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Railway System Impact on Voltage Quality at the Level of the Croatian Transmission Network

SUMMARY

Railway systems are single-phase loads, connected to two-phase of the three-phase supply network. Therefore, they negatively affect the voltage quality, primarily the voltage unbalance. In addition to voltage unbalance, railway systems inject current harmonics into the network due to controllable diode or thyristor drives used to operate the train.

The paper gives a short theoretical description of the harmonic distortion and the voltage unbalance as well as the results of the voltage quality measurement. Moreover, the paper shows the impact of the railway system on the transmission network in the case that the facilities are connected to the 110 kV voltage level.

KEYWORDS

Railway system, voltage quality, voltage harmonics, voltage unbalance

INTRODUCTION

In the last decade, the Third energy package and the Clean energy for all Europeans package (so-called 'Winter Package') represent two major milestones in the frame of the EU energy legislation. The Clean energy for all Europeans package consists of eight legislative acts and represents a major step towards decarbonizing energy, facilitating better consumer outcomes and completing the Energy Union.

The Third energy package created a requirement for European network codes that cover grid connections, markets, and system operation. According to Hancher and Winters [1], »networks are often referred to as the 'hardware' of a well-functioning wholesale market«. In fact, operational security of transmission networks is crucial for the functioning of a sustainable electricity market. The network codes are designed to ensure a secure and competitive electricity market across Europe. A voltage deviation management procedure is prescribed in Article 19 of the Commission regulation (EU) 2017/2196 establishing a network code on electricity emergency and restoration [2] as follows: the procedure for the management of voltage deviations of the system defence plan shall contain a set of measures to manage voltage deviations outside the operational security limits set out in Article 25 of the Commission regulation (EU) 2017/1485 establishing a guideline on electricity transmission system operation [3]. Moreover, Article 17 of the Commission regulation (EU) 2017/2196 describes the automatic scheme against voltage collapse of the system defence plan, which may include a scheme for low voltage demand disconnection, a blocking scheme for on load tap changer and system protection schemes for voltage management.

In general, poor voltage quality can cause high costs for both the transmission system operator and network users, and technical solutions are very expensive [4]. Railway systems, supplied by the high voltage network, represent the main source of voltage unbalance, leading to voltage quality problems that affect the normal operation of the equipment connected to the point of common coupling or in the rest of power network [5]. Furthermore, with the use of motor starters and variable speed drives (which represent non-linear loads), they inject harmonic currents directly into the supply network causing harmonic voltages throughout the network [6].

Locating the source of disturbance at supplier and customer's point of common connection is important criteria in power quality assessment. Voltage quality problems, such as harmonics and unbalance, have both technical and economic consequences. Power quality assessment and localization of disturbance sources are becoming matters of great interest to both utilities and customers [7].

Nowadays, great attention is paid to the problem of power quality. This can be explained by the following arguments. Firstly, there is a trend towards an increase in technologically advanced equipment and production processes. This imposes high requirements on the quality of power to be supplied. In this context, it should be stressed that electricity has a market-driven value. Furthermore, most of the modern loads are nonlinear and their number is increasing. The nonlinear load generates harmonics, which leads to the distortion of voltage and current wave forms and changes in the characteristics of supplied power. This requires an increase in the power of the system by the value spent on their distortions [8].

The content of the harmonics level in the supply voltage has a significant effect on the efficiency of electricity usage. Therefore, there is a need for using a voltage quality monitoring system to ensure continuous monitoring of the harmonics level throughout the power system. Voltage quality monitoring system allows a real time determination of the harmonics direction and levels in the supply voltage.

The effect of non-sinusoidal power supply can be approximately mitigated by device derating, by installing K-rated distribution transformers and harmonic filters, or by complex network management, which aggregate the non-linear consumers [9].

Altogether, railway systems represent an undesirable load on the supply network.

DISTURBANCES

A number of studies point to railway influence on power supply system. Bearing in mind the findings in [5-6] and [10-11], it is important to clarify that voltage harmonics and voltage unbalance are disturbances of main interest.

