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ELIMINATION OF ASYMMETRY IN A 3-PHASE POWER SYSTEM SUPPLYING A 25 kV AC TRACTION SUBSTATION – COMPARISON OF SELECTED SOLUTIONS

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Abstract

A 25 kV 50 Hz system is recognized as a system recommended for supply of electrified railways systems due to its significant advantages. However, there exist significant drawbacks in asymmetry introduced due to one-phase character of traction substations into 3-phase power supply.

When projects on development of a 25 kV 50 Hz power supply system are being worked out, it is required to analyse the influence of a traction substation on a supplying power system, and the level of expected asymmetry should be assessed and proper measures undertaken.

The paper presents results of research during which a comparative analysis of operation of different circuits with application of symmetrizing devices applied in 25 kV 50 Hz traction system substations. Simulation of different schemes and control methods were undertaken and as the most perspective symmetrizing device was recognized a local symmetrizing device with regulation of P and Q power between secondary windings of a Scott transformer.

Introduction

Nowadays in Poland interest and need towards construction of new high speed lines or reconstruction of the existing one for speed of trains above 200 km/h have increase. So it is necessary to prepare a new power supply system (25 kV 50Hz) in parallel to the existing one 3 kV DC for introduction in Poland. Thus it is worth undertaking a comparison of these two systems, especially from the point of view technical requirements and Technical Specification of Interoperability in Europe. Costs of required investment, service and efficiency are another important issues. 25 kV AC system has advantages comparing to a 3 kV DC system, but there are drawbacks observed as well, among them asymmetry caused in public power supply system and other negative influence on the technical infrastructure around the line [1,2,3,5,6,7,8].

AC supply systems are widely used for supplying trains reaching speeds above 200 km/h and there are the only ones recommended for high speed traffic above 250 km/h.

25 kV 50 Hz power supply system

Different variants of 25 kV AC systems, which could be applied on railway lines close together, are used. For instance, main track lines (with high power demand) may be electrified under a 2x25 kV AC variant, while side-track, parking tracks could be electrified under a 1x25 kV variant.

According to the adopted markings of electrical equipment, the variants of 25 kV 50 Hz could be denoted: 1×25 kV as 1 AC 25 kV, 2×25 kV as 2 AC 50/25 kV 50 Hz, 2 AC 43,3/25 kV 50 Hz or 2 AC 35,4/25 kV 50 Hz, which results from a phase shift (180º, 120º or 90º) between phases of secondary phases of main transformers.

Since the 1950s, the 1x25 kV system evolved into: 1×25 kV, 1×25 kV with booster transformers, 2×25 kV with autotransformers AT.

Voltage and current asymmetry

3-phase power supply system is asymmetrical when 3 vectors of voltage and (or) currents have different amplitudes and/or a phase shift between them is not equal to 120º. One of the significant sources of asymmetrical load is in fact 25 kV 50 Hz AC due to application in a traction substation of one-phase or 3-phase, but not symmetrically loaded traction transformers. The level of allowed asymmetry is being defined by local or international standards [10].

When projects on construction of a 25 kV 50 Hz power supply system are being worked out, it is required to analyse the influence of a traction substation on a supplying power system, furthermore the level of expected asymmetry should be assessed.

When the allowed level of asymmetry is exceeded, there is a need for application of symmetrizing equipment.

In the paper, the following four symmetrizing devices are analysed:

- external symmetrizing device in a Steinmetz scheme with a 3-phase transformer,
- external symmetrizing device with local symmetrization by application of a 1-phase 3-winding transformer,
- external symmetrizing device with local symmetrization by application of a Scott transformer,

- local symmetrizing device with smooth regulation of P and Q powers flow between secondary side windings of a Scott transformer.

Aim of research

The objective of the presented research was to compare known and applied till now symmetrizing devices in AC traction power supply systems.

Different variants of concepts of these devices were studied in order to find a solution which could fulfil the following criteria:

a) values of amplitudes of currents in the primary 3-phase winding of a main transformer will differ less than in 5%,

b) only active power (P) is taken from a power network by the traction transformer,

c) main transformer of the traction substation is loaded only by an active power P.

On the basis of the research results, as a next step, a recommended variant of a symmetrizing device is to be chosen for construction of a laboratory model, which after pilot research could be possibly applied in a perspective 25 kV 50 Hz traction substation on electrified, under this system, railway lines in Poland.

Research of an external symmetrizing device in a Steinmetz scheme with a 3-phase transformer

A Steinmetz symmetrizing device [7] makes a 3-phase electric circuit with a symmetrizing circuit composed of passive elements as an inductance and a capacitor (Fig. 1 and Fig. 2), having values that modules of phase currents fulfil the equations (1).

$$I_{L12} = I_{L23} = \frac{1}{\sqrt{3}} \cdot I_{L31} \qquad (1)$$

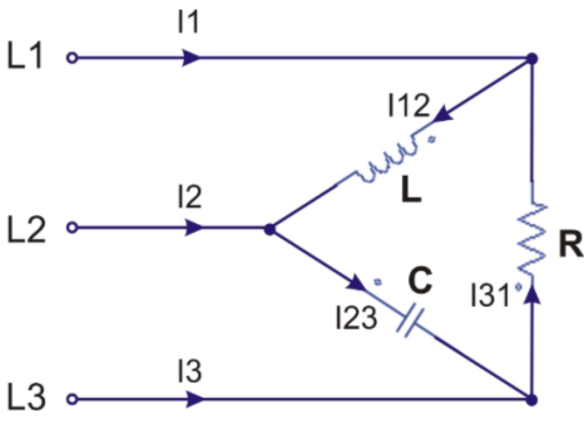

Fig. 1 Steinmetz circuit scheme

It is possible to present a Steinmetz circuit as in Fig. 2.

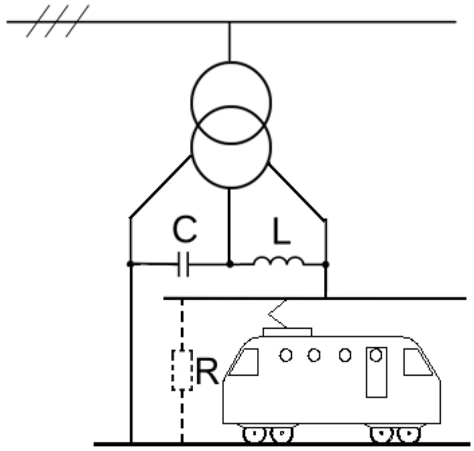

Fig. 2. Steinmetz circuit scheme in an AC traction system

The above circuit was tested by application of a simulation model (using software [3]) with a 3-phase 3x400 V 50 Hz line supplying voltage and 3.08 Ω load. In a scheme presented in Fig. 3, the load was represented as a resistor supplied by a transformer with a transformer ratio θ=0.5.

