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Assessment of AC traction substation influence on energy quality in a supplying grid

Ocena oddziaływania podstacji trakcyjnej prądu przemiennego na jakość energii elektrycznej w sieci zasilającej

Abstract

This article presents investigations performed on a 25 kV AC system with a Scott transformer simulation model. The model includes an energy quality parameter calculation algorithm with consideration to the train timetable. The simulation results enable an analysis of the energy quality parameters at the point of connection of the traction substation to the supplying grid. The presented tool enables the simultaneous calculation of voltage unbalance and harmonic content. The article presents the results of the energy quality analysis at the substation connection point for the specific location. The simulation results of the energy quality parameters are appraised on the basis of standard EN 50160:2010. The tool may prove helpful in the process of designing electrification systems, especially in the choice of traction transformer and power electronics device mitigating an imbalance and harmonic impact.

Streszczenie

Keywords: AC electrification system, electric energy quality, simulation modelling, Scott transformer

Artykuł przedstawia badania przeprowadzone z wykorzystaniem modelu symulacyjnego systemu zasilania prądu przemiennego 25 kV 50 Hz z transformatorem Scotta, uwzględniającym wszystkie czynniki jakości energii elektrycznej przy uwzględnieniu rozkładu jazdy pociągów. Wyniki badań pozwalają na kompleksową analizę parametrów jakości energii w punkcie przyłączenia podstacji trakcyjnej do systemu elektroenergetycznego przy uwzględnieniu rozkładu jazdy pociągów oraz rodzaju taboru. W porównaniu z innymi opublikowanymi pracami przedstawione narzędzie pozwala na określenie zarówno asymetrii napięciowej jak i harmonicznych napięcia w punkcie przyłączenia podstacji trakcyjnej. Narzędzie może być przydatne procesie projektowania układu zasilania, w szczególności doboru urządzenia symetryzującego na podstacji trakcyjnej dla danej lokalizacji tak, aby uzyskać spełnienie wymagań normatywnych.

Słowa kluczowe: System elektryfikacji prądu przemiennego, jakość energii elektrycznej, modelowanie symulacyjne, transformator Scotta.

1. Introduction

Railway electrification systems of 50 Hz AC in Europe are powered by traction substations, which cause a number of disturbances into the power system. They contribute to the deterioration of the energy quality parameters in distribution and transmission networks. In general, three factors can be mentioned that affect the energy quality in power grids supplying traction substations: negative sequence component, harmonic content and load variability. The effects of asymmetry has been thoroughly investigated by a number of researchers [1][2][3][4][5][7][13][20]. A number of solutions to reduce current asymmetry were presented. The second factor affecting the quality of energy is the high harmonic content in traction currents drawn by electric vehicles, in particular the old type of electric vehicles equipped with thyristor rectifiers [8]. The last factor is the variable power consumption and the presence of relatively high peaks of power demand [9]. In most publications, the abovementioned interfering factors and their effects are discussed separately; there are no power supply models that take all factors into account [10]. The impact of these factors depends on the number of loads and their power; therefore, on the traffic situation on railway lines supplied by traction substation. There are no publications which describe the impact of train timetables on the energy quality in the power supply network. This article describes the complete simulation model of a 25 kV AC power system with the Scott transformer, taking into account all the factors of electric energy quality with consideration to parameters of train traffic such as the train timetable. Simulation results can be used in the designing process, especially for sizing of power equipment such as Scott transformers for a given substation location.

2. Simulation model

The simulation model consists of two parts: the Scott transformer model and the model of the traction load of the Scott transformer. Corresponding elements are presented later in this paper.

2.1. 2Scott transformer

Figure 1 shows the general scheme of the Scott transformer. The voltages on the secondary side is equal to the module with the shift angle between them 90°, if voltage vectors in the primary side are symmetrical. Figure 2 presents voltage and current vector graphs of the primary and secondary side of the Scott transformer. Figure 2 shows the situation in which the secondary winding currents are not equal to the module and phase; this results in the primary currents being asymmetric. Formulas 1-3 show the relationships between the complex values of the primary currents and the secondary winding Scott transformers [14].

The load on the primary side of the Scott transformer is symmetrical if the values and phase of the secondary currents are equal. The coefficient of the current asymmetry, which is a negative sequence component on the primary side of the Scott transformer, is a function of the modules and phase angles of the secondary side currents.

