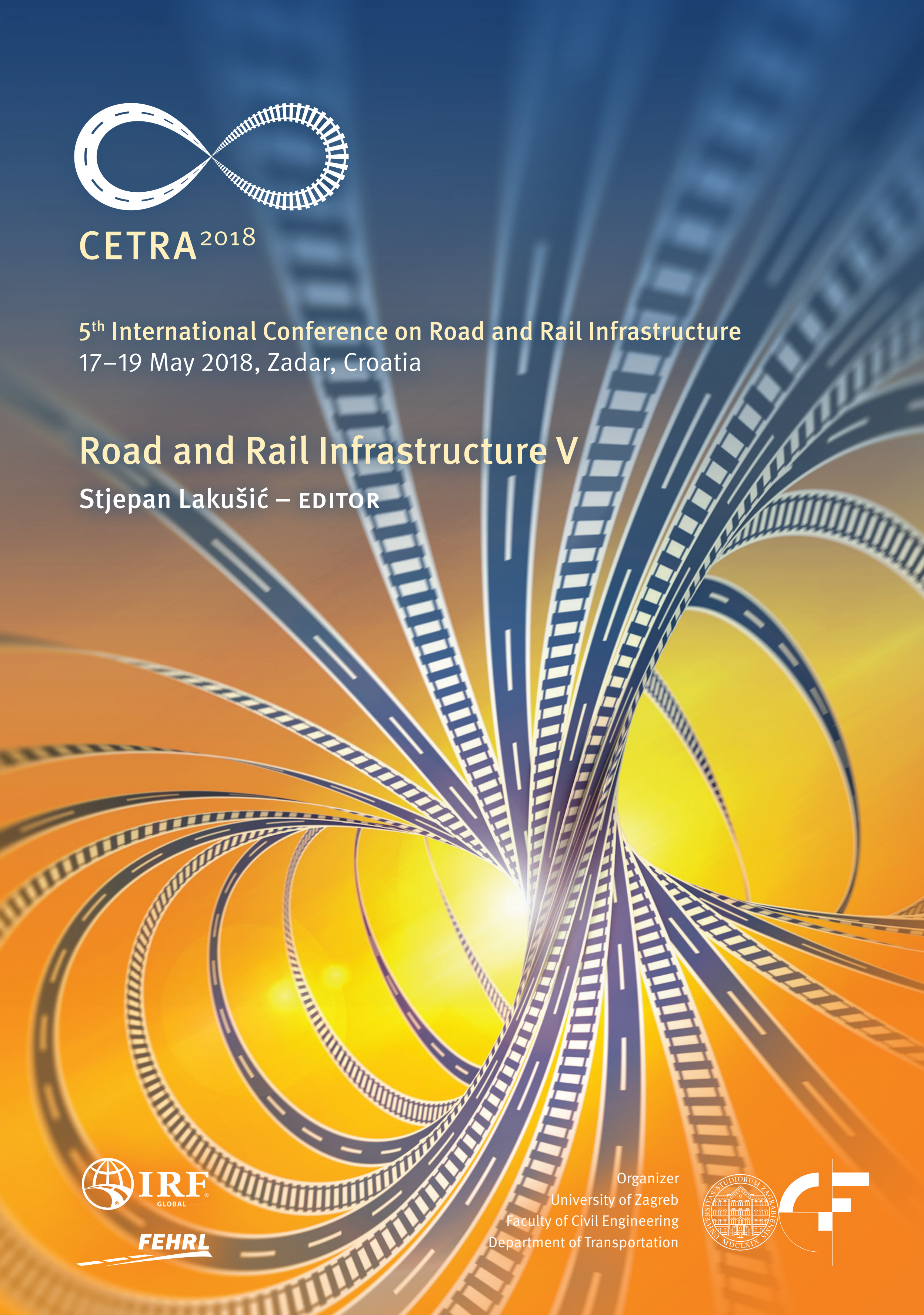

CETRA2018

5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – EDITOR

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DYNAMIC REACTIVE POWER COMPENSATION IN TRACTION SUBSTATIONS

Dubravko Krušelj, Miroslav Macan, Hrvoje Pauković
Končar – Electronics and Informatics, Inc., Croatia

Abstract

The converter for dynamic reactive power compensation KONTRAC PN225AC is produced by Končar – Electronics and Informatics, Inc. and is built in traction substations 25 kV, 50 Hz. The rated power of the converter is 225 kvar and a response of the converter to step change of rated reactive power is less than few periods of the supply voltage main harmonic. The converter is therefore able to compensate reactive power practically continuous in a range from 225 kvar inductive to 225 kvar capacitive. In traction substations overall reactive power for compensation can be adjusted either by installation of appropriate number of the converters which are connected in parallel or a combination of the parallel connected converters and the facility with fixed reactive power compensation can be used. In this way reactive power of the traction substation can be compensated but without excessive reactive power and associated costs. In the paper are presented overall costs of electrical energy for electric traction in Croatia in few past years and an influence of electric railway system on power quality in transmission system is briefly described. A description of the converter comprises work principle, technical data and measurement results which were made in laboratory and in traction substation. Namely, the facility with fixed reactive power compensation and two converters connected in parallel are installed in traction substation Mrzlo Polje in 2017 and a trial operation has been started since the beginning of the December 2017.