2.1. Voltage Harmonics-

Harmonics are mathematical descriptions of current or voltage waveforms. Ideally, voltage and current waveforms are perfect sinusoids. However, because of the increased presence of electronic and other non-linear loads, these waveforms often become distorted. This deviation from a perfect sine wave can be represented by harmonics–sinusoidal components with a frequency that is an integral multiple of the fundamental frequency [12]. Thus, a pure voltage or current sine wave has no distortion and no harmonics, and a non-sinusoidal wave has distortion and harmonics, as shown in Figure 1.

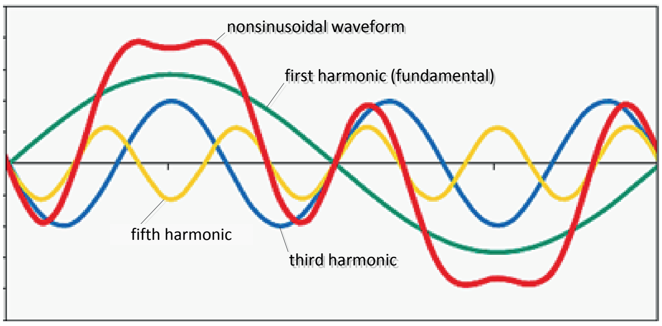

Figure 1. Distorted waveform consisting of the fundamental, third and fifth harmonics

Harmonic disturbances are generated generally from equipment with a non-linear voltage-current characteristic. A variety of harmonic sources exists – magnetic core equipment (like transformers, electric motors, generators, etc.), arc furnaces, arc welders same as electronic and power electronic equipment [10].

The total harmonic distortion (THD) is used to quantify distortion. THD expresses the distortion as a percentage of the fundamental (pure sine) of voltage and current waveforms. It is defined as:

$$THD_V = \frac{\sqrt{\sum_{h=2}^{40} V_h^2}}{V_1} \quad (1)$$

where: THD_V – total harmonic distortion, V_h – effective value of the h^{th} harmonic, h – harmonic order, V_1 – fundamental harmonic.

Voltage distortion affects not only sensitive electronic loads, but also electric motors and capacitor banks. In electric motors, negative sequence harmonics (the sequence of which is opposite to the fundamental sequence, i.e. 5th, 11th, 17th) produce rotating magnetic fields. These fields rotate in the opposite direction of the fundamental magnetic field and could cause overheating and mechanical oscillations in the motor-load system.

Many problems are also caused by 3rd harmonic and odd multiples of the 3rd (9th, 15th, 21st, etc.). These harmonics are called "triplens" (the A-phase triplen harmonics, B-phase triplen harmonics and C-phase triplen harmonics are all in phase with each other). According to [13], they will add rather than cancel on the neutral conductor of a 3-phase, 4-wire system (this can overload the neutral conductor if it is not sized to handle this type of load).

Harmonic problems are mitigated by linear chokes, multi-pulse convertor systems, passive or active filters, and broadband or tuned filters [14].

2.2. Voltage Unbalance

The three-phase power system is called balanced or symmetrical if the three-phase voltages and currents have the same amplitude and are phase shifted by 120° with respect to each other. If these conditions are not met, the system is called unbalanced or asymmetrical [15].

Voltage unbalance used to be defined as the maximum deviation from the average of the three-phase voltages, divided by the average of the three-phase voltages, expressed in percent [16].

$$V_{UN}[\%] = \frac{\max voltage\ deviation\ from\ avg\ line\ voltage}{avg\ line\ voltage} \cdot 100 \quad (2)$$

The unbalance is more rigorously defined using symmetrical components. The ratio of the negative-sequence component to the positive-sequence component can be used to specify the percent unbalance [12].

$$V_{UN}[\%] = \frac{negative\ sequence\ voltage\ component}{positive\ sequence\ voltage\ component} \cdot 100 \quad (3)$$

The positive and negative sequence voltage components are obtained by resolving three-phase unbalanced line voltages V_{ab}, V_{bc}, and V_{ca} into two symmetrical components – V_p and V_n. The two balanced components are given by:

$$V_p = \frac{V_{ab}+a\cdot V_{bc}+a^2\cdot V_{ca}}{3} \quad (4)$$

$$V_n = \frac{V_{ab}+a^2\cdot V_{bc}+a\cdot V_{ca}}{3} \quad (5)$$

where: $a = 1\angle 120°$, and $a^2 = 1\angle 240°$.