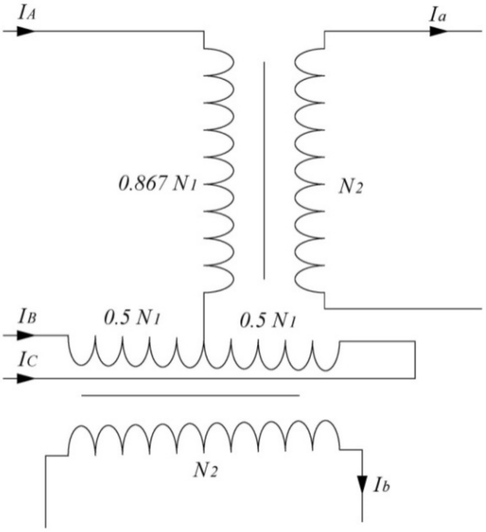

Fig. 1. A general scheme of the Scott transformer

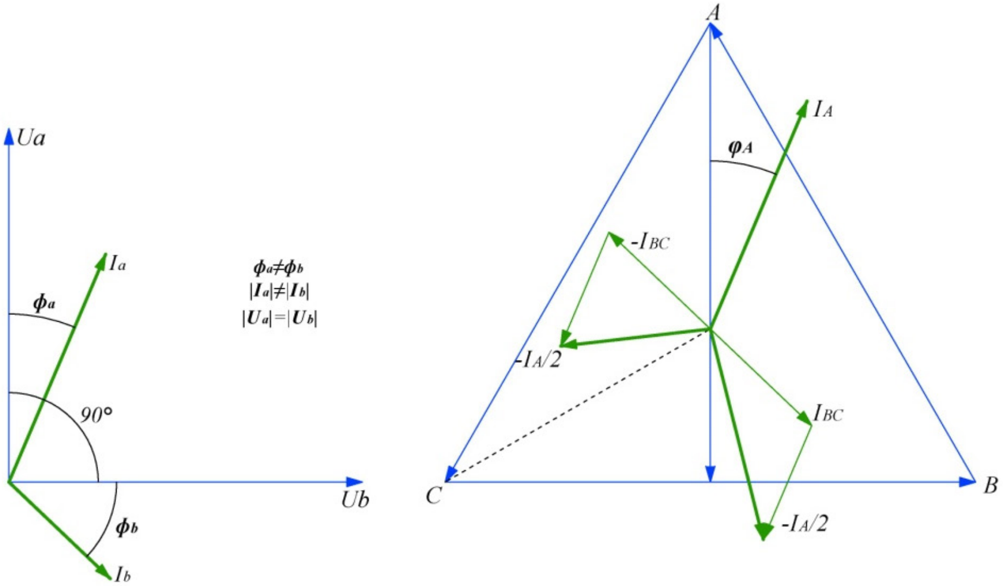

Fig. 2. Vector graphs of the voltage and currents of the Scott transformer in asymmetric load condition

$$I_A = \frac{2}{\sqrt{3}}\frac{N_2}{N_1} I_a \tag{1}$$

$$I_B = \frac{N_2}{N_1}\left(I_b - \frac{1}{\sqrt{3}} I_a\right) \tag{2}$$

$$I_B = -\frac{N_2}{N_1}\left(I_b + \frac{1}{\sqrt{3}} I_a\right) \tag{3}$$

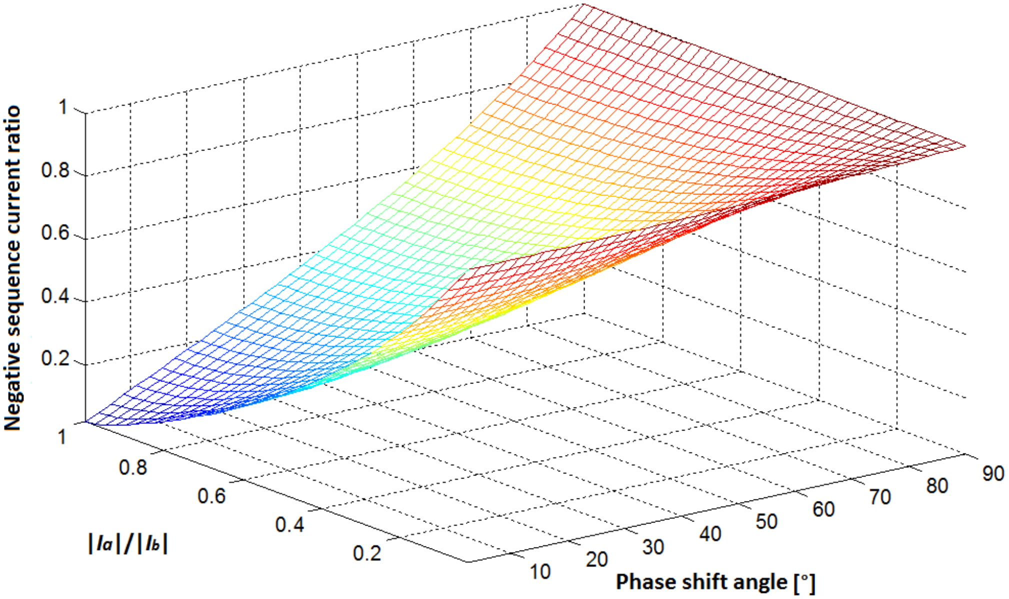

Fig. 3. Graph of the current asymmetry coefficient (negative sequence current ratio) on the primary side of the Scott transformer as a function of the current modules ratio and the difference between the current angle shifts on the secondary side [6][10]