Keywords: converter, reactive power compensation, traction substation

1 Introduction

Electric railway system is in Croatia one-phase consumer which is connected to two phase of 110 kV transmission system. An overhead catenary voltage 25 kV, 50 Hz is transformed in traction substations from 110 kV, 50 Hz using one or more transformers.

Croatian Railway Infrastructure is a privileged client on the market for electric energy supply. In this market there are two crucial subjects: electric energy supplier and operator of transmission system [1]. The supplier ensures electric energy and the operator is in charge of transmission system management. According to that, appropriate tariff systems are defined, each one with its' own tariff items. In Tariff system for electric energy supply there are: active energy with definition of higher and lower tariff (kn/kWh), active power (kn/kW), fee for electric energy production from renewable sources (kn/kWh) and fee for fiscal use of electric energy (kn/kWh). In Tariff system for electric energy transmission there are: active energy with definition of higher and lower tariff (kn/kWh), active power (kn/kW), excessive reactive energy (kn/kvarh) and fee for measurement service (kn/measurement). It should be pointed out that one of significant item in overall costs is excessive reactive energy cost.

In Croatia are nowadays totally 21 traction substations. 12 of them are facilities with fixed reactive power compensation in which installed reactive power cannot be changed and cannot be

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adjusted according to the condition on power network [2]. Such technical solution is able to reduce only excessive inductive reactive power and not excessive capacitive reactive power. The converter for dynamic reactive power compensation KONTRAC PN225AC produced by Končar – Electronics and Informatics, Inc. has rated power 225 kvar and can provide practically continuous reactive power compensation in a range from 225 kvar inductive to 225 kvar capacitive. Different number of the converters can be connected in parallel and therefore, total reactive power for compensation can be adjusted. A combination of the parallel connected converters and the facility with fixed reactive power compensation also can be used. Inductive reactive power is in both cases compensated but without excessive capacitive reactive power and associated costs.

In the paper are firstly presented overall costs for power supply of electric railway system in Croatia. Then an influence of electric railway system on power quality in transmission system is briefly described. The main part of the paper comprises description of the converter, work principles, technical data and measurement results which were made in traction substation (the facility with fixed reactive power compensation and two converters connected in parallel are installed in traction substation Mrzlo Polje in 2017).

2 Overall costs for power supply of electric railway system in Croatia

Overall costs for power supply of electric railway system were in 2015 according to [1] 77,5 mil. kn. A structure of costs is presented in Fig. 1. The excessive reactive energy costs were 10,5 % of overall costs (8,1 mil. kn). They participated with 42,4 % in Tariff system for electric energy transmission and were the biggest item in that tariff system. Similar situation was in 2014, when the excessive reactive energy costs participated in Tariff system for electric energy transmission with 47,8 % and were also the biggest item [2].

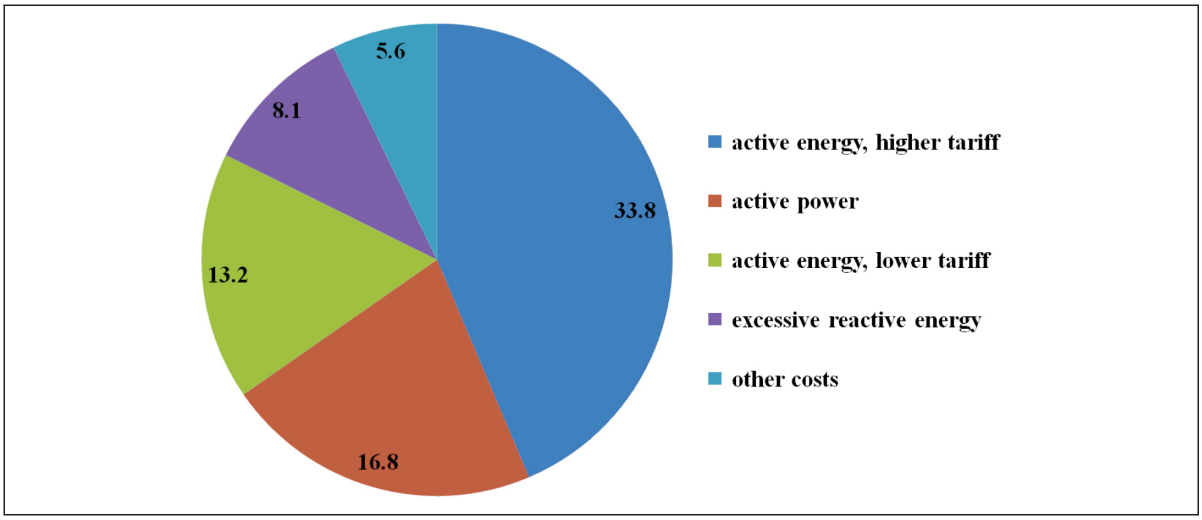

Figure 1 Overall costs for power supply of electric railway system in Croatia in 2015 [mil. kn]

The excessive reactive energy is positive difference between total measured reactive energy and reactive energy that corresponds to average power factor less than 0,95. At the beginning of 2007 in Croatia became valid Tariff system for electric energy transmission, without tariff items proportion. According to this rule book, both an inductive and a capacitive reactive energy should be taken into account for excessive reactive energy costs. As a result, an excessive capacitive reactive energy costs significantly increased and the facilities with fixed reactive power compensation were turned off in eight traction substations.

