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DISTURBING IMPACT OF AC RAILWAY POWER SUPPLY WITH A SCOTT TRANSFORMER ON A SUPPLYING GRID - LABORATORY TESTS

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Abstract.

The paper presents investigation of the influence of the AC autotransformer power supply system on the energy quality in a public grid. The research includes construction of a laboratory model of AC autotransformer railway power supply system. The model consists of a power substation with a Scott transformer, overhead catenary system with the inductances of the contact wire, parallel feeder and running rails, autotransformers and two trains. The first one with the inverter-asynchronous drive and the second with the diode rectifier and DC motor drive. The influence of the AC autotransformer system on the public grid considering all types of the disturbing influence including voltage unbalance, voltage harmonic generation and power fluctuation in aggregated.

1. Introduction.

AC electrified systems have the disturbing influence on the power quality in a public grid to which they are connected. In general this is caused by few factors. First of them, very often considered as the most significant is the unbalance of the load [1,2,3,4,5,7,14,15,16]. There are many different solutions which could be used to mitigate the influence of this factor. The most reasonable of them in terms of costs is implementation of Scott-connected or V-connected transformer. The specifics of these solutions has been investigated by many authors [6,11]. The next factor influencing the power quality is the harmonic content in a current drawn by locomotives, as in many countries most of them are equipped with the diode or thyristor rectifiers [8]. The last disturbing factor which is specific for all electrification system is unpredictable peak power demand (power strike) [13]. Most of the papers consider each of this phenomenon separately, while they appear simultaneously in the same system and are mutually related. It is necessary to mention that the influence of each of the factors above on energy quality depends on the short circuit power at the point of connection of the power substations to the public grid (point of common coupling – PCC) . The different solutions are used to mitigate the disturbing influence of the railway system when the short circuit power is not high enough and the parameters of the energy quality doesn't meet the values specified in the appropriate standards. In EU the following documents are applicable: EN 50160 [9], IEC 61000-3-6.

2. Model of the electrified line as a disturbing load.

The current chapter presents the physical model- laboratory stand of the railway power supply system as the source of disturbances from the point of view of the public grid. The whole system is composed of the subsystems (supply line, 3-phase/3-phase and traction substation transformers, models of load) and elements, in order to create mutual interdependencies and the particular type of disturbance generated.

2.1. The model of the power substation as the asymmetrical load.

The overhead catenary system in AC power supply systems including an autotransformer system is supplied from a single phase voltage source while a public grid is the three phase source. Hence a power substation must convert the electric energy from a three phase into a single (double phase). The general view of the traction substation model is shown in Figure 1 [6]. In the paper only the cases with the single phase and Scott transformer have been presented.

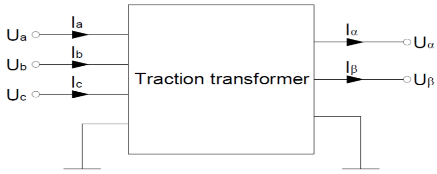

Fig. 1. General model of the traction transformer.

2.1.1. Single phase transformer.

Single phase transformer is commonly used as the traction transformer in a power substations. The general scheme is presented in Figure 2. Due to the simple construction the investment costs in case of this solution are relatively low. The main disadvantage is the asymmetry of the load.

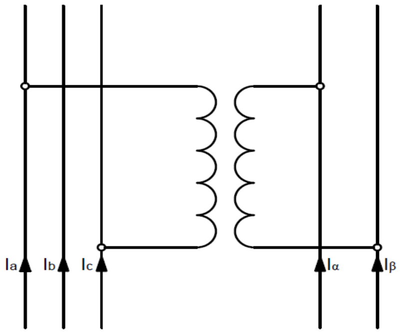

Fig. 2. Single phase transformer.