2.2. Model of the traction load

The load of the Scott transformer is determined using the simulation program modelling an electrified railway line. It consists of two main elements – the train performance calculation algorithm, which determines the motion parameters of trains driving according to the given timetable, and the power flow algorithm determining the substation load. The flowchart of the whole simulation program is presented in Figure 4. The results of the train performance calculation algorithm, in particular, results relating to electrical power and the position of trains are used in the power flow algorithm at each time step of simulation. Performance of the algorithms is being repeated at every time-step of the simulation.

The acceleration a of each electric vehicle is calculated in accordance with (4).

$$a(t_i, j) = \frac{dv_j(t)}{dt} = \frac{Ft(v_j, U_j) - W(v_j)}{m(1+\eta)} \tag{4}$$

In the algorithm, a three-phase drive cycle is modelled. The drive cycle consists of a start-up phase, a constant speed phase, and a braking phase. In a start-up mode, a maximum tractive effort available based on the traction characteristics is generated. The traction characteristics and rolling resistance versus speed for a five-carriage electric multiple unit are presented in Fig.5. During the constant speed phase, the tractive effort is adjusted by the speed regulator model; the reference speed is given either by the speed limit for a given track or by the maximum value of the train speed.

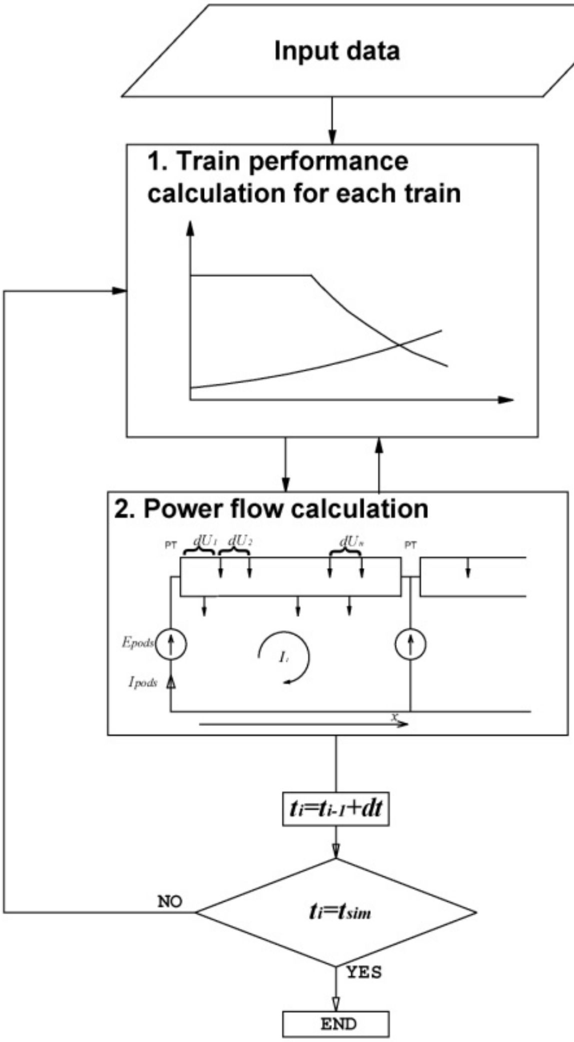

Fig. 4. General flowchart of the model of electrified railway line

A train performance calculation for each time step of simulation is carried out for all trains operating in the modelled electrified line simultaneously. The number of trains modelled is not constant throughout the simulation. Trains operate according to the timetable, where the locations and departure time values are given. In the simulation study, the constant headway time is modelled; the timetable with the headway time is presented in Figure 6.