3 Influence of electric railway system on power quality in transmission system

For power quality of transmission system are responsible both the operator of transmission system and users connected to the power network. Each user should constrain and limit negative influence to the network, i.e. backward effects of the user should be less than normative and prescribed values which are usually defined from the operator of transmission system.
An example of an influence of electric railway system on power quality in 110 kV transmission system is presented in [3], where measurement results are compared with values in normative reference IEC 61000-3-6:2008 [4]. Measurements were made in traction substation Oštarije at 110 kV network in a period of one week. Some of highlighted results are: total value of voltage harmonic distortion factor is increased in two phases to which traction substation is connected (phase L2 and L3) compared to value for phase L1 which is connected only to 110 kV transmission system; value of the third voltage harmonic is 0,9 % for phases L2 and L3 and is three times greater than value for phase L1, but is lower than 2 % level which is directive in normative reference [4]; value of the ninth voltage harmonic is 0,3 % for phases L2 and L3 (for phase L1 is equal zero) and is lower than 1 % level in [4]; value of the 15th voltage harmonic is 0,4 % for phases L2 and L3 and is four times greater than value for phase L1, this value is also greater than 0,3 % level which is directive in normative reference [4]; value of the 21st voltage harmonic is 0,5 % for phases L2 and L3 (for phase L1 is equal zero) and is also greater than 0,2 % level in [4].
Aforementioned results confirm the fact that electric railway system generates higher voltage and current harmonics, which frequencies are equal to multiples of three time main frequency. It should be also emphasized that total harmonic distortion values of some harmonics are greater than values in normative reference [4]. Although values given in [4] are nowadays only directives, it should be expected that these values soon will be mandatory.

4 Converter for dynamic reactive power compensation KONTRAC PN225AC

4.1 Purpose of the converter

The converter for dynamic reactive power compensation KONTRAC PN225AC is built in traction substations 25 kV, 50 Hz. One converter or different number of parallel connected converters can be used in traction substations as standalone devices. Also a combination of the parallel connected converters and the facility with fixed reactive power compensation can be used.
Two converters and the facility with fixed reactive power compensation are built in traction substations Mrzlo Polje and Oštarije. In the future is planned to build additional two converters. Fig. 2 depicts single-pole scheme of total facility for reactive energy compensation in before mentioned traction substations [2]. The converters are denoted with –UC1, –UC2, –UC3 and –UC4. They are connected in parallel to the power transformer which is in Fig. 2 denoted with –TC and has rated power 1000 kVA and transfer ratio 25 kV/0,4 kV.
The rated power of the converter is 225 kvar and a response of the converter to step change of rated reactive power is less than few periods of the supply voltage main harmonic. Therefore, one converter is able to compensate reactive power practically continuous in a range from 225 kvar inductive to 225 kvar capacitive. The rated power of the facility with fixed reactive power compensation is 463 kvar and therefore total facility is able to compensated reactive power up to 913 kvar, but without excessive capacitive reactive power. If additional two converters were built in, reactive power up to 1827 kvar could be compensated.