The negative sequence current ratio on the primary side for single phase transformer is always equal to 1. [6]:

$$\varepsilon = \frac{I_2}{I_1} = 1 \tag{1}$$

2.1.2. Scott transformer.

Scott transformer is one of the solutions leading to decrease of the negative sequence current. It consists of two single phases transformer M and T. The voltage magnitude is equal on both secondary windings and phase angle between the voltages is 90°.

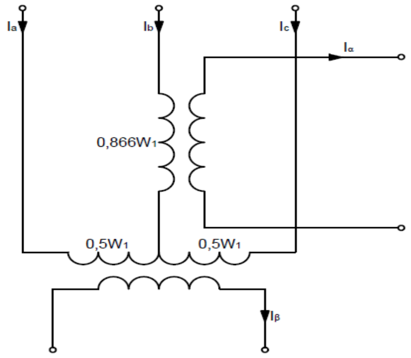

Fig. 3. Scott transformer configuration

The negative sequence current ratio could be obtained [6]:

$$\varepsilon = \frac{\sqrt{1+\eta^2 - 2\eta\cos(\varphi_\alpha - \varphi_\beta)}}{\sqrt{1+\eta^2 + 2\eta\cos(\varphi_\alpha - \varphi_\beta)}} \tag{2}$$

where:

η– the load ratio between the secondary windings,

$\varphi_\alpha - \varphi_\beta$ the phase angles between the voltage Ua on the primary side of the transformer and the secondary voltages.

The graphical representation of the equation 2 is presented in Figure 4.

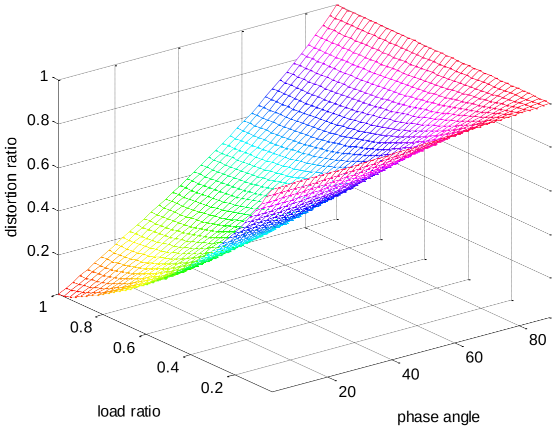

Fig. 4. Negative sequence current ratio

If given are the RMS values of the phase voltages or currents, the negative sequence voltage or current could be calculated according to the following formula [4].

$$\varepsilon_U = \frac{U_2}{U_1} = \sqrt{\frac{U_{L1}^2 + U_{L2}^2 + U_{L3}^2 - 4\sqrt{3}s}{U_{L1}^2 + U_{L2}^2 + U_{L3}^2 + 4\sqrt{3}s}} \tag{3}$$

where:

$$s = \sqrt{b(b-U_{L1})(b-U_{L2})(b-U_{L3})} \tag{4}$$

where:

$$b = \frac{1}{2}(U_{L1} + U_{L2} + U_{L3}) \tag{5}$$

Analogously the current unbalance could be calculated.

2.2. Model of the electric vehicle as the source of harmonics

The harmonic content in pantograph current waveform depends on the type of a vehicle [12]. New generation vehicles with 4QS converter and asynchronous motors draw current with comparatively low level of harmonics [14]. While the older types of locomotives with diode rectifiers and DC motors generate the current harmonics on much higher level. The electrical scheme of locomotive with diode rectifier and DC motors is shown in Figure 5, and with PWM 4QC/inverter control in Figure 6.

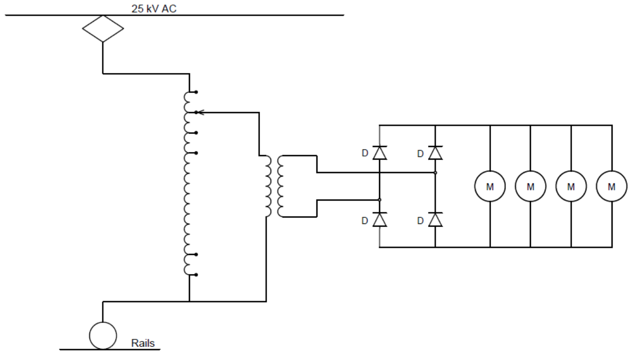

Fig. 5. General electrical scheme of a locomotive with a diode rectifier.