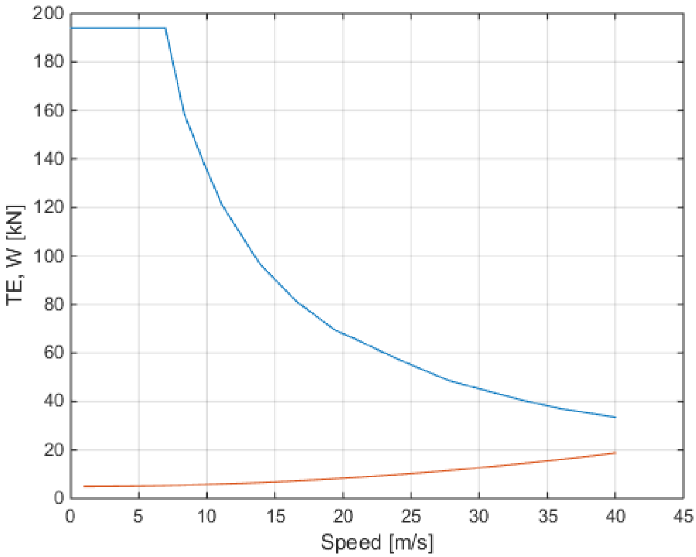

Fig. 5. Traction characteristics and rolling resistance of an electric multiple unit

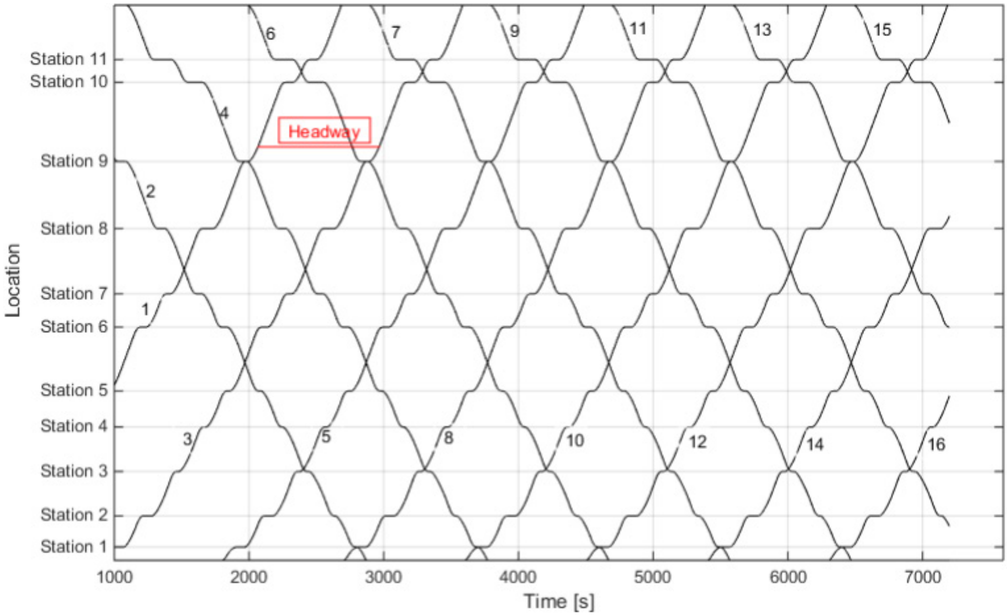

Fig. 6. The timetable modelled in the simulation study.

The power flow algorithm is based on the equivalent circuit presented in Figure 7 [19].

The power flow method is based on the mesh method of circuit analysis. The current in each mesh of the equivalent circuit can be determined based on matrix equation (5).

$$[Z][I]=[U] \tag{5}$$

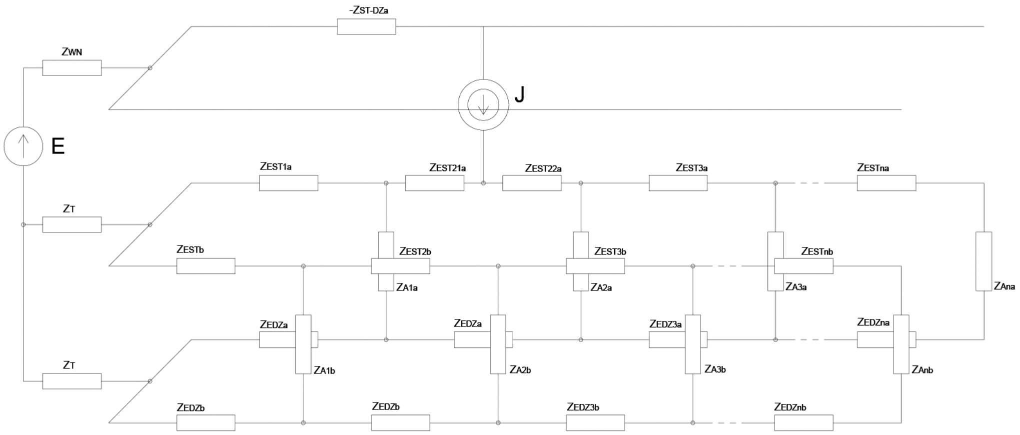

Fig. 7. Circuit model of electrified railway line in 2 x 25 kV system

At the first step, the currents are calculated according to equation (5). The resultant currents are obtained based on the superposition method (6).

$$I_k = \sum_{i=1}^{n} I_{ki} \tag{6}$$

The current values in each time step of the individual secondary windings of the Scott transformer, as well as the harmonic content in each time step are the final data obtained from the simulation program presented in Figure 4. It is assumed that the supply system is in steady state in each time step of simulation. In the simulation study, the central-side traction substation location is modelled – this is presented in Figure 8.