There were obtained:

- symmetrical line currents *IL1*, *IL2*, *IL3* (modules and phases).
- currents in branches with L and C elements fulfilling acc. to eq. (1).,
- cos φ =1,

this confirms the idea of this circuit.

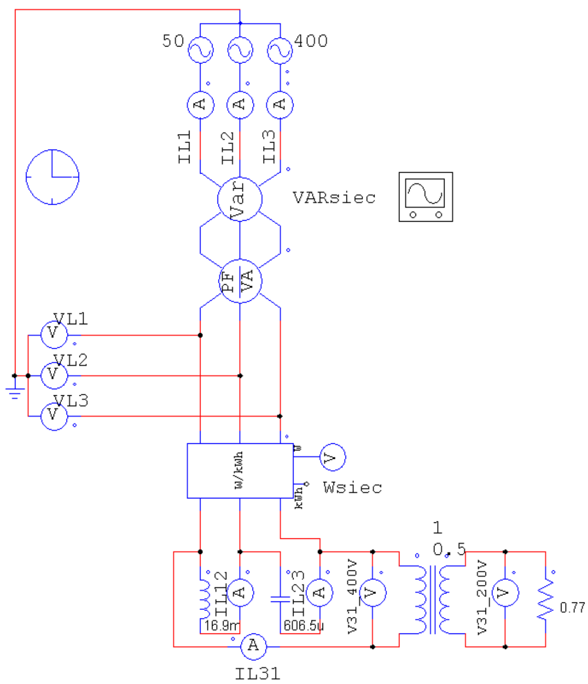

Fig. 3 Scheme of simulated Steinmetz circuit with a load supplied by a step-down transformer.

Time-curves obtained from the simulation are presented in Fig. 4. It may be observed that this simple circuit fulfils the assumed criteria when for a specific value of R proper values of C and L are chosen.

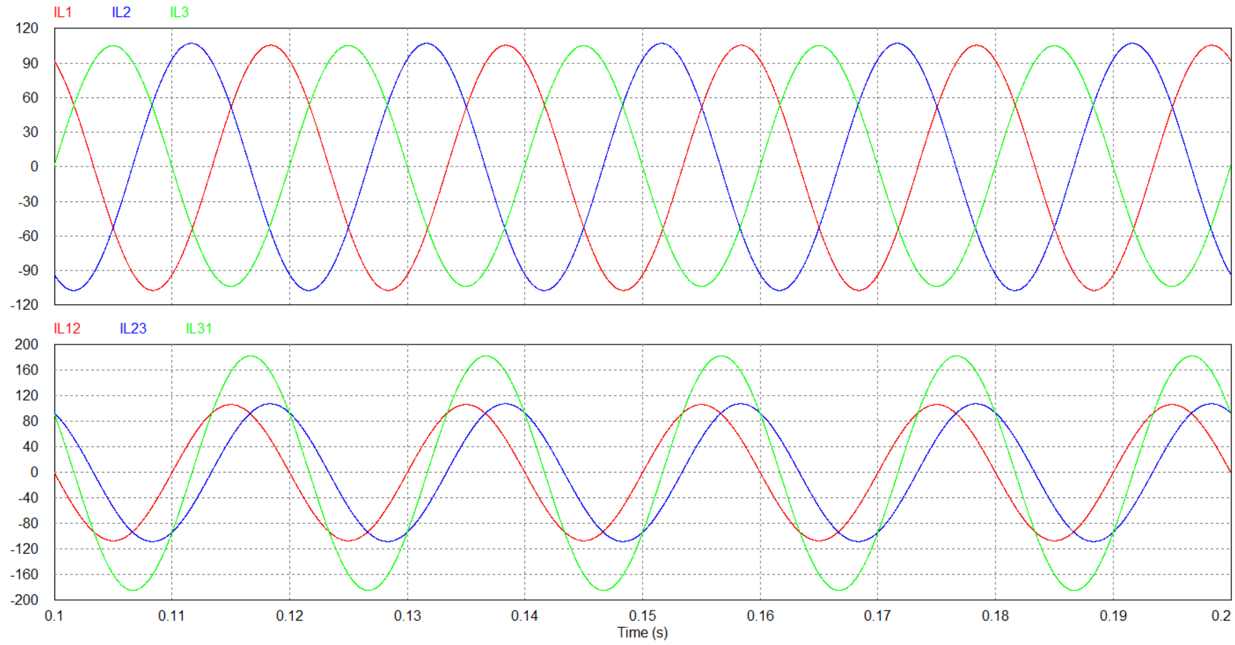

Fig. 4 Time curves of phase currents I_{L1}, I_{L2}, I_{L3} and line currents I_{L12}, I_{L23}, I_{L31} in a circuit described in Fig. 3