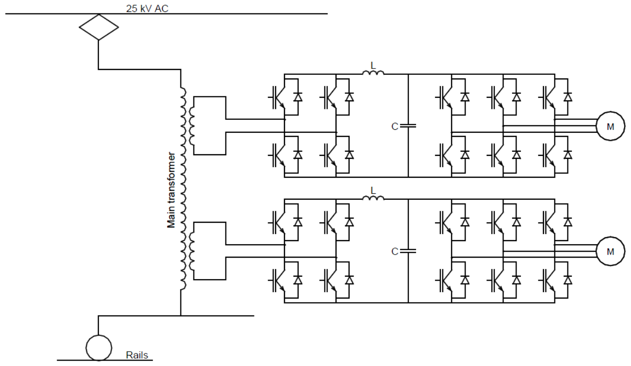

Fig. 6. General electrical scheme of a modern PWM controlled locomotive.

3. Laboratory model.

General aim of the model is obtaining the representation of an autotransformer power supply system (2 x 25 kV) with a different type of rolling stock operating. The general scheme of the laboratory model is presented in Figure 7.

The model consists of a step down transformer Dd0 400/230 V (1) (rated power: 3.5 kW), Scott transformer (rated power 2.5 kW) equipped with tap changers on the primary side (2). First winding of the traction transformer is connected to the autotransformer AT1 (3), supplies the inverter (4) with the induction motor (5), which is loaded with the DC generator (6). The load variation could be achieved by changing the excitation current of the generator. This load of the traction transformer is the model of new type of vehicle, the model represents the situation when the train is located near to the autotransformer feeder station. The second winding of the traction transformer is connected to the autotransformer AT2 (7) which is connected in parallel to the autotransformer AT3 (9) via the inductions (8), modelling the catenary wire, running rails and the parallel feeder respectively. The inductances are set to model 10 km distance between autotransformer feeder stations. The autotransformer AT3 is loaded by the single pulse diode rectifier and the adjustable resistor (10). The model is equipped with the measurement system, which enables to measure and collect the values of the electrical quantities. The system consists of voltage and current transducers (LEM) fixed on the primary side of step-down transformer, primary side of Scott transformer and secondary side of Scott transformer (11). Transducers are connected to the analog inputs of the acquisition card (12), which is connected to the PC via the USB port.

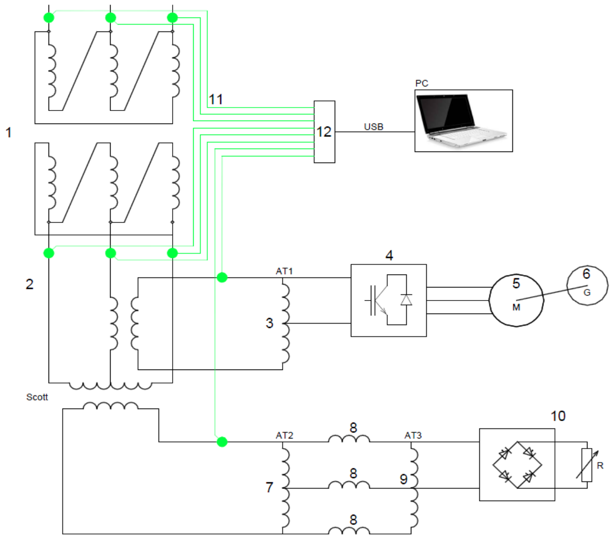

Fig. 7. The scheme of the laboratory model of the system.