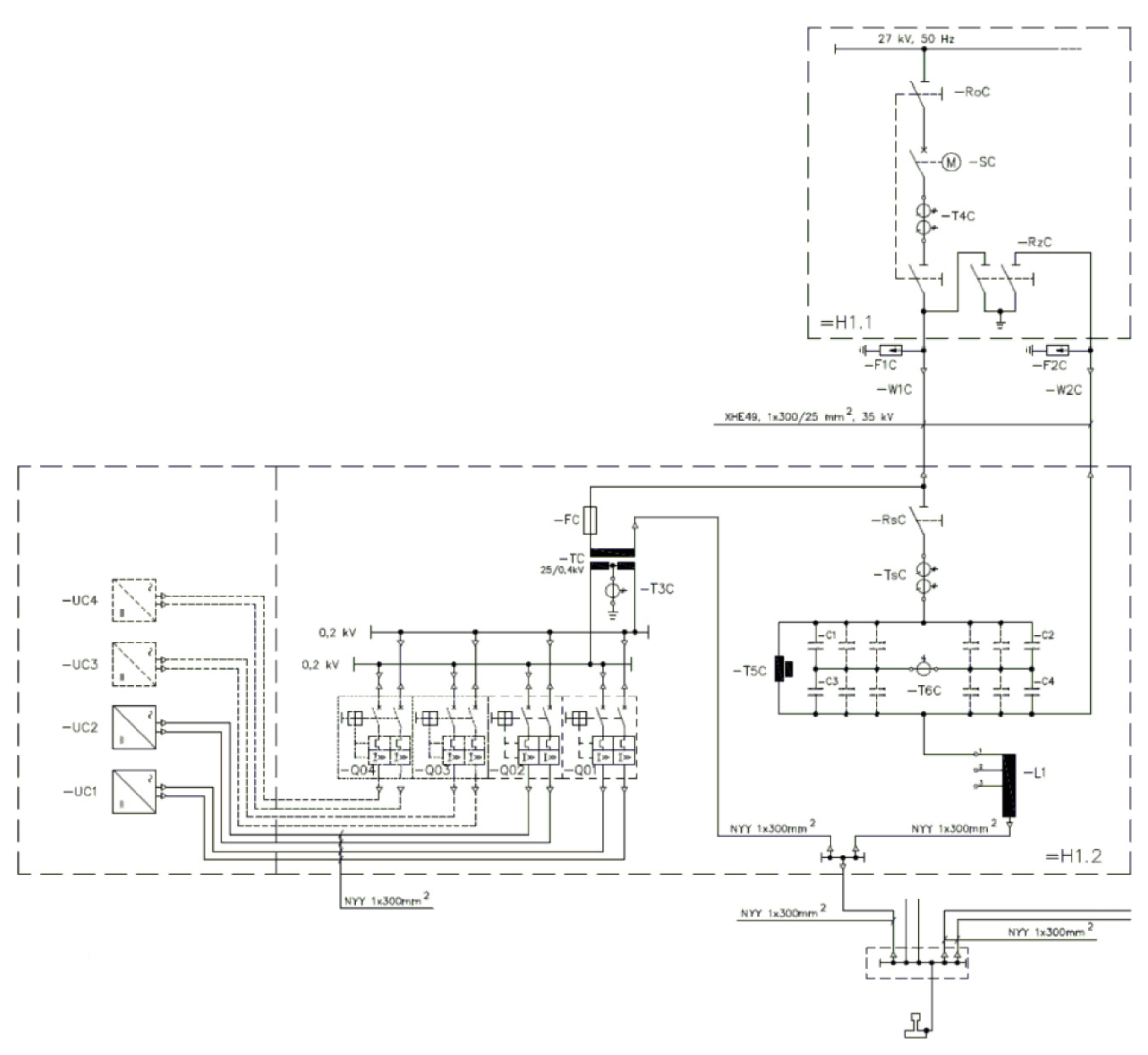

Figure 2 Single-pole scheme of total facility for reactive energy compensation in traction substations Mrzlo Polje and Oštarije

4.2 Design of the converter

Block scheme of the converter is presented in Fig. 3. The converter is connected to secondary winding of the power transformer which has rated power 1000 kVA and transfer ratio 25 kV/0,4 kV. The secondary winding has two parts and intermediate point is connected to total facility grounding. The main parts of the converter are two one-phase converters. Each converter is connected to the secondary winding through inductor and on the output side are capacitors.

Apart from power supply, the converter uses two auxiliary supplies. Auxiliary a.c. supply 230 V, 50 Hz is used for the supply of two one-phase a.c. motors with ventilator. Auxiliary d.c. supply 110 V is used for control electronics, contactors, relays, display and signalisation. Signals of traction substation total current (in Fig. 3 is denoted with iVN) and signal of high voltage (uVN in Fig. 3) should be measured and are used as input data for control algorithm of the converter.