Unbalance is a serious power quality problem [17]. The unbalance affects the voltage quality, but also the additional heating of the generator rotor due to the inverse magnetic field caused by the inverse currents. The unbalance, therefore, affects the safety, reliability and economy of the transmission system. It is also important to mention that unbalance can cause great material damage as well as damage due to the inability of the electricity supply.

VOLTAGE QUALITY MONITORING

It is important to ensure voltage quality due to the susceptibility of industrial installations and end-user equipment to voltage disturbances. Therefore, voltage quality monitoring systems are implemented worldwide with the differences between countries in the choice of monitored voltage quality parameters. Regarding the voltage quality parameters monitored in different European countries, it is important to mention that a total of 15 countries are monitoring voltage unbalance [18].

The reason to monitor voltage quality parameters directly relied to railway system operation is spreading of electrified railway network and increase in traffic density and velocity, which causes higher power demand and, possibly, poor power quality [19]. Thus, European railway system operators are creating electrical system configurations that are less susceptible to disorders [20].

In order to ensure keeping the voltage quality parameters within the allowable limits, the system operators conduct measurement throughout the railway network [21–24], using the measurement results to improve the network stability. For example, part of the measurement results regarding the filtered spectra of pantograph voltage and current recorded in Germany and Switzerland have been included in the EN 50238-2 standard [21]. Furthermore, well known high-speed railways and intense traffic in Italy and France represent the maximum voltage quality impact. The measurements performed in Italy and France showed that voltage harmonic distortion in France was up to 3,5%, and in Italy up to 1,2% [23].

A more detailed explanation of voltage quality monitoring is interesting but is outside the scope of this paper.

MEASUREMENT RESULTS

Protecting the customer (consuming electricity with a satisfactory voltage quality) as well as the transmission system (that customer feedback is within the allowed limit) is an explicit aim of monitoring voltage quality parameters at the point of common coupling (PCC).

According to the Transmission network grid code [25], the limit for THD at the 110 kV level is 3%, and for voltage unbalance the limit is 1.4%.

The voltage harmonics measurements were performed in the 110/X kV transmission system substations, marked with letters A, B, C and D as shown in Figure 2. The reason for choosing those substations is that they are located in the weaker parts of the network (less installed power, only one transmission line connection, no 220 or 400 kV transmission lines in the substation), contributing to the more pronounced impact of the railway facilities.

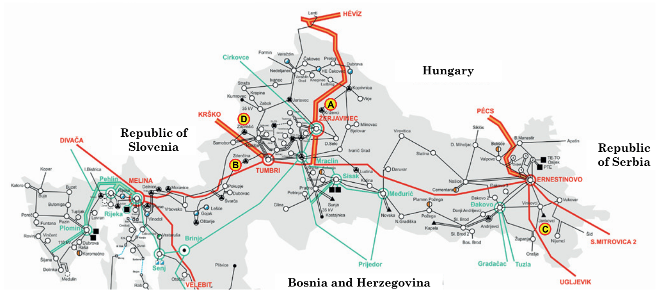

Figure 2. Northern part of the Croatian transmission system

4.1. Voltage Harmonics Measurements

Figures 3-6 show the measured harmonic distortion values in the facilities containing the railway system transformer field. The harmonic distortion measurements were performed on the voltage bus where the railway transformers are connected, since the maximum value of the harmonic distortion occurs there.

The maximum harmonic distortion values in facilities A and B were 2% and 1.5%, respectively (as is shown in Figure 3 and Figure 4).

Figures 5 and 6 show the maximum harmonic distortion values in C and D facilities, which were 2%.