The software installed on the computer (PC) enables an automatic saving of the results of the measurements and carrying out the basic calculations of the negative sequence ratio. The calculations are based on the formula (3).

The model of the modern vehicle drive (4 in Fig. 7) is the frequency converter, whose current waveform is much more distorted than in case of the typical modern vehicle presented in the drawing 6. Exchanging of the model of the modern vehicle is the next step of the laboratory model development.

4. Survey results.

The measurements have been made during the following options of the system operation:

1) Diode rectifier out of operation, inverter asynchronous drive is performing a typical drive cycle – start up mode, constant speed mode and braking. The excitation current of the DC generator is constant.
2) The inverter drive is out of operation while the rectifier is operating according to the running cycle of the vehicle.
3) Inverter drive is operating with the constant power value 800 W, while the rectifier unit is operating according to the running cycle of the vehicle.
4) The rectifier unit is operating with the constant power, the current is equal to 5 A, while the inverter drive is operating with the running cycle as in point 1.

Figures 8-11 present the Scott transformer secondary winding RMS currents during the cases of operation listed above.

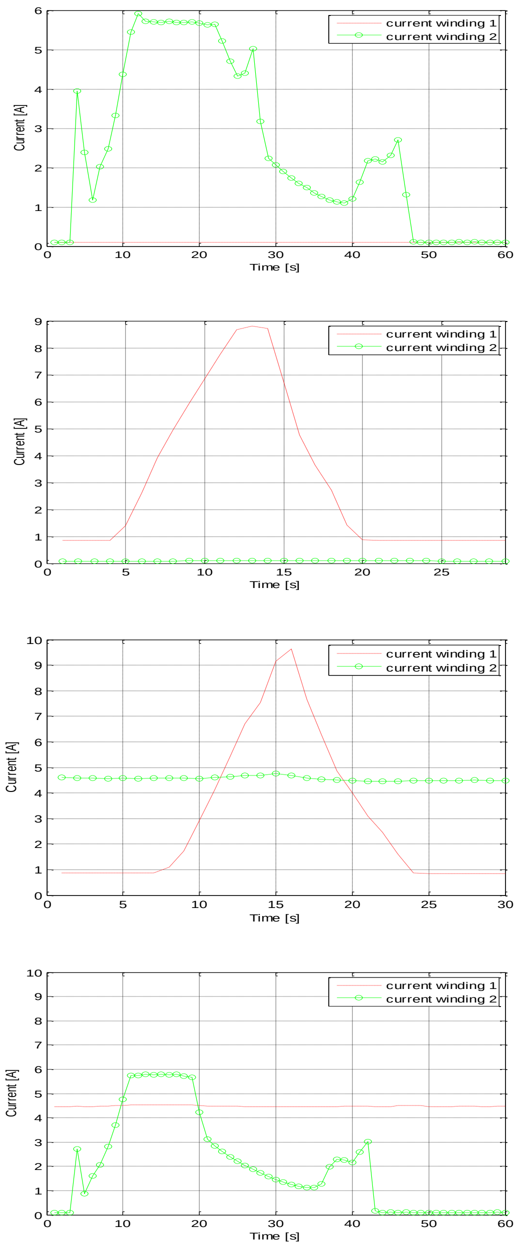

Fig. 8-11. The RMS values of the secondary winding currents of the Scott transformer during the options of operation 1-4 respectively.

The variants above have been investigated to obtain the typical situations in terms of the traction transformer load. The first and the second option present the situation when only one Scott transformer winding is loaded by the traction load, while through the another one only no-load current of autotransformer is flowing. Third and forth option model the situation with both windings loaded, the ratio between each of the windings RMS currents is variable during the time of operation.

The article focuses on the influence of the railway system on the energy quality in public grid, hence the energy quality parameters have been presented. The parameters have been measured at the point between the step-down transformer (1) and Scott transformer (2). The short circuit power is much lower at this point than on the primary side of the step-down transformer, due to the relatively high value of short circuit impedance of the transformer. According to that, the voltage distortions are much higher on the secondary side. Short circuit power has been calculated based on the short circuit impedance measurement at that point and was equal to 27.8 kVA.