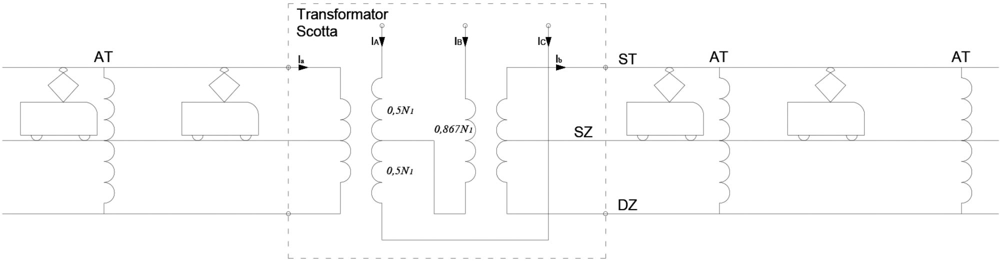

Fig. 8. Scheme of one track power supply system with a central-side traction substation with a Scott transformer

3. Simulation model verification

In order to verify the model, the results of computer simulation of the Scott transformer operation were compared with the results of laboratory tests presented in [10]. In [10], the tests on the physical model presented in Fig.8 were undertaken.

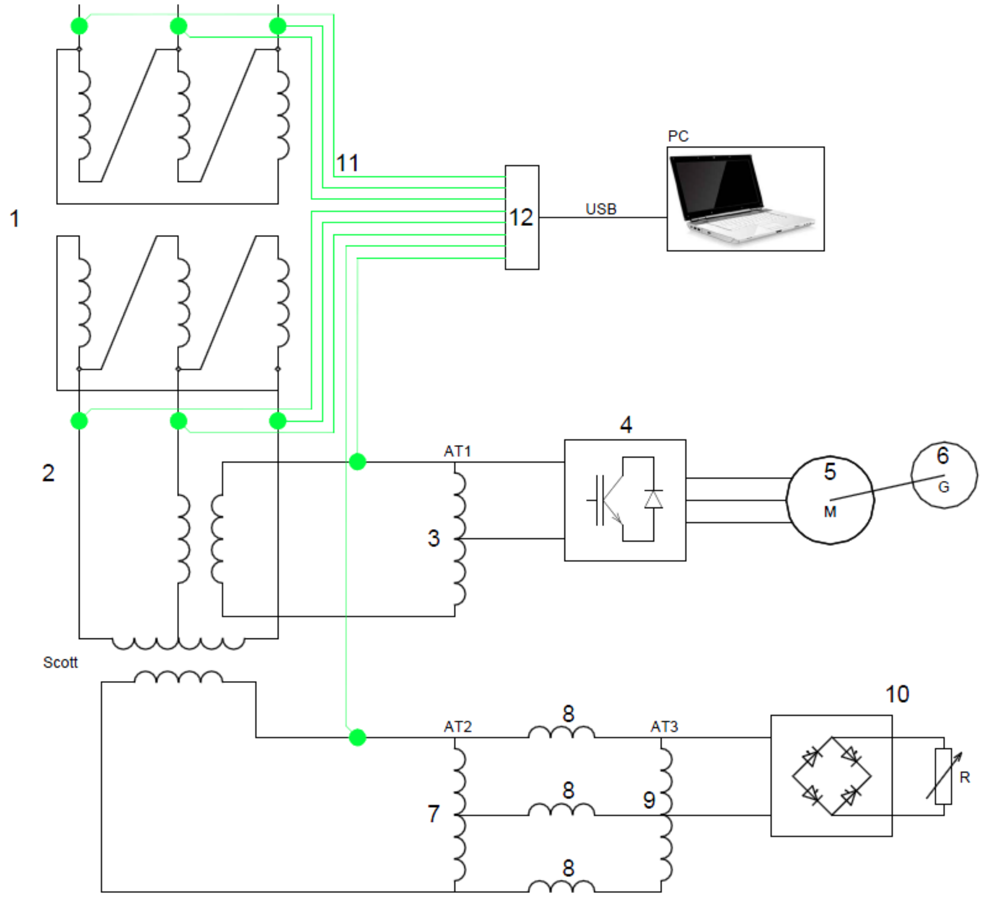

Fig. 9. Diagram of a laboratory model of a Scott transformer feeding nonlinear loads via autotransformers: 1 – step down transformer; 2 - Scott transformer; 3, 7, 9 – autotransformers; 4 – AC/DC/AC converter; 5 – three-phase induction motor; 6 – DC machine;8 – reactance modelling overhead catenary; running rails and parallel feeder; 10 – diode rectifier and resistor