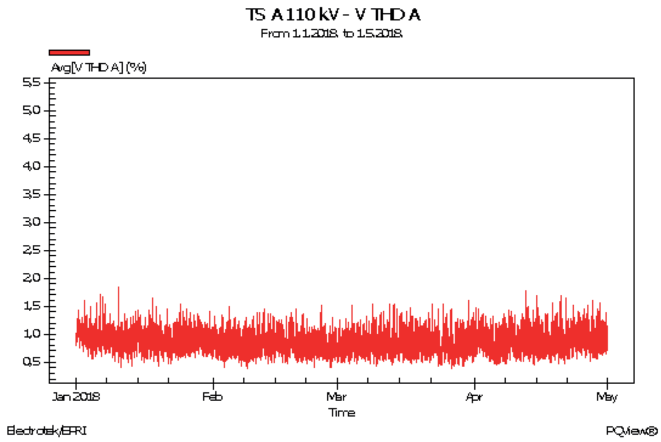

Figure 3. Value of the voltage THD in the facility A (TS 110 kV)

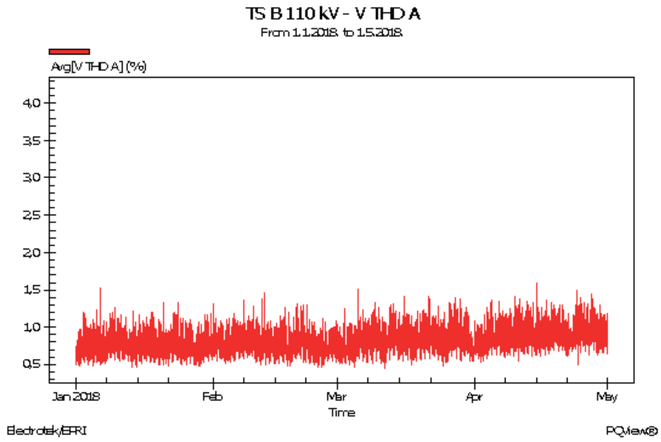

Figure 4. Value of the voltage THD in the facility B (TS 110 kV)

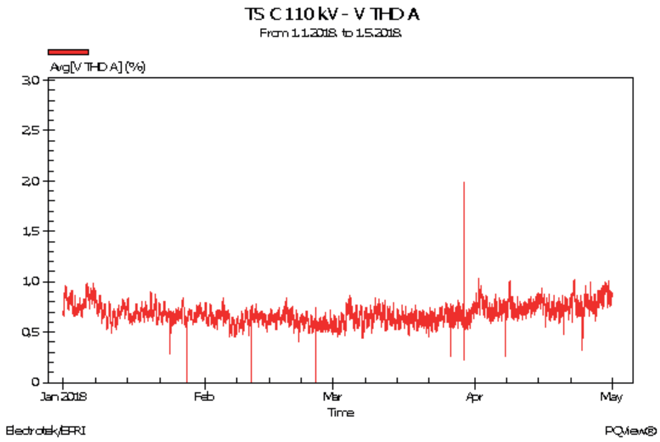

Figure 5. Value of the voltage THD in the facility C (TS 110 kV)

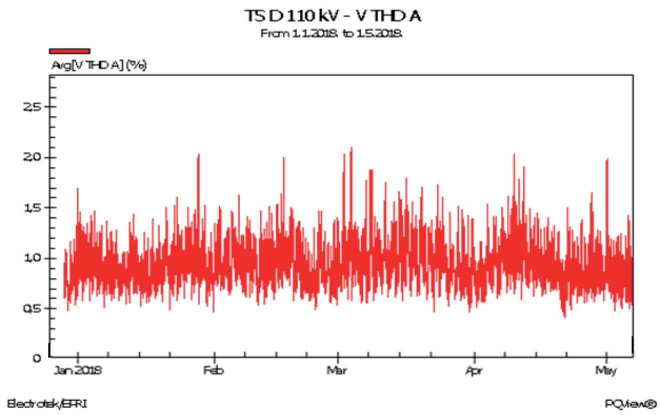

Figure 6. Value of the voltage THD in the facility D (TS 110 kV)

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At the transmission network level, CP95 value of voltage harmonic distortion is 1.15%, as is shown in Figure 7.