The results have been presented as per parameters of energy quality, depicted in [9] and affected by the railway power supply system.

4.1. Voltage variations.

The lowest value of voltage has been noticed in option 3. The time series of the voltage values for this case has been shown in Figure 12. The lowest instantaneous value is equal to 84.4 % of the nominal value.

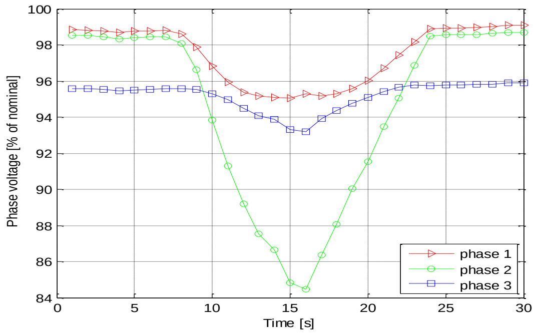

Fig. 12. Voltage values on the primary side of Scott transformer in option 3.

4.2. Supply voltage unbalance.

Figures 12-13 present the comparisons of the voltage unbalance ratio between pairs of options, calculated according to the formula (3).

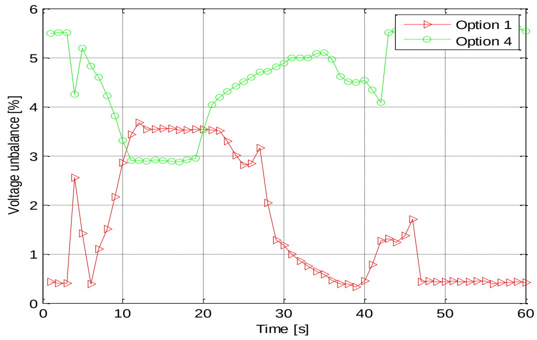

Fig. 13. Negative sequence voltage for option 1 and 4.

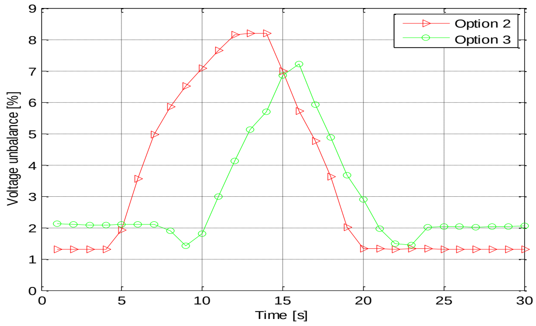

Fig. 14. Negative sequence voltage for option 2 and 3.

4.3. Harmonic voltage.

Figures 14-17 show the voltage harmonics time series during the test options 1-4 on the first phase at the primary side of the Scott transformer. The figures present examples from phase 1 among 3 obtained during the measurements as the most illustrative.

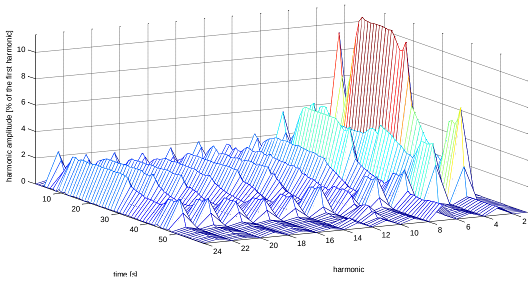

Fig. 15. Voltage harmonics on phase 1 on the primary side of a Scott transformer during the option 1 operation.