4. Simulation modelling

The study analyses the influence of the rail power supply system on electric energy quality in the power system for the selected location. A 25 MVA Scott transformer was connected to a 110 kV distribution network with a short-circuit power level of 900 MVA. A number of studies of energy quality in cases of various train timetable was conducted. Different traffic patterns were modelled for different types of trains – suburban electric *m*ultiple units and freight trains. The harmonic contents drawn by different train types are different [8][15]. For electric multiple units, the harmonic contents are taken from [15], whereas for the freight trains, they are taken from [8]. The parametric analysis has been performed for different values of short-circuit power.

4.1. Electric multiple units

In the study, a 50 km railway simulation model was constructed with a 25 km central-side traction substation. The assumption is that the first secondary winding of the Scott transformer feeds the section before the substation (km 0–25) and the second winding feeds the section behind the substation (km 25–50). In the positive direction, 7 stations were modelled, while in the negative direction, 11 were modelled. The operation of 10-car multiple units was modelled. The rolling stock data was updated with data provided by the manufacturers for the rolling stock. Figure 9 presents the negative sequence voltage ratio of the primary side of the Scott transformer for the different headway time of train operation. The results of the voltage harmonic content in the voltage supplying traction substation are presented in Figure 10; the time plot of each harmonic is presented.

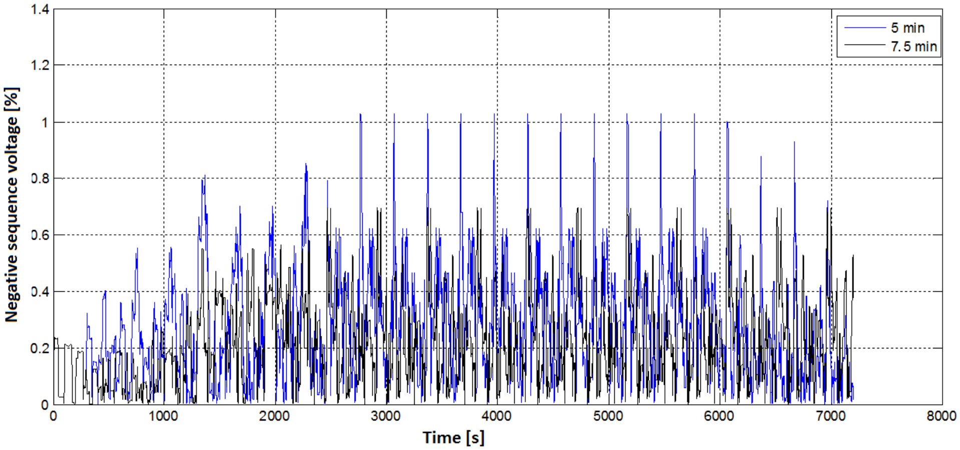

Fig. 10. Negative sequence of the primary side voltage for the different headway time of the electric multiple units operation