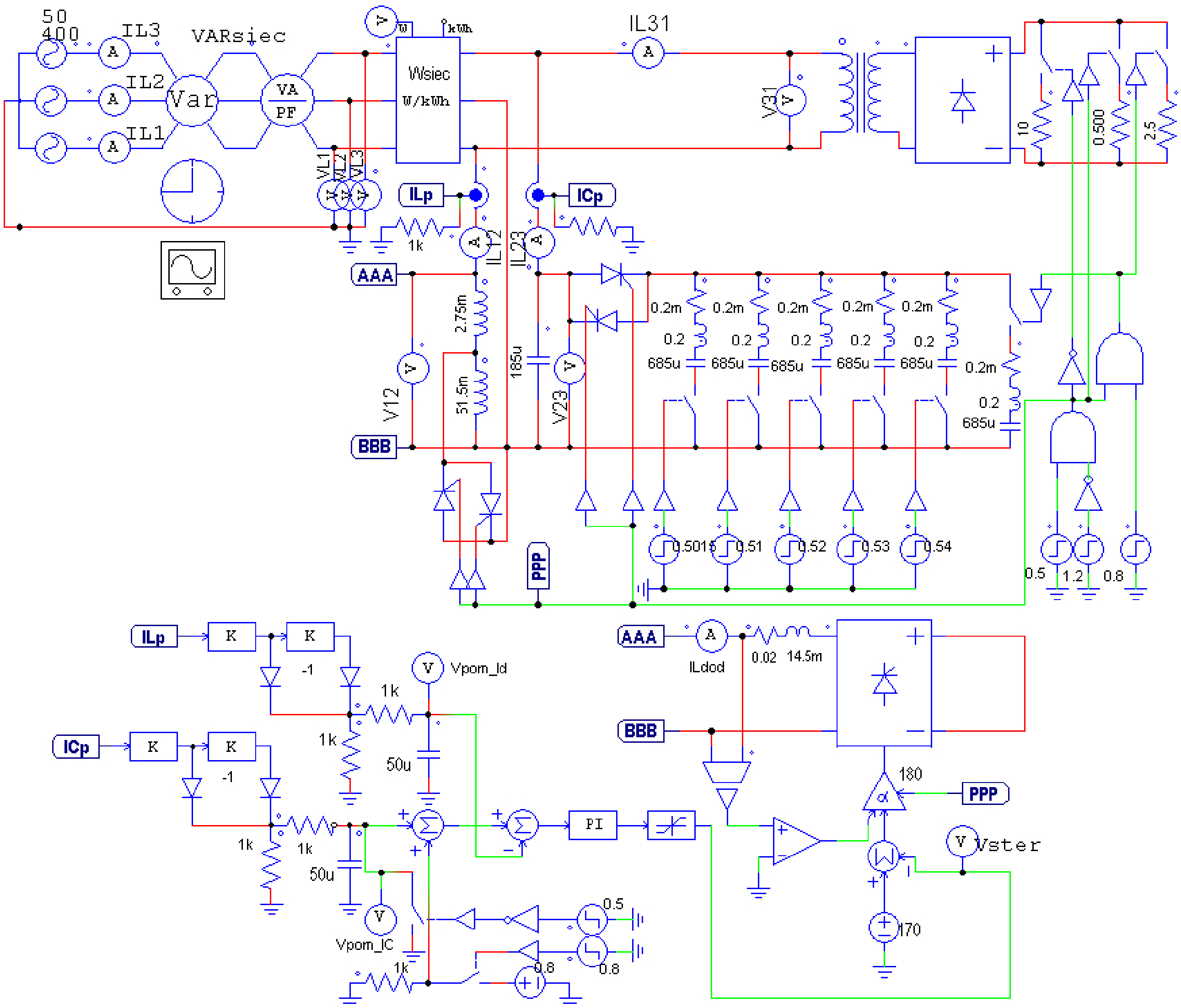

Fig. 5 One of simulated methods of 3 steps load of a Steinmetz circuit.

But it must be pointed out that in real conditions load of the receiver R (changes of power taken by a traction vehicle) is changing and so the parameters of L and C are to be changed.

At least some steps of possible changes of L and C parameters are needed.

Due to readability of the results and requirements of the simulation software (time of simulation), the analysis was limited to only 3 steps of regulation.

One of a such circuits is presented in Fig. 5, while the obtained results of the simulation are shown in Fig. 6 and Fig. 7.

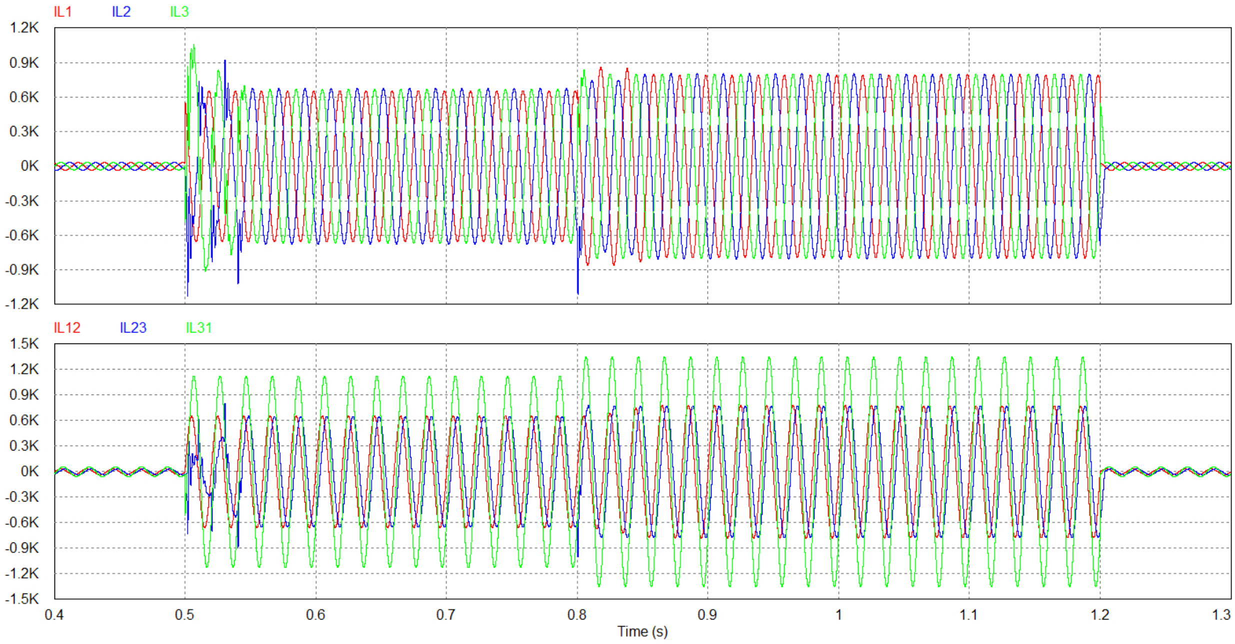

Fig. 6 Time curves of a phase I_{L1}, I_{L2}, I_{L3} and line currents I_{L12}, I_{L23}, I_{L31} in a circuit presented in Fig. 5.