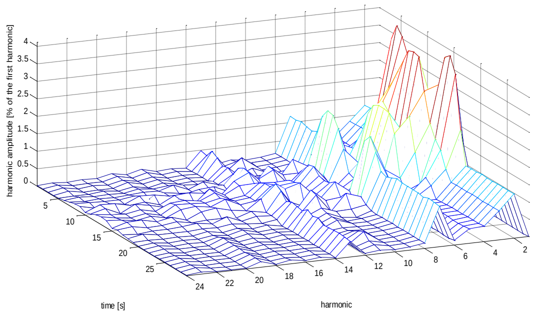

Fig. 16. Voltage harmonics on phase 1 on the primary side of a Scott transformer during the option 2 operation.

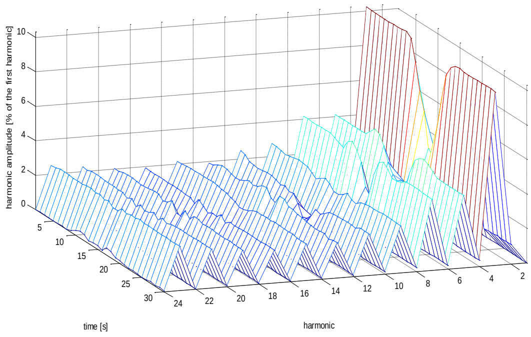

Fig. 17. Voltage harmonics on phase 1 on the primary side of a Scott transformer during the option 3 operation.

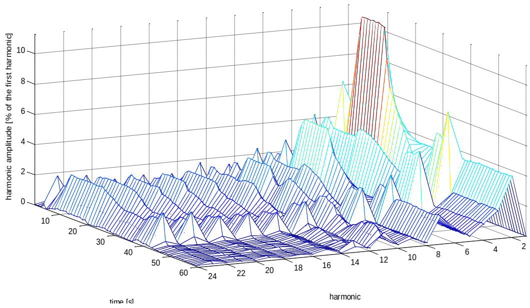

Fig. 18. Voltage harmonics in phase 1 on the primary side of a Scott transformer during the option 4 operation.

Conclusions.

It should be noticed that the factors in the AC railway power supply system leading to the disturbances of the power quality and the effects caused by each of them are mutually linked. It could easily be proved that both current unbalance provided to the public grid as well as the harmonic values of the current depend on the power and the position of each vehicle.

The lowest instantaneous voltage occurs during the test in option 3 in which the maximum voltage unbalance is much higher than in option 4, it testifies that the power demand was the highest in case with the diode rectifier.

However comparing the windings RMS current values (Fig. 8-11) from which the current unbalance, based on the formula (2) could be obtained with the voltage unbalance shown in Fig. 13-14, it could be noticed that the voltage unbalance is not, in this case dependent on the Scott transformer secondary currents, analogously to the current unbalance, according to the formula (2). For example the maximum unbalance factor is higher in option 3 (7.1%) than in option 1 (3.7%), regardless that the current ratio between secondary Scott transformer is much higher in option 3 than in option 1, where is close to 0.

With regards to the harmonic content, a few examples are used to explain the specifics of the phenomenon which take place in the system. During the test in option 2 the peak power occurs at around 13 second of the test (Fig 9). Figure 16 shows that even harmonics achieve the maximum value when the load of the Scott transformer winding is between 60 and 70 % of the maximum load value. In the meanwhile the odd harmonics are maximum, when the load is maximum. Figure 17, which presents the voltage harmonics in option 3 shows that during the switching off of the diode rectifier the harmonics caused by the constant work of the asynchronous drive are being "compensated" by the harmonics derived from the rectifier.

The results presented in the paper are focused only on some, the most representative, of the aspects of phenomenon taking place in the system. The voltage unbalance values obtained during the tests show that the relation (2) under the real conditions could not be used to determine the value of the current unbalance factor and based on this voltage unbalance. In order to achieve more precise relation the further investigation is required. It will include the new realization of the locomotive models, more coherent with the reality including the possibility of the step switching of the load – the situation of passing the section insulator. The expand of the laboratory model will enable to create more precise model of the system.

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