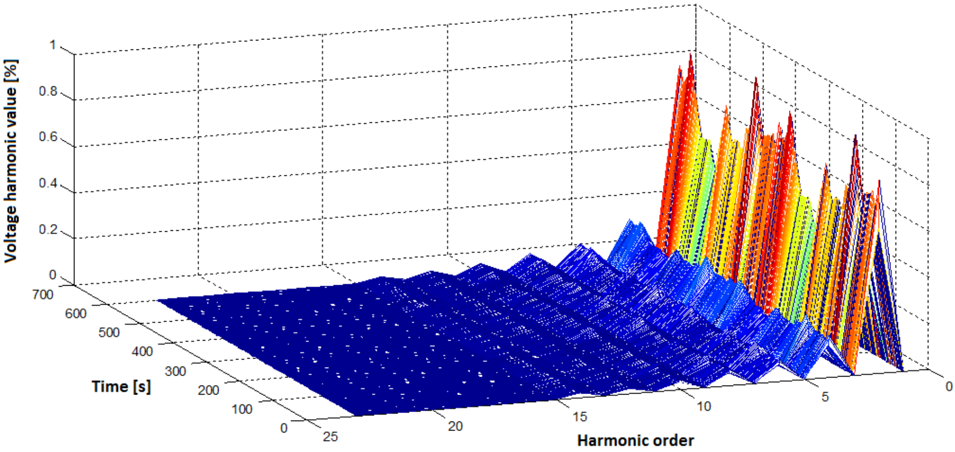

Fig. 11. Voltage harmonic content in the voltage supplying traction substation

4.2. Mixed train operation

This section presents the results of simulations of electric multiple units and freight train operation. The situation is modelled in which electric multiple units alternate with freight trains on the railway line. The operation for multiple units was assumed with the headway time of 20 min and the same for the freight trains. Thus, the headway time between *consecutive* trains is 10 min. An assumption of the equal average speed for each type of train was made. Freight trains do not stop on the stations. Figure 11 shows the voltage negative sequence current coefficient for short-circuit power levels of 900 and 1200 MVA. Figure 12 shows the voltage harmonics for the above presented traffic situation for the short-circuit power level of 900 MVA.

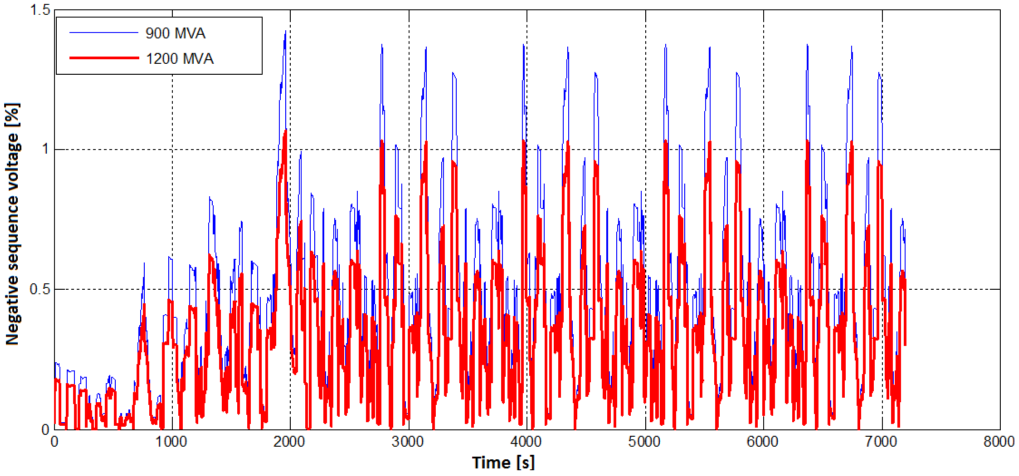

Fig. 12. Time course of the negative sequence voltage for the mixed traffic for the two different short-circuit power levels

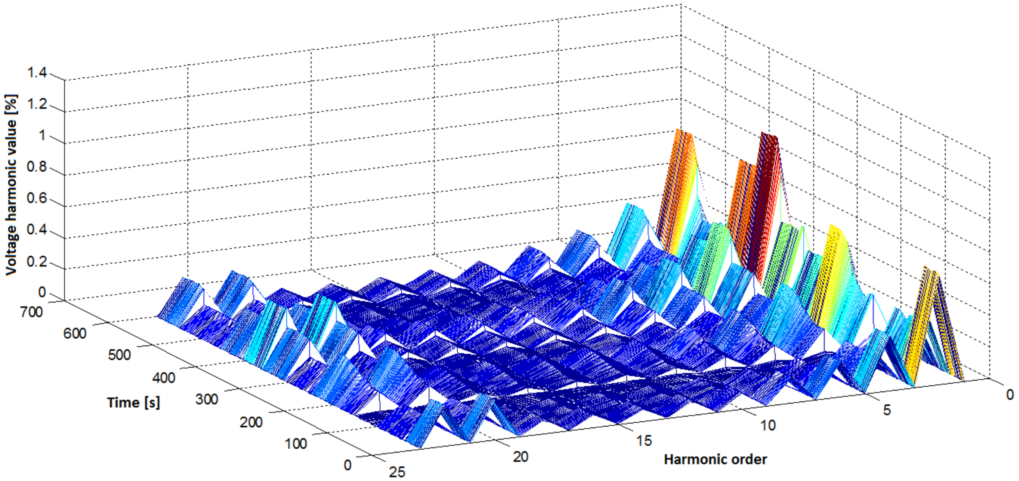

Fig. 13. Voltage harmonic content at the point of connection of the traction transformer to the supply grid

5. Conclusions

The results show that at a short-circuit power of the grid of the 900 MVA, the value of the negative sequence voltage in an assumed traffic scenarios does not exceed the 2% limit given in the standard [11]. According to estimates [2,3], when using typical transformers at the AC substation, the required short-circuit power should be (assuming a limit of 2%) at least 50 times the expected power of the asymmetry. Therefore, for the traction power level 25 MVA short circuit power should not be less than 1250 MVA. Thus, in the case in question, the use of the Scott transformer would allow the substation to be connected to a node with considerably lower short-circuit power. Voltage harmonics were not exceeded in any of the simulated scenarios.