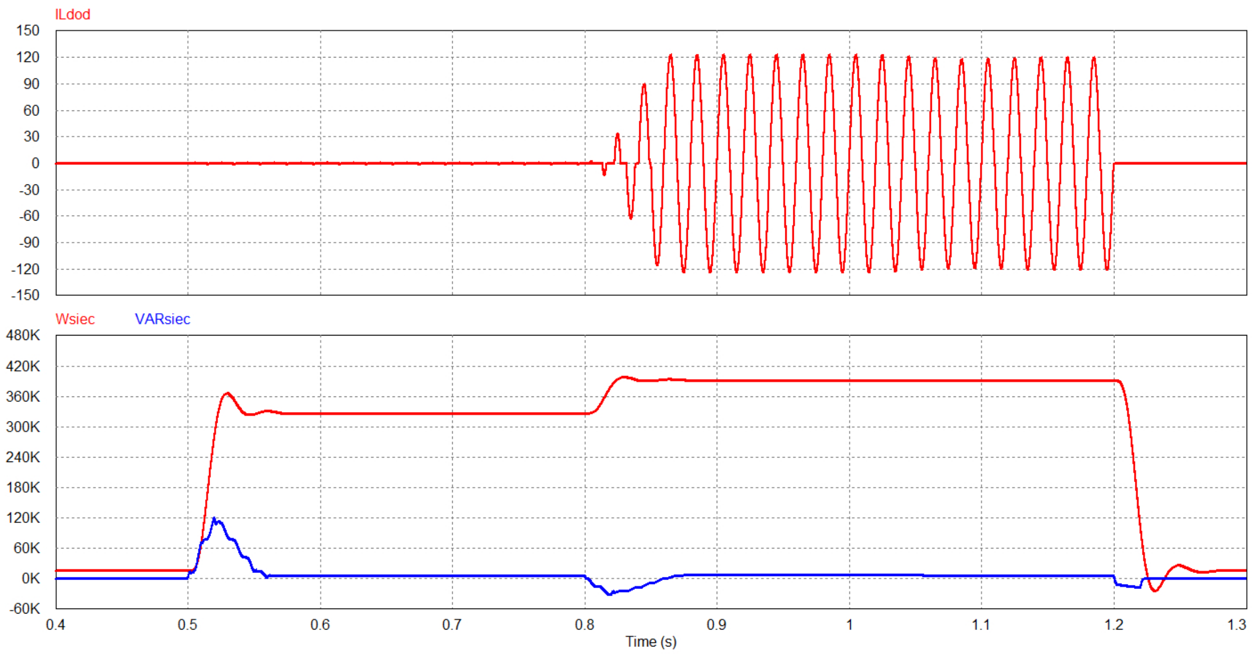

Fig. 7 Time curves of an additional load current I_{Ldod} and active $Wsiec$ and reactive powers $VARsiec$ in a scheme presented in Fig.

At every value of load, the symmetrical phase currents I_{L1}, I_{L2}, I_{L3} were obtained. Time of adjusting an additional load current I_{dled} was about 70 ms and amplitudes of phase currents , after switching additional elements L and C, did not exceed 140% values of their amplitudes in a steady state. Proper adjustment of L and C elements to the load caused that the coefficient of power taken by a circuit from power supply was practically every time nearly 1.

Further modifications of the circuit consisting in introduction of a smooth regulation of a load (power taken by a traction vehicle) and the value of current in an impedance branch brought positive results as well.

Study of an external symmetrizing device with local symmetrization by application of a 1-phase 3-winding transformer

In a circuit applied during simulation, secondary winding voltages were shifted between themselves by 180°.

Each of the secondary windings was loaded independently.

In one of the performed tests the circuit was modelled acc. to the simplified scheme presented in Fig. 8.

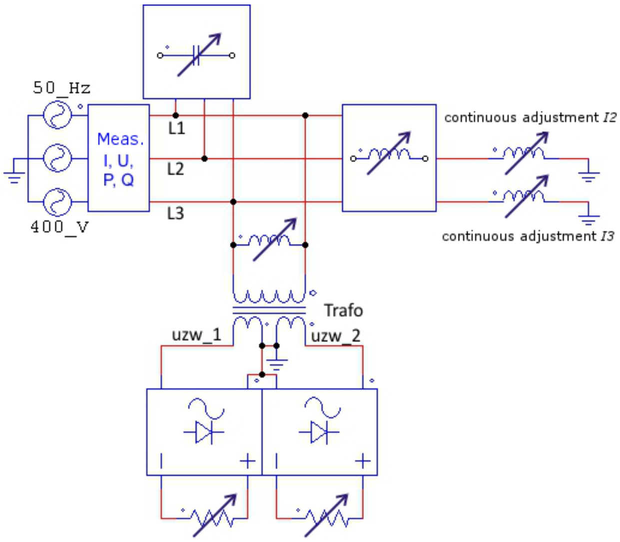

Fig. 8 Simplified scheme of a circuit of an external symmetrizing device with local symmetrization by application of a 1-phase 3-winding transformer

The obtained results are presented in Fig. 9. One may observe that it was possible to obtain satisfactory symmetry of line currents *IL1*, *IL2*, *IL3* with significantly different load currents *I_uzw_1* , *I_uzw_2* of a transformer.

By proper choice of compensators, it is also possible to eliminate reactive power (*VAR*) taken from a supply and reactive power (*VAR_Trafo*) taken by a transformer. Reactive power VAR_AC is measured in a point of a transformer supply, but before an inductance controller (seen from a supply side).

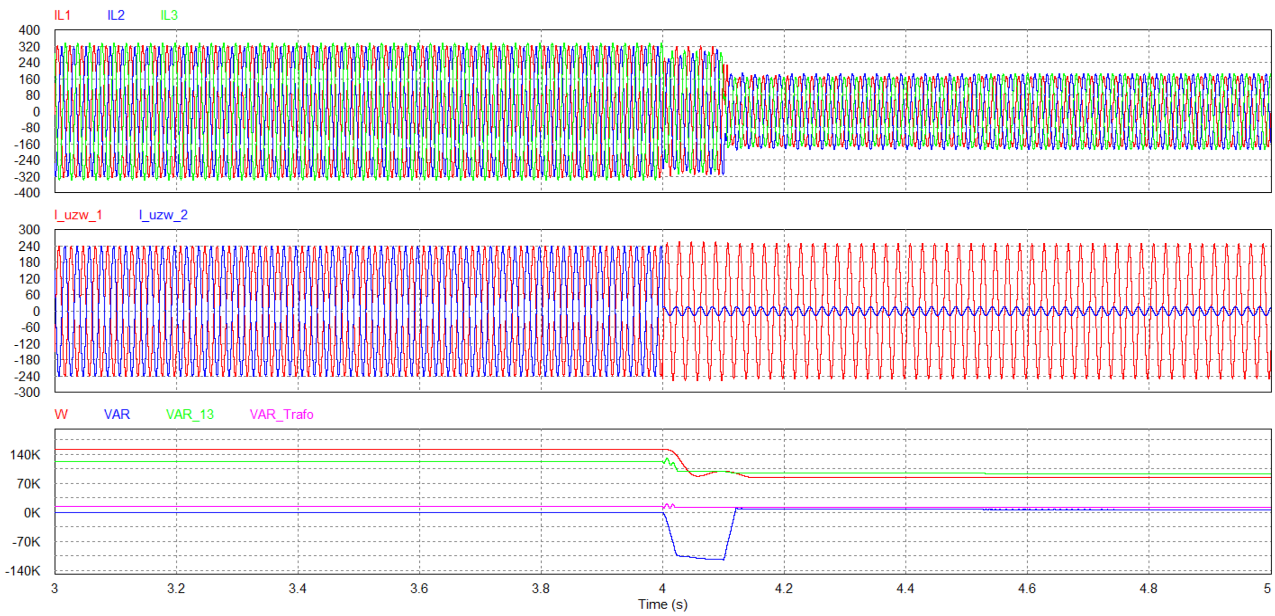

Fig. 9 Time curves of phase currents I_{L1}, I_{L2}, I_{L3}, transformer load currents *I_uzw_1*, *I_uzw_2* and active and reactive power taken by a circuit presented in Fig. 8

Study of an external symmetrizing device with local symmetrization by application of a Scott transformer, with in series connection of secondary windings

As a next part of the research, there were performed simulation studies oriented towards elimination of asymmetry in power supply system supplying a traction substation equipped with a Scott transformer.

