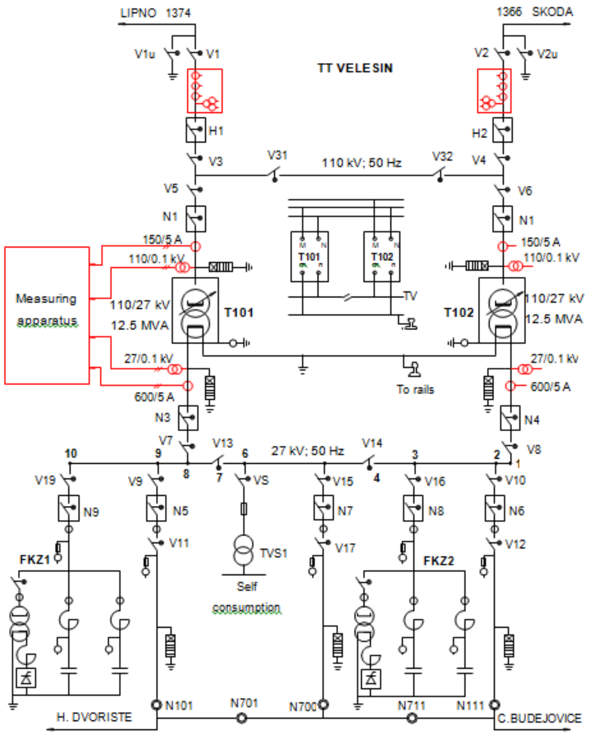

Fig. 2. Simplified diagram of traction transformer substation with connected measuring equipment

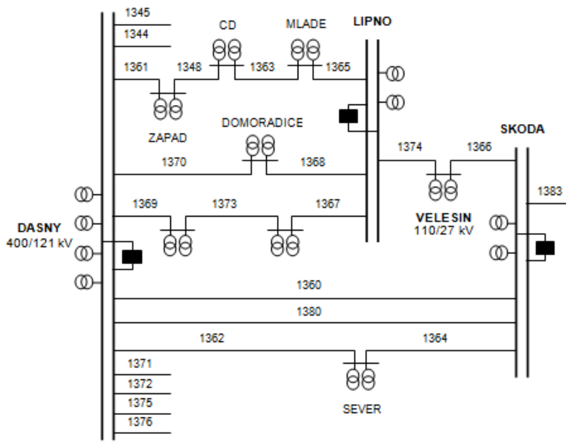

Fig. 3 Diagram of power distribution network

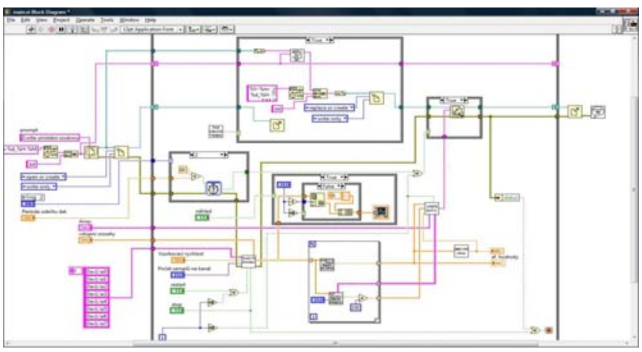

Fig. 4.Block diagram of measurement application

Measurement Results

Measurements were carried out at the traction transformer substation in Velešín, Czech Republic, on July 11-17, 2011. Measurements of harmonics were carried out on 110kV high voltage network. Total harmonic distortion was calculated according to standards, as a 95% percentile. Illustrations of total harmonic distortions of voltages in 110kV high voltage network at Velešín substation are presented in Figs 5, 6, and 7.