The presented simulation tool and the results of the tests allow a comprehensive analysis of the parameters of the energy quality at the point of connection of the traction substation to the power system taking into account the train timetable and the type of rolling stock. Compared to other published works, the presented tool allows determination of both the voltage asymmetry and the harmonic voltage at the point of connection of the traction substation. The tool may be useful in the process of designing power supply systems, in particular, for the sizing of a power device at the traction substation for the given location.

References

[1] Altus J., Novak M., Otcenasova A., Pokorny M., Szeląg A., *Quality parameters of electricity supplied to electric railways,* Scientific Letters of the University of Żilina-Communications 2–3/2001.

[2] Barnes R., Wong K.T., *Unbalance and harmonic studies for the Channel Tunnel railway system,* IEE Proc. B, vol. 138, no. 2, March 1991.

[3] Matta V., Kumar G. *Unbalance and voltage fluctuation study on AC traction system*. Electric Power Quality and Supply Reliability Conference, 2014, pp. 303–308.

[4] Kowalski Z., *Jakość energii elektrycznej* – Monografie Politechniki Łódzkiej, 2008.

[5] Ogunsola A., Mariscotti A., *Electromagnetic Compatibility in Railways. Analysis and Management,* Springer 2013.

[6] Wang H., Tian Y., Qin-chang G., *Evaluation of negative sequence current injecting into the public grid from different traction substation in electrical railways. Electricity Distribution – Part 1,* 2009. CIRED 2009. 20th International Conference and Exhibition on, vol., no., 8–11 June 2009, pp. 1–4.

[7] Tien-Trung V., Paleček J. and Kolář V., *Influence of AC Electric Traction on Harmonic Distortion in 110 kV Supply Voltage Network: Measurement and Simulation.* Przegląd Elektrotechniczny 89 (2013).

[8] ZupanA., TeklicA.T., Filipovic-Grcic B., *Modeling of 25 kV electric railway system for power quality studies*. EUROCON, 2013 IEEE , vol., no., 1–4 July 2013, pp. 844–849.

[9] Takeuchi H., Goodman C., Sone S., *Peak demand reduction techniques when starting under moving block signaling.* Developments in Mass Transit Systems, 1998. International Conference on (Conf. Publ. No. 453) , vol., no., 20–23 Apr 1998, pp. 280–285.

[10] Jefimowski W., Burak-Romanowski R., *Disturbing impact of AC railway power supply with a Scott transformer on a supplying grid – laboratory tests.* MET'2015 12th International Conference Modern Electric Transport, Trogir, October 4–7, 2015.

[11] European standard. *EN 50160:2010 Voltage characteristics of electricity supplied by public electricity networks.* European Committee for Electrotechnical Standardization. 2010.

[12] Kowalski Z., *Jakość energii elektrycznel.* Monografie Politechniki Łódzkiej, 2008.

[13] Szeląg A., Patoka M., *Some aspects of impact analysis of a planned new 25kV AC railway lines system on the existing 3 kV DC railway system in a traction supply transition zone.* Power Electronics, Electrical Drives, Automation and Motion *(SPEEDAM)*, 2014 International Symposium on. IEEE, 2014.

[14] John J., Winders Jr., *Power Transformers Principles and Applications.* Marcel Dekker Inc. New York–Basel 2002.

[15] Bekele H. M., *Harmonic Analysis in 25 kV AC Railway Electrification system: The case of proposed Etiopian Railway System.* PhD thesis, Addis Ababa, August 2014.

[16] Firpo F., Fracchia M. and Savio S., *Locomotive drive harmonic pollution in AC traction systems.* Industrial Electronics, 1993. Conference Proceedings, ISIE'93 – Budapest., IEEE International Symposium on, Budapest, Hungary, 1993, pp. 622–628

[17] Liu S.M., Chen D.X., LiQ. L., Zhang X.D. and YuX. P., *The Impact of 350 km/h High-Speed Railway to Grid Power Quality*, 2012 Asia-Pacific Power and Energy Engineering Conference, Shanghai, 2012, pp. 1–4.

[18] Jefimowski W., *Koncepcja zasilania linii kolejowej dużej prędkości w systemie 2 x 25 kV.* Master of Science Thesis, Electric Traction Division, Warsaw University of Technology, 2011.

[19] Бородулин Б.М., Векслер М.И., *Система тягового електроснабжения 2 x 25 кВ*, Москва 1989

[20] Mandić M., Uglešić I., Milardić V., *Design and testing of 25 kV AC electric railway power supply systems*. Tehnički Vjesnik 20, 3(2013), pp. 505–509.

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