At the first step, the simulation was performed without an additional static symmetrizing device. A simplified scheme of that circuit is presented in Fig. 10, while results in Fig. 11.

From the obtained results, one may observe that when windings of a transformer are identically loaded (*IS1, IS2*) there exist significant differences in currents taken by Scott's transformer from a supply.

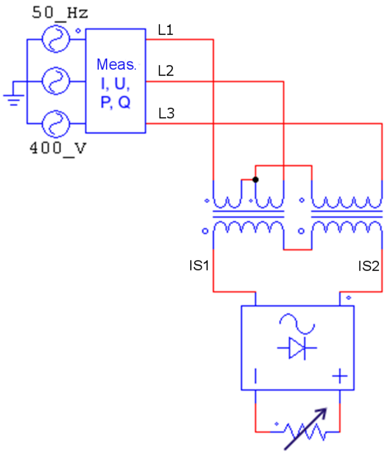

Fig. 10 Simplified scheme of a circuit with external symmetrizing device without local symmetrization by application of a Scott transformer (secondary windings connected in series).

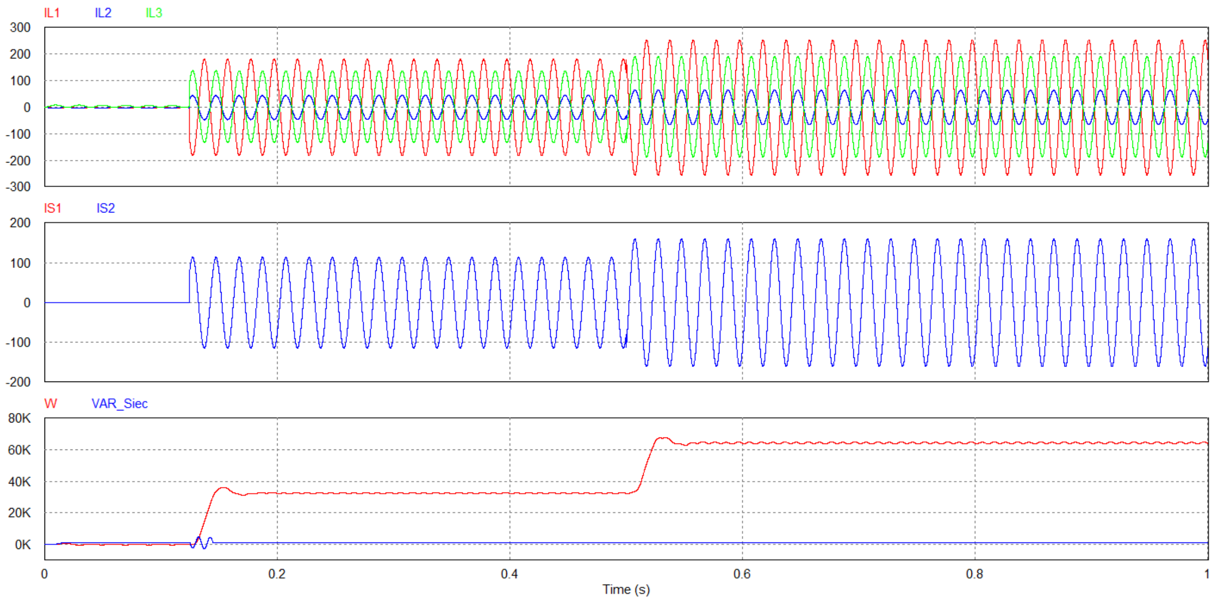

Fig. 11. Time curves of phase currents I_{L1}, I_{L2}, I_{L3},, load currents of transformers - *IS1*, *IS2* and active/reactive powers taken by a circuit in Fig. 8

What appeared effective for symmetrisation of line currents taken from supply is the following simple solution: installation of capacitances at secondary side of a Scot transformer. Proper selection of parameters of capacitors (for a specific load) could cause full symmetrisation of line currents taken from power supply. A simplified scheme of that circuit is presented in Fig. 12.

However this circuit has two significant disadvantages. Application of capacitors at the output of a Scott transformer causes a need of installation at the primary side of inductances reducing charging currents of capacitors. Additionally reactive power is taken from a supply so a set of inductances is to be installed. Because it does not reduce reactive power intake by a Scott transformer, so in this case the transformer is to be oversized in relation to forecast power load.

Results of simulation in this case are shown in Fig. 13.

The second method of symmetrization of line currents taken from power supply consists in installation of inductances at secondary size of a Scott transformer.

This circuit:

- is more stable due to occurrence of shorter dynamic states,
- application of inductances causes reactive power intake from power supply, which should be compensated by installation of capacitances. However it does not reduce reactive power intake by a Scott transformer. So in this case the Scott transformer should be oversized in relation to the forecast power load.

Results of simulation are presented in Fig. 14.

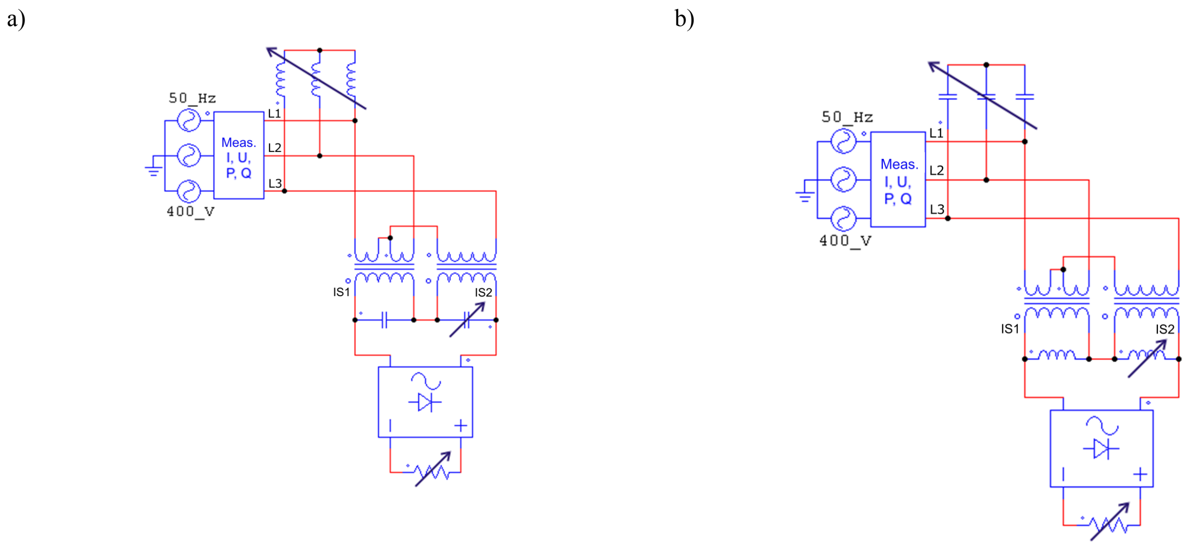

Fig. 12 Simplified schemes of circuits for two ways of external local symmetrization with a Scott transformer.