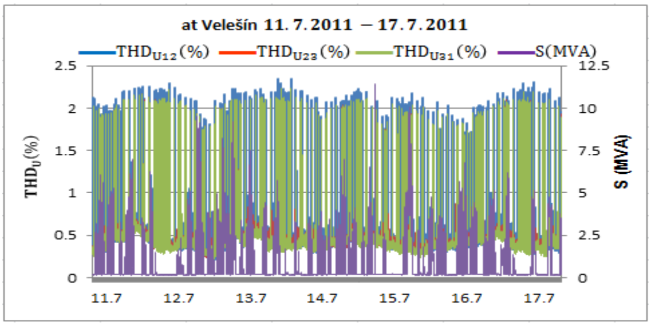

Fig.5. THD$_U$ at Velešín substation

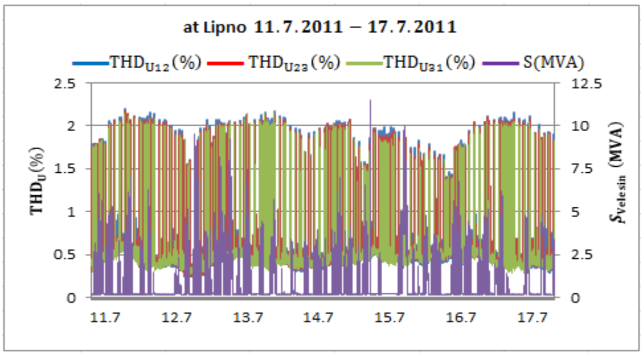

Fig.6. THD$_U$ at 110 kV Lipno substation

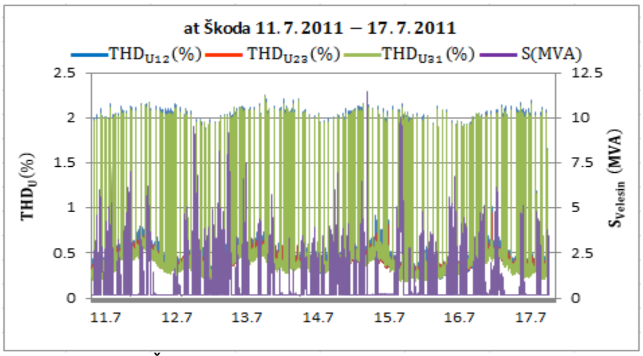

Fig. 7. THD$_U$ at Škoda substation

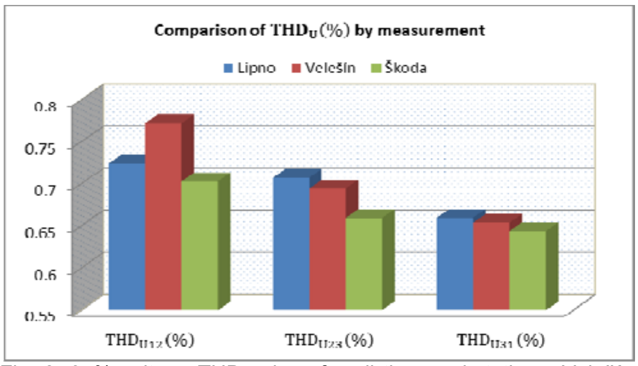

Fig. 8. 95% voltage THD values for all three substations, Velešín, Lipno, and Škoda: measurement results.

Simulation

Simulation focused on line-to-line voltage harmonic distortion in a 3-phase 110 kV system which was influenced by single-phase traction load. Simulation was carried out in ATP software, which is a version of the Electromagnetic Transient Program (EMTP). The ATP model is shown in Figure 9.

In the coupling point, a locomotive can be represented by several current harmonic generators, whose frequencies are multiples of the fundamental harmonic. Simulation was carried out for odd harmonics from 1st to 19th. Values of current harmonics were put in in accordance with measurement results.

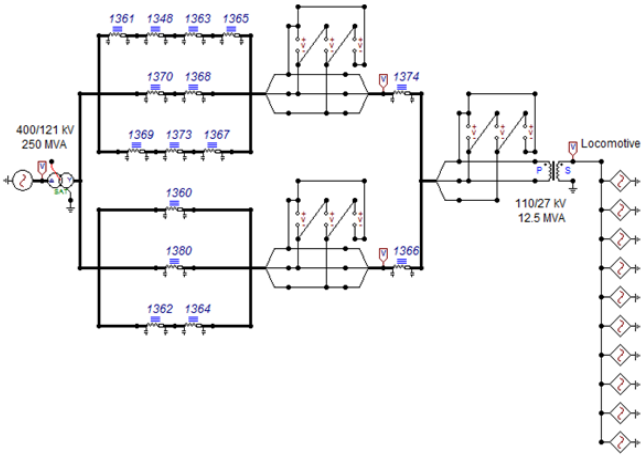

Fig 9. Simulation diagram

Fig 10 shows a comparison between measurement and simulation results, for voltage harmonics at substation Velešín. Fig 11 shows the results of harmonic voltages simulation for all three substations.