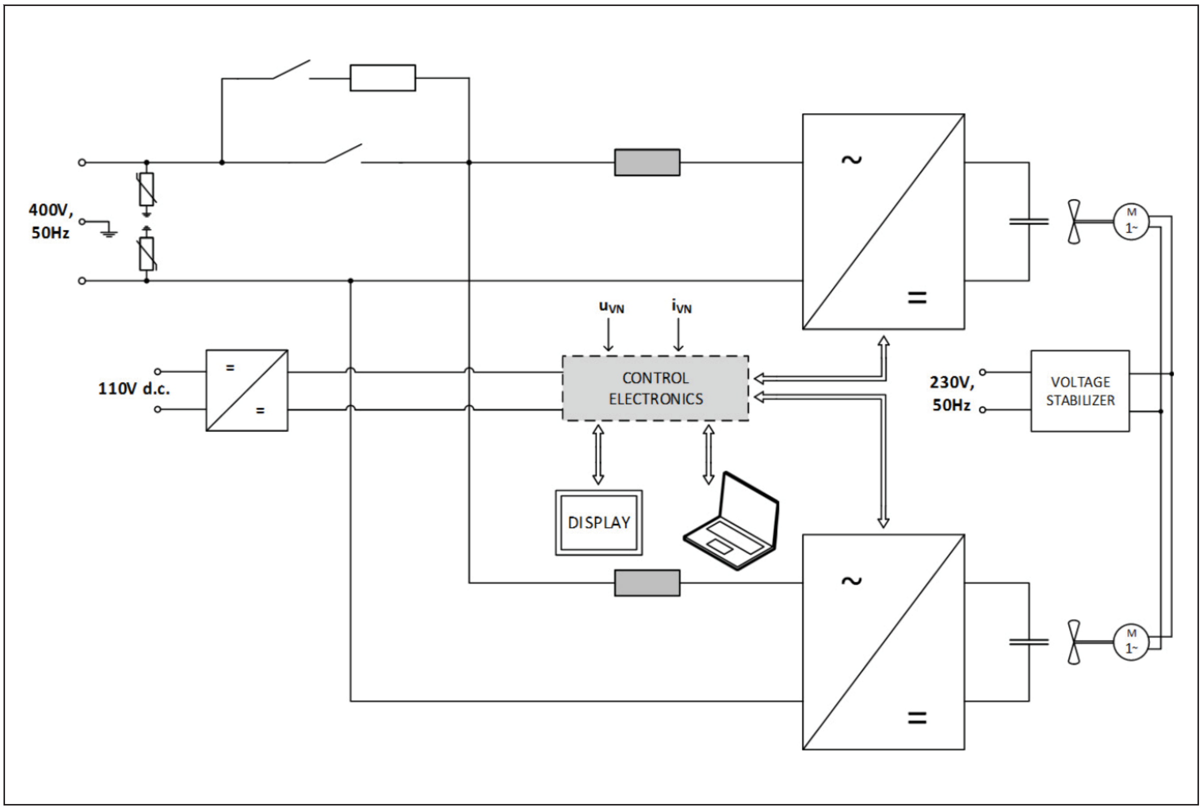

Figure 3 Block scheme of the converter

The-state-of-the-art concept is applied in the converter design:

- IGBT components are used (latest IGBT technology);
- digital control unit is based on proprietary embedded control platform which has been used for years in Končar's rail solutions;
- digital signal controller with floating point is used for control algorithm;
- modern communication protocols are implemented;
- sequence control, protection, supervision tasks and diagnostics tasks are provided;
- powerful diagnostics and visualization tool are provided.

4.3 Work principle of the converter

A converter work principle can be explained with help of simplified scheme of the converter which is shown in Fig. 4. uS and iS represent voltage and current of the power transformer secondary side, respectively, uP1 and uP2 represent voltages generated by one-phase converters and i1 and i2 are currents of the inductors.

The voltages uP1 and uP2 are pulse-width-modulated. Their main harmonic frequency must be equal to the main harmonic frequency of the secondary side voltage uS and their main harmonic amplitude value is adjusted. If the main harmonic amplitude of the uP1 and uP2 is less than the main harmonic amplitude of uS, the converter actually acts as a current source inverter which imposes to the power transformer secondary side inductive current. Vice versa, i.e. if the main harmonic amplitude of the uP1 and uP2 is greater than the main harmonic amplitude of uS, the converter imposes capacitive current.