Since these circuits require application of transformers with power being significantly oversized in comparison to the forecast load power, it was decided not to develop the system further; however an attempt was made at simulating the system, with the concept presented in the paper [4].

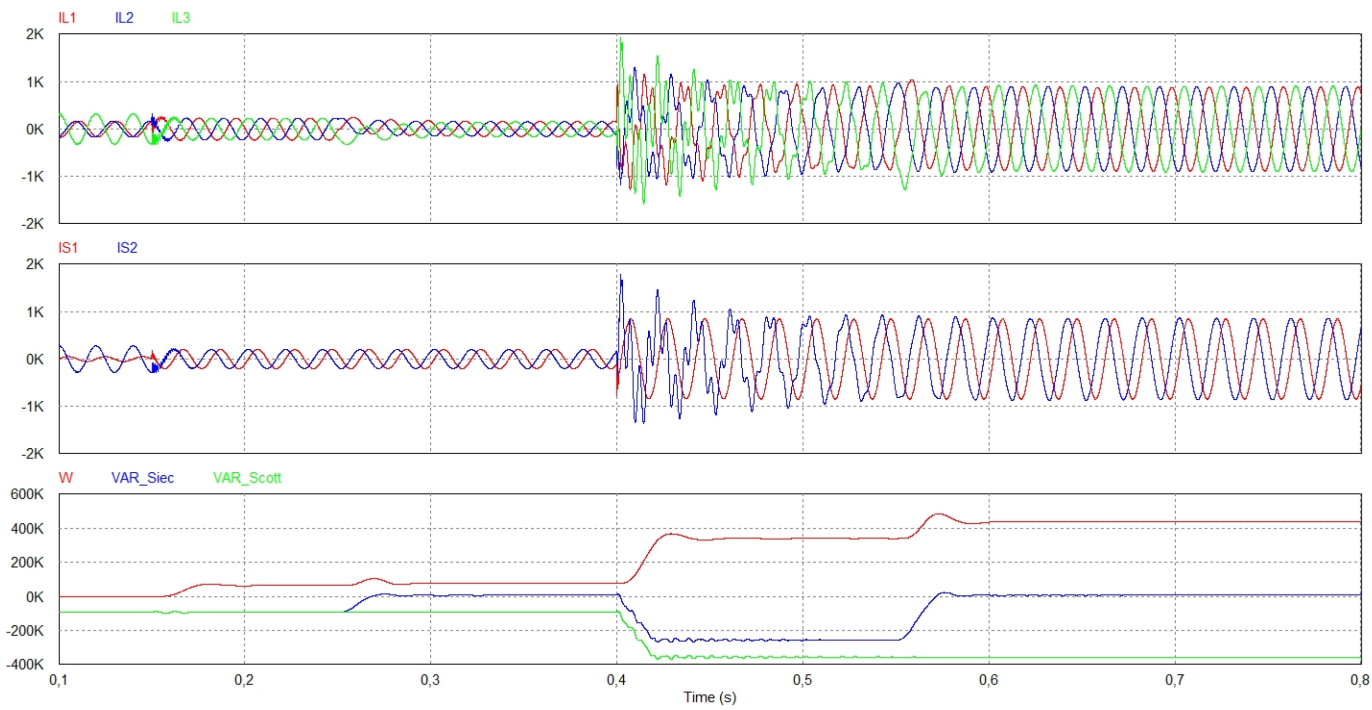

Fig. 13 Time curves of line currents I_{L1}, I_{L2}, I_{L3}, transformer load currents *IS1*, *IS2* and active/reactive power taken by a circuit presented in Fig. 12a