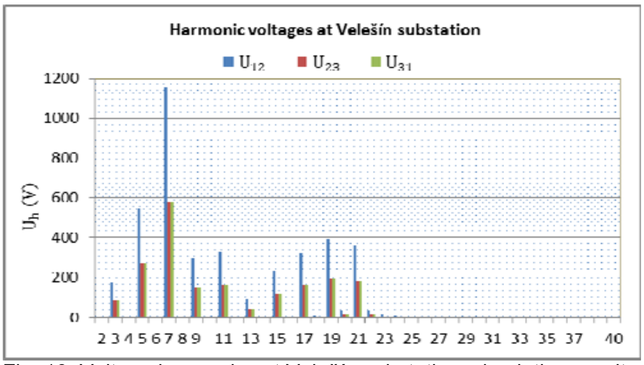

Fig. 10. Voltage harmonics at Velešín substation: simulation results

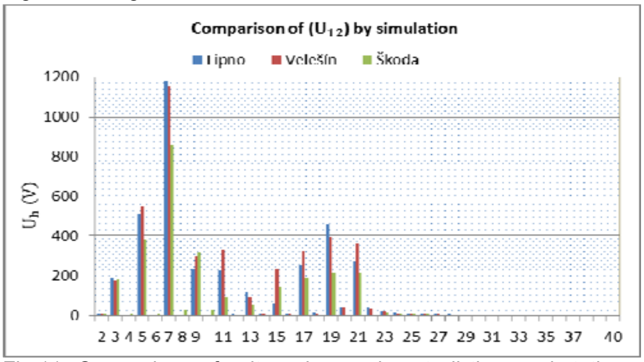

Fig.11. Comparison of voltage harmonics at all three substations: simulation results

Line-to-line voltage U_{12} harmonics are considerable, due to the single phase load connected to the system. This load also causes differences in voltage amplitudes in the three-phase system, i.e. voltage unbalance. The highest values are typical of low orders odd harmonics, such as 3rd, 5th and 7th harmonic component. 7th harmonic has the highest value. From 21st harmonic on, values are very low for both substations. Generally speaking, single-phase nonlinear loads cause high 5th and 7th harmonics. The fact that 5th harmonic is lower than 7th can be attributed to negative sequence impedance of electrical machines, or to long line resonance.

3rd and 7th current harmonics are higher than the rest, 3rd and 9th voltage harmonics are lower than 5th and 7th harmonics, and they show a rather constant level with no obvious load variations. A comparison of current harmonics between measurements and simulation results, is shown in Figs. 12, 13 and 14.

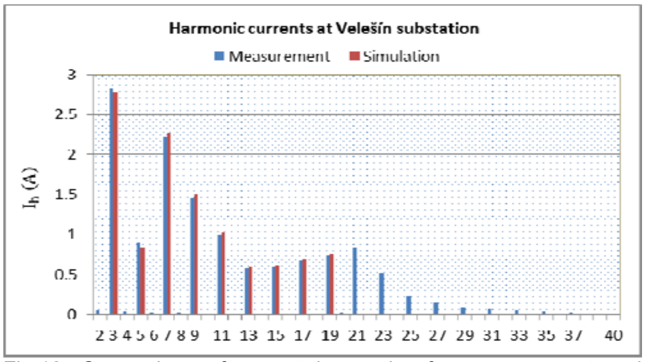

Fig.12. Comparison of current harmonics for measurement and simulation at Velešín substation