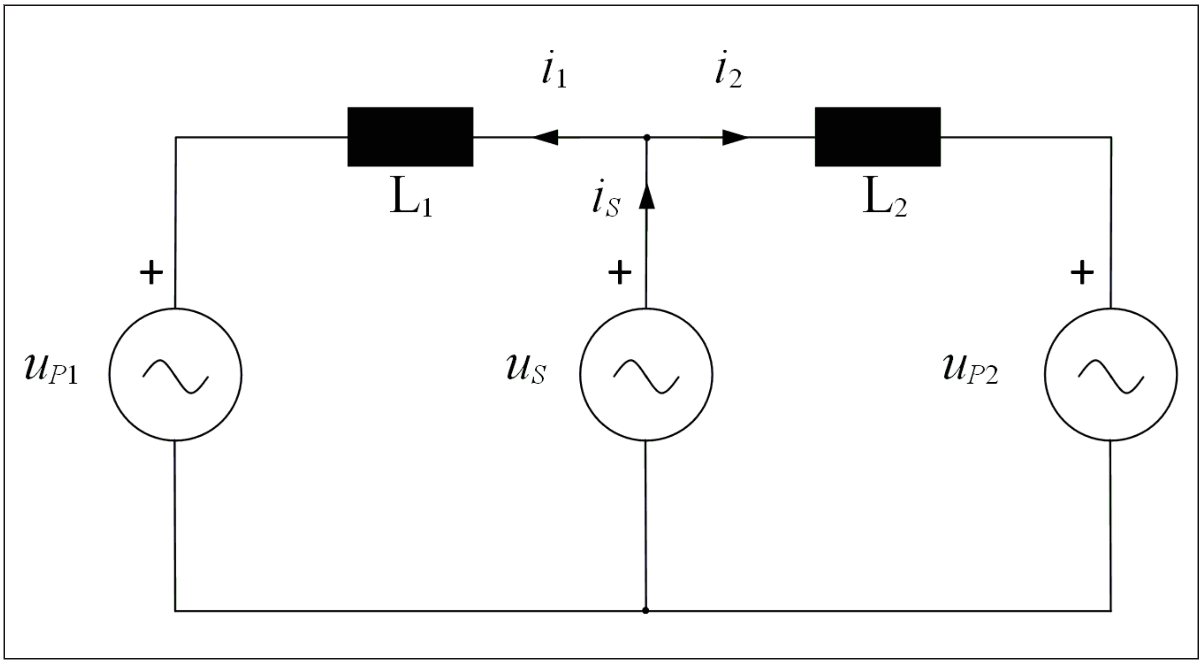

Figure 4 Simplified scheme of the converter

Required amount and character of the imposed current is determined according to the measured signals on the high voltage side (u_{VN} and i_{VN} in Fig. 3). Fig. 5 shows phasor diagram of the quantities in the case when the traction substation total current i_P is inductive (the main harmonic of the high voltage u_P is in Fig. 5 denoted with adequate phasor). The current i_P can be divided into two components: component i_D is a direct component which is in phase with the voltage u_P and i_Q is a quadrature component which is orthogonal to the voltage u_P. According to [5], reactive power is consequence of a phase shift between voltages and currents with equal frequencies. Therefore, the main harmonics of the voltage and current on the high voltage side and their phase shift should be calculated and in order to compensate reactive power, the converter should impose the reactive current i_{Qref} main harmonic which is opposite to the main harmonic of the quadrature current component i_Q.

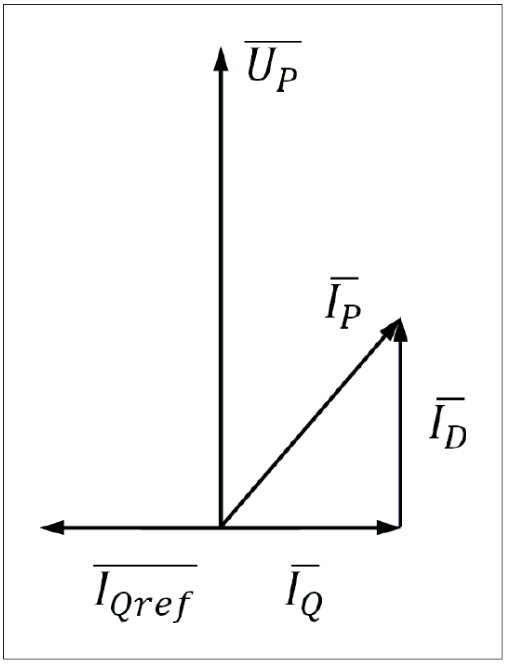

Figure 5 Phasor diagram of the quantities on the high voltage side

4.4 Technical data of the converter

Technical data of the converter is given in Table 1.

Table 1 Technical data of the converter

Power	Rated power	225 kvar
	Power for input voltage greater than 360 V	225 kvar
	Power for input voltage in the range (280 ÷ 360) V	(175 ÷ 225) kvar
Input voltage	Rated input voltage, r.m.s. value	400 V
	Variation of input voltage, r.m.s. value	(280 ÷ 480) V
	Rated frequency of input voltage	50 Hz
	Variation of input voltage frequency	(48 ÷ 52) Hz
Current	Rated current, r.m.s. value	562,5 A
	Maximum current, peak value	980 A
	Current limit, r.m.s. value	625 A
Mechanical and climate data	Dimension (W x H x D)	1210 x 2105 x 810 mm
	Weight	844 kg
	Mechanical protection	IP30
	Working ambient temperature	(-25 ÷ +40) °C

5 Measurement results

Type and routine tests have been carried out in the laboratory of Končar – Electronics and Informatics, Inc. according to the normative reference EN 50328:2003 Railway applications – Fixed installations – Electronic power converters for substations [6]. Due to the fact that large currents (rated value of the converter current is 562,5 A, Table 1) could not be imposed in single-phase grid, two converters were tested with so called back-to-back method. In that method one converter has been in inductive mode and other in capacitive mode. Fig. 6 depicts currents of the inductors in the case when the converter worked in current limit mode (r.m.s. value of the current was 625 A). It can be noted that the phase shift between the main harmonics of the currents is 180 °el.