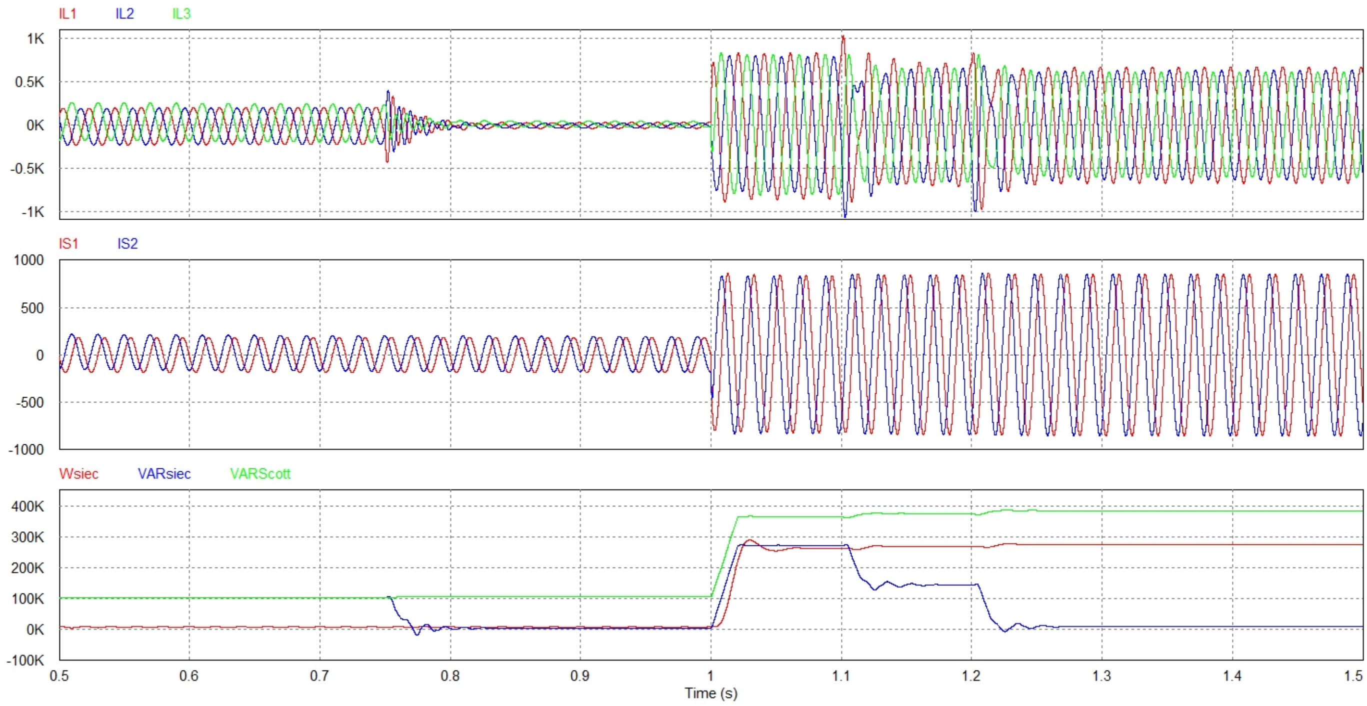

Fig. 14 Time curves of line currents I_{L1}, I_{L2}, I_{L3}, ,Scott transformer load currents *IS1*, *IS2* and active/reactive powers taken by a circuit presented in Fig. 12b.

Study of a local symmetrizing device with smooth regulation of P and Q powers flow between secondary side windings of a Scott transformer.

In this part of the paper, there are presented the results of study of a circuit, in which it is possible to obtain smooth regulation of an active/reactive power flow between secondary windings with simultaneous application of power electronic switches instead of the analogue one.

A circuit presented in Fig. 16 makes a pair of self-commutating converters with PWM control, so they could transfer active and reactive power. Converters compensate reactive power of each the winding of a secondary side of a Scott transformer, in order to compensate supplying voltage fluctuation.

And converters connected at a DC side mutually reduce active power of both secondary windings of a transformer in order to balance active power at its primary side.

The idea of compensation based on parallel operation of voltage sources [3, 4, 7] is shown in Fig. 15

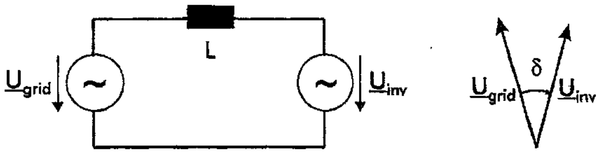

Fig. 15 Voltage sources connected via inductance.

Active power *Pinv* and reactive power *Qinv* of voltage sources (an inverter connected to supply) could be described as:

$$P_{inv} = \frac{U_{inv} \cdot U_{grid}}{\omega_N L} sin\delta \qquad (2)$$

$$Q_{inv} = \frac{U_{inv}^2}{\omega_N L} - \frac{U_{inv} \cdot U_{grid}}{\omega_N L} cos\delta \qquad (3)$$

Phase shift d between two voltage sources makes active power flow. Reactive power flow is resulted from voltage difference *Uinv - Ugrid.*

The circuit proposed on this basis is composed of two connected in parallel converters: a transistor rectifier with a sinusoidal input current and a transistor inverter with a sinusoidal output. All controllers regulating active power flow, fluctuation of DC voltage and compensation of reactive power generate control signals for the specific converters. The circuit which controls current integrates these signals and rules current controllers in converters. A PWM module controls MOSFET transistors of converters for supplying specific circuits.

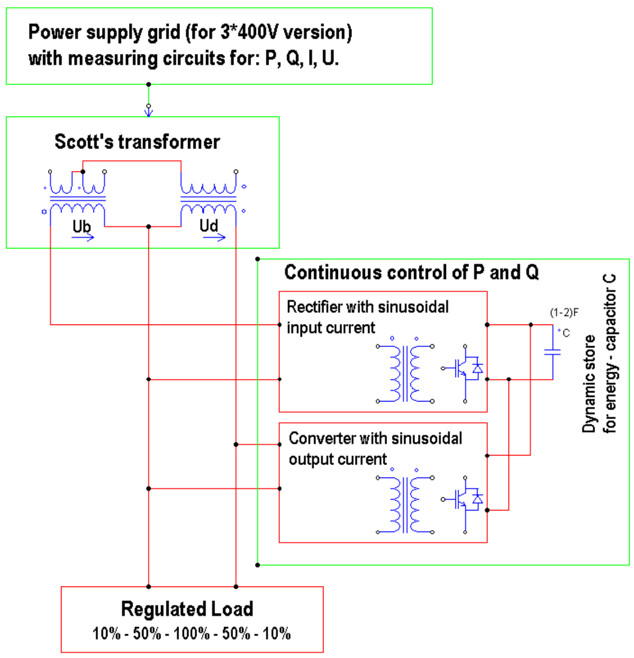

Fig. 16 A simplified scheme of a local symmetrising device with smooth regulation of a P and Q powers flow between secondary side windings of a Scott transformer.

Conclusions

The comparative analysis of operation of different circuits showed that it is possible to construct a device for symmetrizing asymmetry in power supply caused by different types of transformers applied in 25 kV 50 Hz traction system substations.

The Steinmetz circuit proved to be a simple solution in terms of design, with 3-phase transformer applied for supply by one of three phases of the electric traction system secondary side.

In a case of application of a 1-phase 3-winding transformer with a controller of external compensator, it is possible to use two secondary windings for supplying two different traction circuits.

It is as also possible to develop a controlled external symmetrizing device for compensating reactive power taken by Scott transformer at the level (or even higher) of active power taken from power supply. Since in this case the transformer should be oversized with respect to the forecast load power, this circuit was recognised as non-perspective.

The local symmetrizing device with regulation of P and Q power between secondary windings of a Scott transformer proves to be the most prospective one. The device does not need application of any external symmetrizing, which allows for eliminating analogue switches from power circuits.

Spread of technology of modern transistors creates possibility of application of power electronic devices for economically effective high power (in a range of few MW) converters (rectifiers, converters).