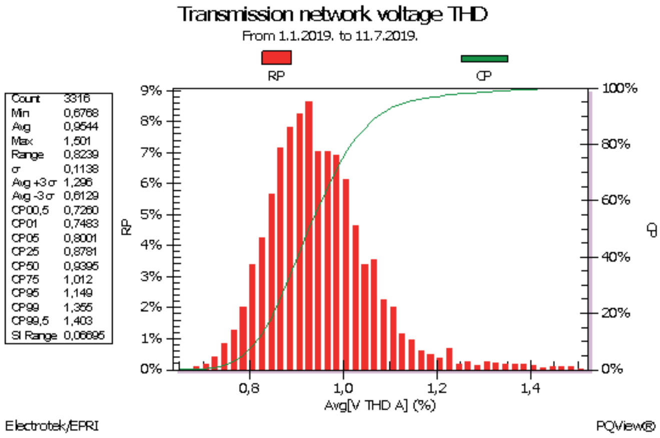

Figure 7. CP95 histogram for voltage THD in the transmission network

4.2. Voltage Unbalance Measurements

Figures 8-11 show the measured voltage unbalance values in the facilities containing a railway system transformer field. Voltage unbalance measurements were performed on the voltage bus where the railway transformers are connected, expecting the maximum value of the voltage unbalance.

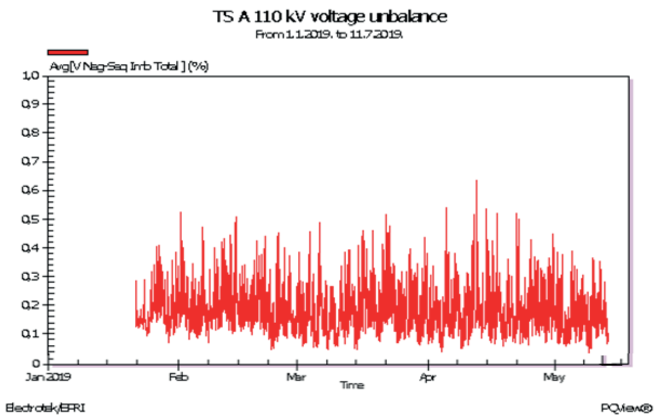

Figure 8. Value of the voltage unbalance in the facility A (TS 110 kV)

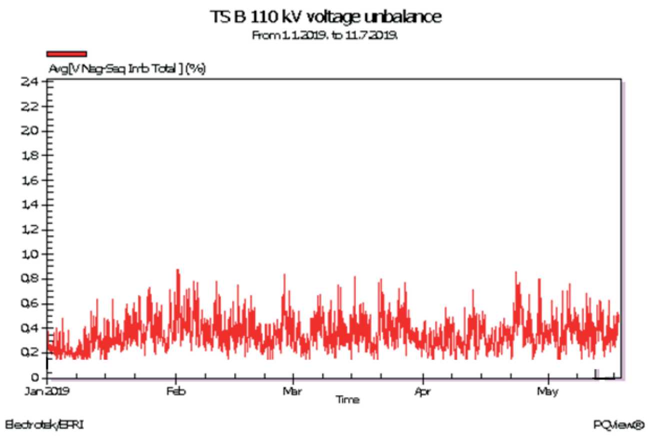

Figure 9. Value of the voltage unbalance in the facility B (TS 110 kV)

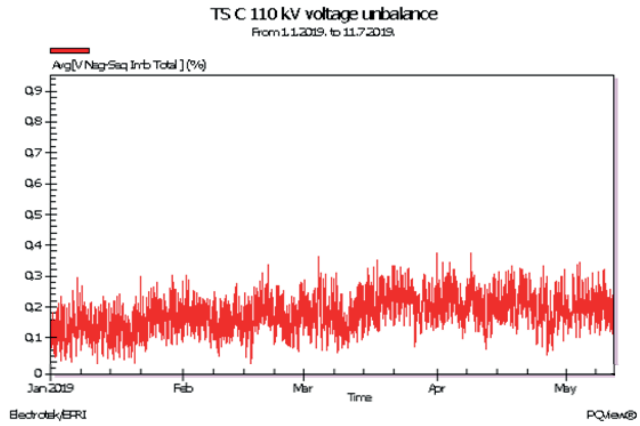

Figure 10. Value of the voltage unbalance in the facility C (TS 110 kV)