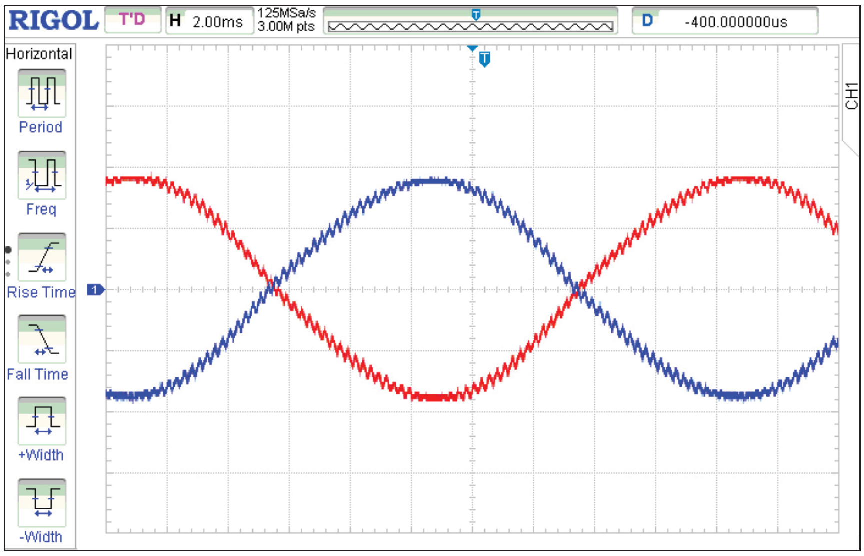

Figure 6 Currents of the inductors, measurement results (2 ms/div, 250 A/div)

After successful type and routine tests, two converters were built in traction substations Mrzlo Polje where trial operation has been started since the beginning of the December 2017. In Fig. 7 is shown 25 kV traction network voltage, Fig. 8 depicts the total traction substation current in the case of heavy load and Fig. 9 depicts the total traction substation current with low load. In these figures can be noted very high distortion of all quantities and presence of higher time harmonics.

Apart from monitoring of the converter operation and correct working during trial operation, the most important and actually quintessential result was cost for the excessive reactive energy. The results are very promising: during January and February 2018 before mentioned cost was approximately 3 % of the amount when facility for reactive power compensation was not installed. According to that, it might be expected that yearly cost for excessive reactive power in traction substation Mrzlo Polje could be equal to only one third of monthly cost before compensation.

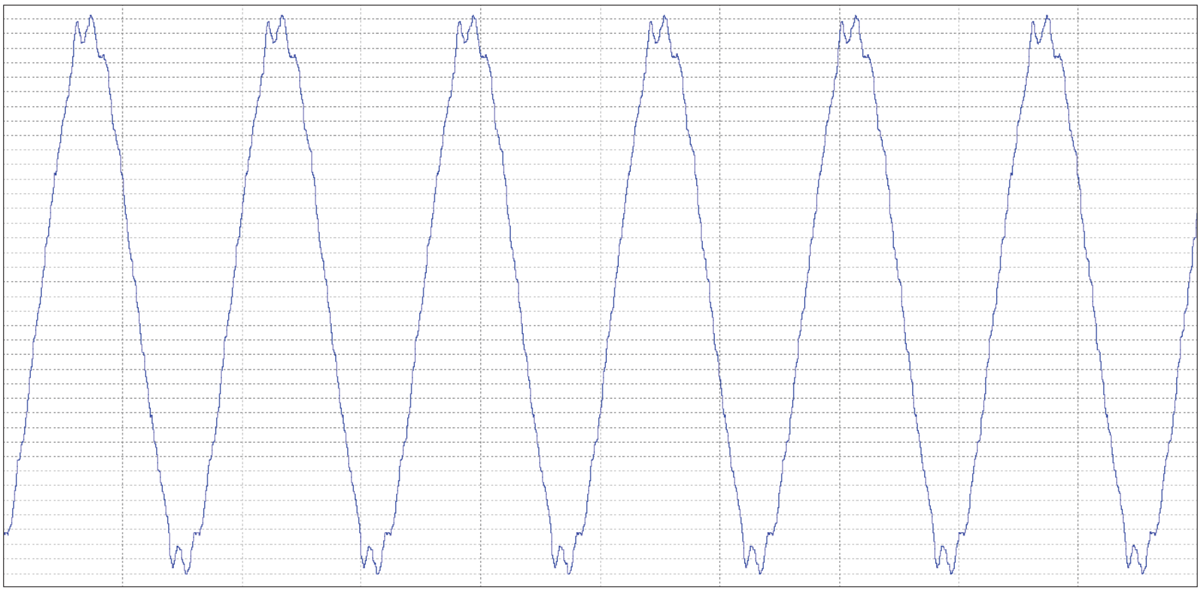

Figure 7 25 kV traction network voltage, measurement result in traction substation Mrzlo Polje (6,25 ms/div, 2 kV/div)