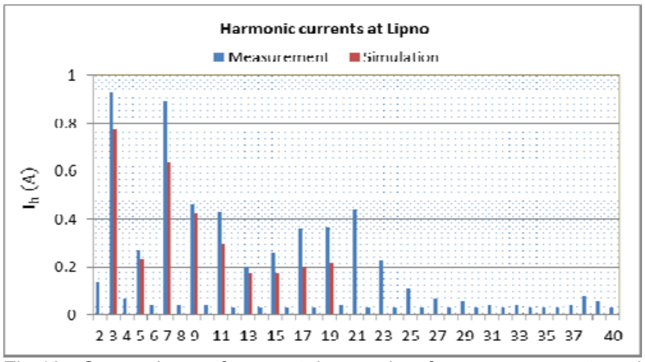

Fig.13. Comparison of current harmonics for measurement and simulation at Lipno substation

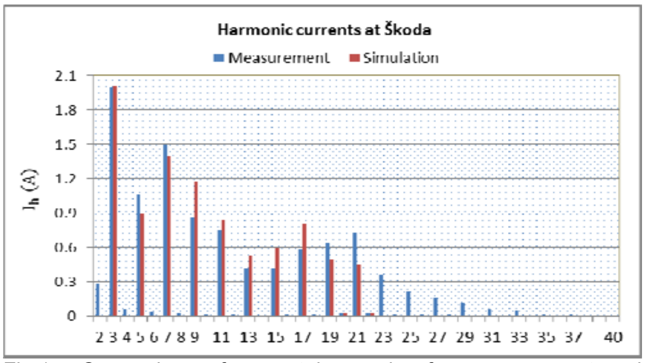

Fig.14. Comparison of current harmonics for measurement and simulation at Škoda substation

Total harmonic distortion for all three substations was larger for simulation than for measurement. At substation Velešín, the highest simulated $THD_{U12}(\%)$ = 1.2787%, the highest harmonics being 5th and 7th. At Lipno, the highest simulated $THD_{U12}(\%)$ = 1.2787%. At Škoda, the highest simulated $THD_{U12}(\%)$ = 0.9072%. At Velešín, the highest recorded $THD_{U12}(\%)$ = 0.9872%, where 5th and 7th harmonics were dominant again. At Lipno, the highest recorded $THD_{U12}(\%)$ = 0.789% at substation Škoda the highest recorded $THD_{U12}(\%)$ = 0.6839%.

Considering the simulation process as opposed to reality, simulation could be more favorable than measurement. These differences can be caused by some error in measurement, the influence of thyristor regulation of current in the decompensating reactor or voltage distortions in the feeding distribution network.

Table 1 shows line-to-line voltage total harmonic distortions for Lipno, Velešín and Škoda substations.

Table 1 Total harmonic distortion of voltages (THD_U) at all three substations by both measurement and simulation

	Content	Total harmonic distortion		
		THD_{U12}(%)	THD_{U23}(%)	THD_{U31}(%)
Lipno	Measurement	0.789	0.6333	0.5778
	Simulation	1.2316	0.6138	0.614
Velešín	Measurement	0.9872	0.7518	0.6088
	Simulation	1.2787	0.636	0.6372
Škoda	Measurement	0.6839	0.6119	0.5612
	Simulation	0.9074	0.4529	0.4522

Conclusion

An analysis of harmonic measurement results was carried out according to international standards and technical reports regarding power quality in distribution networks. Maximum measured values were compared with those given by the standard (maximum 95% weekly values were not reached). Maximum measured values were much lower than limits given in the IEEE Std. 519-1992 standard (2.5% on power supply 110kV) and EN 50160 (8%). Hence, evaluation of the measured data proved that harmonic distortion of the voltages at all three locations (Velešín, Lipno and Škoda substations) met conditions specified by standards for the operation of distribution systems.

Simulation results for all three substations were compared. Maximum THD_U value was simulated for Velešín, for U_{12} line-to-line voltage, the highest harmonic being 5^{th} and 7^{th}. That is caused by single-phase load connected to this phase. Simulation results were later compared with measurement results for all three measuring points, for all three line-to-line voltages. Both measurement and simulation results were within the limits stated by IEEE Std. 519-1992 and EN 50160. Differences were found between measurement and simulation results for line-to-line voltage U_{12}, while for the other two voltages the differences were insignificant.

The lowest values of harmonic distortion were found out by both measurement and simulation for Škoda substation.

Differences between measurement and simulation results may have been caused by a lack of data.

Measurement results for even harmonics were higher than their simulated results, probably due to thyristor regulation of current in the decompensating reactor, or some measurement error.

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