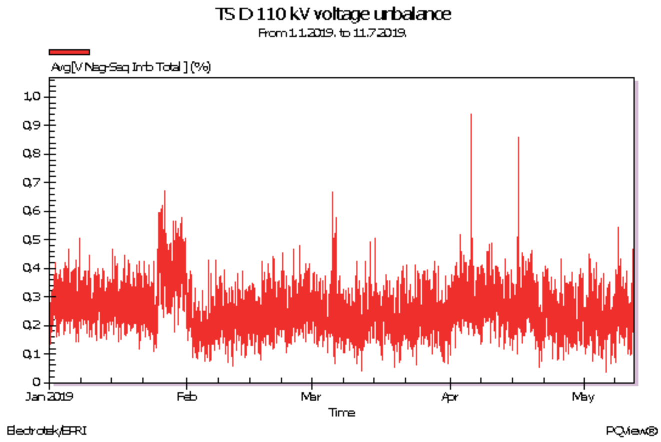

Figure 11. Value of the voltage unbalance in the facility D (TS 110 kV)

The voltage unbalance value measured in facility A is less than 0.65%, and in facility B does not exceed 0.9% A slightly lower unbalanced load with voltage unbalance about 0.35% is measured in facility C, while voltage unbalance measured in facility D is about 0.95%.

The highest values of unbalance appear on the common busbars of the railway facility. Taking into consideration the measured voltage unbalance values shown in Figures 8-11, it can be concluded that the 110 kV transmission network is robust enough to overcome the negative influence of the railway system facilities regarding the voltage unbalance.

Overall at the level of the Croatian transmission system as a whole, the unbalance is less than 0.35% (Figure 12).

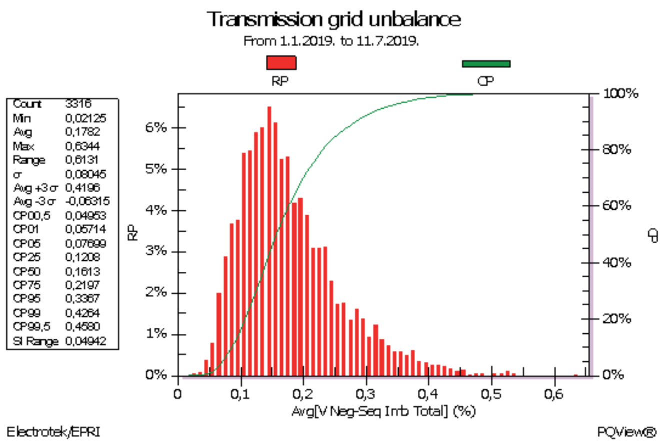

Figure 12. CP95 histogram for voltage unbalance in the transmission network

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CONCLUSION

The railway system is one of the largest voltage quality »polluters« since it is a specific load supplied from two-phase of the three-phase network causing a voltage unbalance. Due to the operation of the thyristor converters in the trains, it also causes a large voltage distortion.

Therefore, it is necessary to verify the impact of the railway system operation on the transmission network, as it may interfere with the operation of other customers connected to the network. In addition, railways are of great socio-economic importance, and their negative impact on the transmission system cannot be eliminated by disconnecting them from the network.

Although the railway is theoretically a major problem for any supply grid, the results of this study show that it does not cause any major issues on the 110 kV voltage level of the Croatian transmission network. In fact, the total consumption of the railway system is relatively small, due to occasional energy needs (train passage). Thus, the average monthly demand in some railway substations is equal to 20% of the installed power. This is the reason why it does not significantly reduce the voltage quality of the transmission network. Taking into consideration the measured voltage unbalance values, it can be concluded that the 110 kV transmission network is robust enough to overcome the negative influence of the railway system facilities regarding the voltage unbalance.

In conclusion, high values of voltage unbalance at the level of the Croatian transmission network may occur only in the case of a single phase drop-out (conductor break due to ice or mechanical damage), rather than a connection of the railway facility to the grid.

Since there is no infrastructure for the high-speed railway in Croatia at this time, taking into account the experience of other European countries, it is certain that there will be no augmentation of the overall railway impact on power quality in the near future.

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