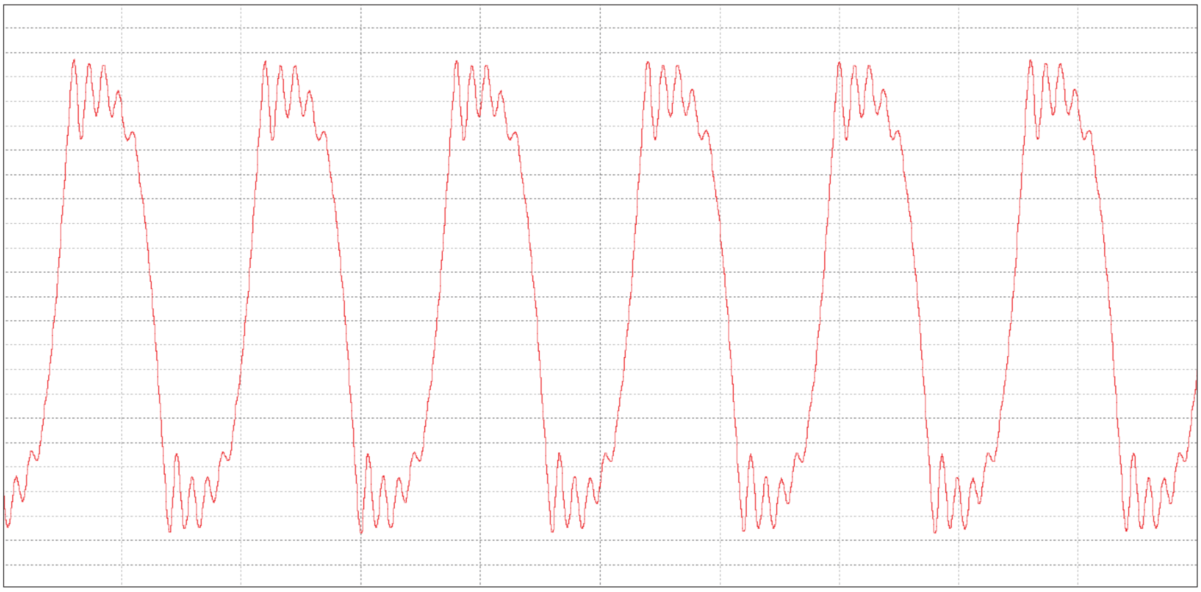

Figure 8 Total traction substation current, measurement result in traction substation Mrzlo Polje (6,25 ms/div, 5 A/div)

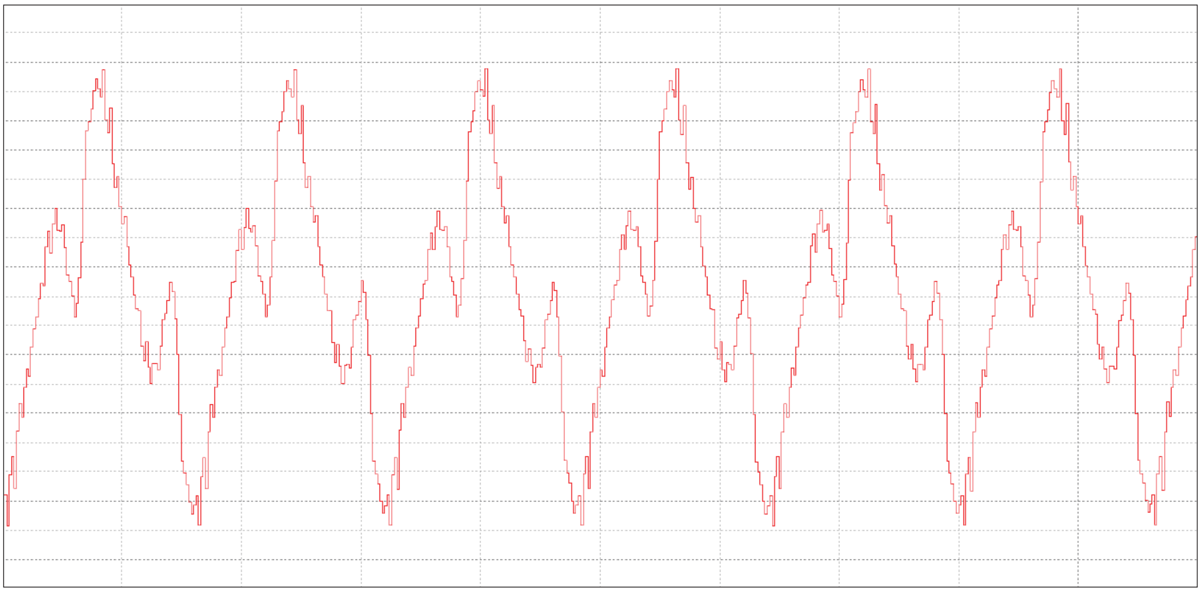

Figure 9 Total traction substation current, measurement result in traction substation Mrzlo Polje (12,5 ms/div, 1 A/div)

6 Conclusion

The excessive reactive energy costs were in Croatia in past few years approximately 10 % of overall costs and were the biggest item in Tariff system for electric energy transmission. The converter for dynamic reactive power compensation KONTRAC PN225AC is aimed for building in traction substations 25 kV, 50 Hz. Either different number of parallel connected converters or a combination of the parallel connected converters and the facility with fixed reactive power compensation can be used in traction substations. In such a manner reactive power of the traction substation can be compensated but without excessive reactive power and associated costs.

The facility with fixed reactive power compensation and two converters connected in parallel are installed in traction substation Mrzlo Polje in 2017 and a trial operation has been started since the beginning of the December 2017. During January and February 2018 before mentioned cost was only 3 % of the cost before compensation. These results indicate that an investment in the facility for reactive power compensation has the investment return period approximately 4-5 years.

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