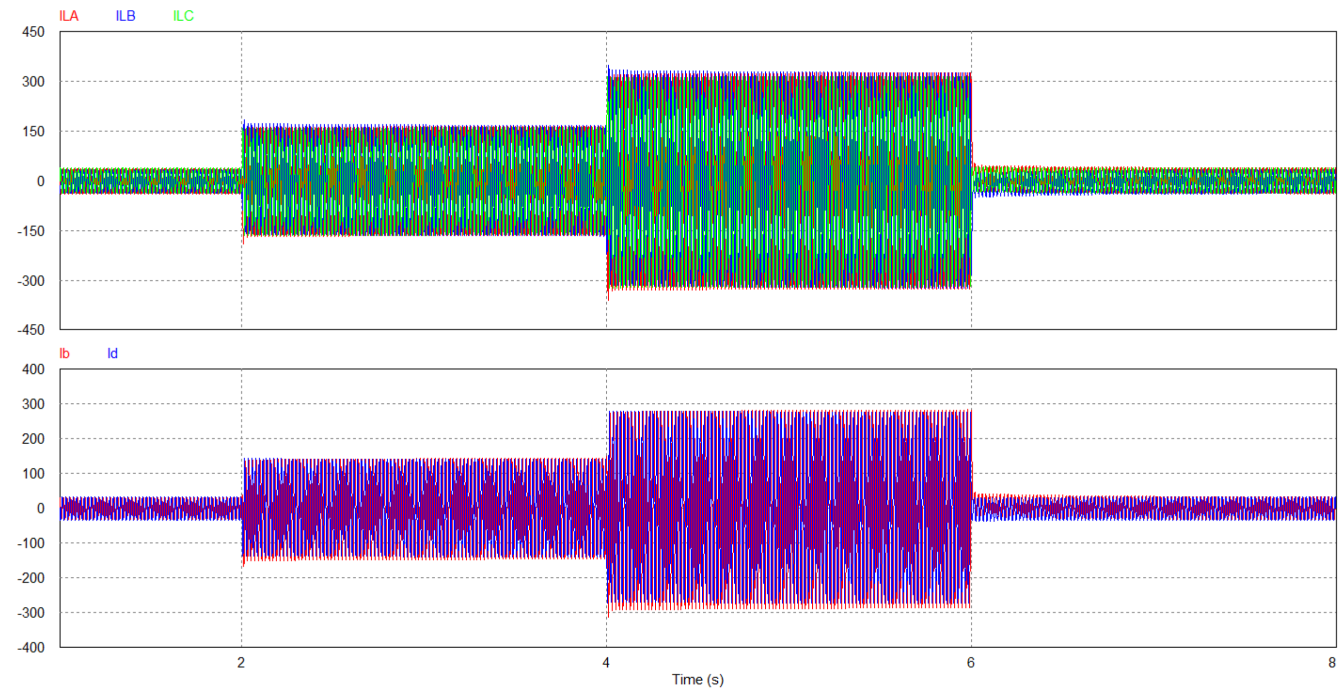

Fig. 17 Time curves of line currents I_{L1}, I_{L2}, I_{L3}, transformer load currents *Ib*, *Id* in a circuit presented in Fig. 16.

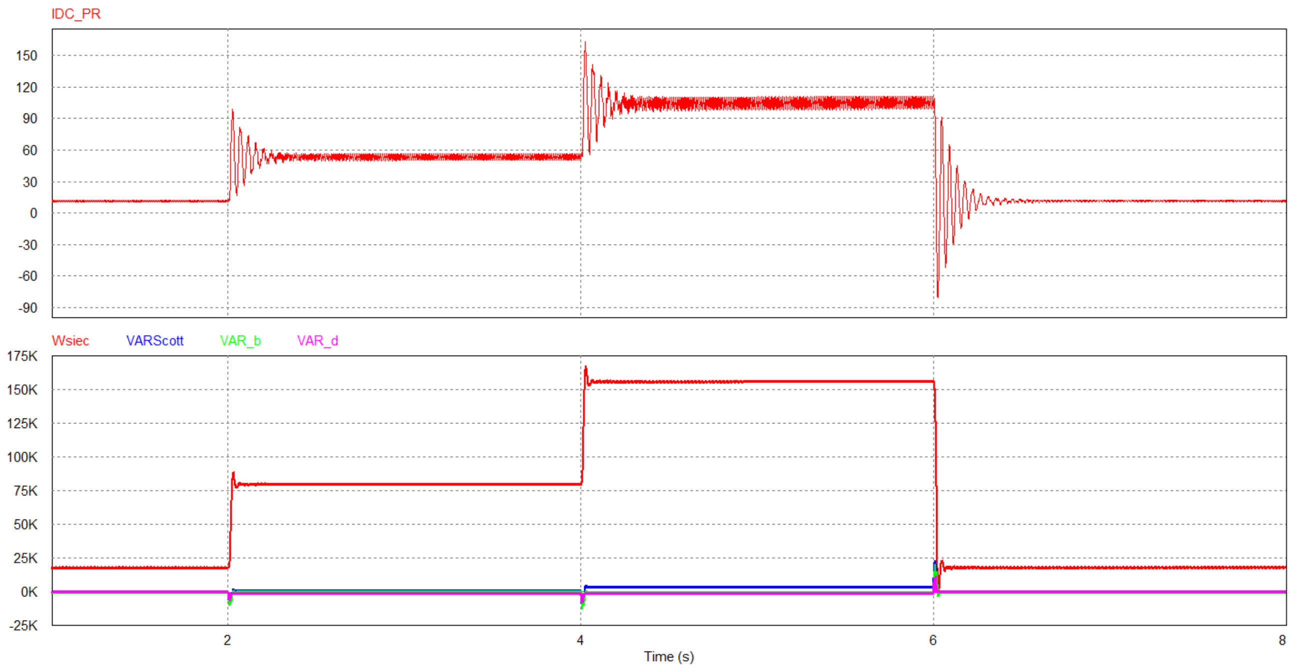

Fig. 18 Time curves of DC intermediate circuit rectifier-inverter current I_{DC_PR} and active/reactive power taken by a circuit presented in Fig. 16.

Bibliography

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

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

[3] T. Dzik *Układ sterowania i nadzoru systemu zasilania potrzeb własnych elektroenergetyki z ogniwami paliwowymi zasilanymi metanolem* Ph.D. (in Polish) Politechnika Warszawska, Warszawa, POLAND, 2008

[4] A. Engler *Applicability of droops in low voltage grids* International Journal of Distributed Energy Resources, ISSN 1614-7138, Volume 1, Number 1, GERMANY, 2005

[5] Z. Hanzelka *Jakość dostawy energii elektrycznej* Wydawnictwa AGH, Kraków, POLAND, 2013

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

[7] T. Uzuka, Y. Mochinaga, S. Hase *Principle theory of single phase feeding power conditioner for AC traction* Railway Technical Research Institute, Tokyo, JAPAN, 1997

[8] H. Wang, Y. Tian, and Q. Gui *Evaluation of negative sequence current injection into the public grid from different traction substation in electrical railways*,ˆ in Proc. 20th Int. Conf. Exhib. Electr. Distrib.—Part 1, 2009, pp. 1–4

[9] A. Zupan, A. Tomasovic Teklic, and B. Filipovic-Grcic. *Modeling of 25 kV electric railway system for power quality studies. EUROCON, 2013 IEEE*. IEEE, 2013.

[10] European standard EN 50160 Voltage characteristics of electricity supplied by public distribution systems, 2006