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MEASUREMENTS AND SIMULATIONS IN TRAIL OPERATION OF ELETRIC TRACTION POWER SUPPLY AFTER ITS MODIFICATION

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Abstract
The modernisation of the railway system on the section of a railway track Moravice – Rijeka – Šapjane was completed in the end of 2012, i.e. transition from a 3 kV DC system to the monophase 25 kV AC system with a frequency of 50 Hz. After changing the rail powering system, the same section underwent operational testing. A test freight train was driven along the section and measurements of currents and voltages were conducted at every electric traction substation.

This paper shows the flowchart of the train movement simulator as well as the comparison of measurement with simulation results. The influence of the train to nearby telecommunication cables is observed, measurements of induced voltage were conducted and the measurements results are compared with the calculated values.

1 Introduction

On the section Moravice – Rijeka – Šapjane, a total length of 128 km, a modernisation of the railway system was recently conducted, i.e. transition from the 3 kV DC system to the mono-phase 25 kV AC system with a frequency of 50 Hz**.** The transition is of exceptional interest to Croatia, since the complete electrified railway network, after nearly 30 years is now unified. Given that Rijeka is the largest Croatian port hub, the main function of this railroad is transport of freight, modifying the railway system increased its transport ability [1].

Modifying the electric traction on the section Moravice – Rijeka – Šapjane from DC to AC power, influences electric conditions in the surrounding transmission grid of a power system. Since the electric traction substations AC are connected via transformers 110/25 kV to two phases of the transmission grid , they represent the unbalanced load for a three-phase system. In addition, the use of locomotives equipped with diode and thyristor rectifiers leads to distortion of voltage and current, and due to sudden changes of load, it can lead to voltage flickers in the power supply network. Therefore, while connecting new electric traction substations to a power system, the study of unbalanced power flow should be conducted in order to determine the level of voltage and current asymmetry in the transmission. [2].

The section of railroad track from Moravice to Rijeka was put into test-operation in the end of 2012. After changing the rail powering system the experimental measurements were conducted.

In this article the results of the electrical measurements during the drive of the test freight train are analysed. They have been compared with simulation results of the developed software. Also, the influence of the freight train on nearby telecommunication cables is studied. The proximity of power transmission lines, electric traction lines and telecommunication networks has become more and more frequent, because of the continual increase in energy consumption and communication requirements. A telecommunication cable, even buried, following an AC electric traction line over a certain distance, is subjected to significant interference. This interference consists mainly of an inductive component, while conductive and capacitive components are less significant.

Test drive of a single train created a unique opportunity to obtain the most accurate measurement results, as the impact of other trains that normally run along the observed section of railroad was avoided [3].

The test freight train was running along the whole supply area of a newly built electric traction substation. The state of the observed section, i.e. the number and arrangement of electric traction substations and section facilities, as well as configuration of the field, is shown in Figure 1 which depicts the mountainous character of a track.

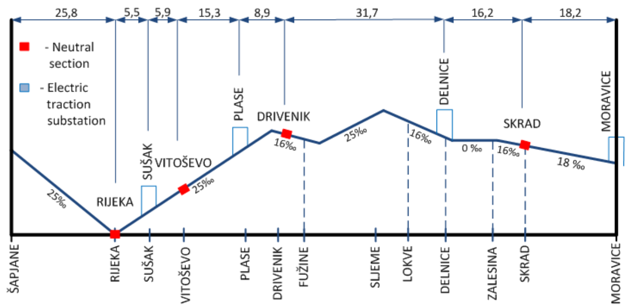


Figure 1. The section of a railroad Moravice – Rijeka – Šapjane

2 Characteristics of test freight train

Test freight train consisted of two locomotives and thirteen carriages; the mass of cargo transported by train was 520 tons, while the total mass of the train 788 t. Locomotives of series 1141 have been produced in the period before thirty–forty years and they do not have the ability of regenerative braking, i.e. of returning the power into the network. Locomotives have built in DC motors, and the conversion from the AC to DC voltage is conducted by diodes. The basic technical specifications for locomotives series 1141 are shown in Table 1.

Table 1. Technical specifications for locomotives series 1141

Number of axies:	4
Continues power for traction:	3860 kW
One-hour output:	4080 kW
Maximum speed:	140 km/h
Mass:	82 ta
Power of electrodynamics brake:	1740 kW (η=0,8)

Indispensable information of locomotive required for electric-traction calculation is tractive force, braking force and power factor cos φ. Figure 2 shows their dependence on the speed. Power factor of locomotives is ranged from 0.65 to 0.85, except for the actual speed which depends on the distance of the power supply [4].

Traction force, besides the speed, also depends on the excitation current, i.e. voltage.

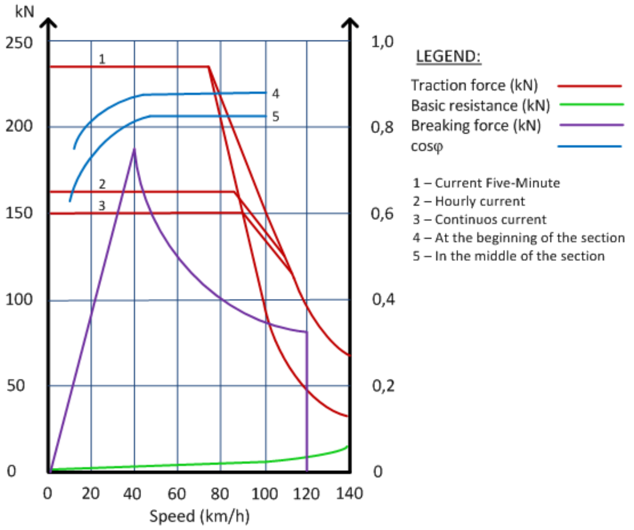


Figure 2. Dependence of traction force, braking force and power factor on the speed

3 Results of measurement

The results of measurements in electric traction power supply ETS Plase are presented and analysed subsequently.

In the ETS Plase two transformers of rated power 10 MVA with transmission ratio 110/27,5 kV±10x1,5% are installed as well as the capacitor bank that has the possibility of reactive power regulation in six degrees, in the no-load condition.

Values and tolerances for voltage limits of electric traction power system 25 kV, 50 Hz are defined according to EN50163 and listed in Table 2.

Table 2. Standard voltage values in Contact Network (CN) for electric system 25 kV, 50 Hz (norm EN50163)

U_{min1}=17,5 kV	Currently allowed minimum voltage CN
U_{min2}=19 kV	Permanently allowed minimum voltage CN
U_{n}=25 kV	Rated voltage CN
U_{max1}=27,5kV	Permanently allowed maximum voltage CN
U_{max2}=29 kV	Maximum voltage CN ($t \leq 5$ min)
U_{max2}=38,75 kV	Maximum voltage CN ($t \leq 20$ ms)

During the train ride along the whole supply area of an electric traction substation Plase voltage oscillations ranges in values of 29.96 kV to 27.16 kV (Figure 3.). Given that the mentioned values, according to EN50163, in permanently permissible limits it can be concluded that stable voltage conditions. were present during the entire period of investigation .

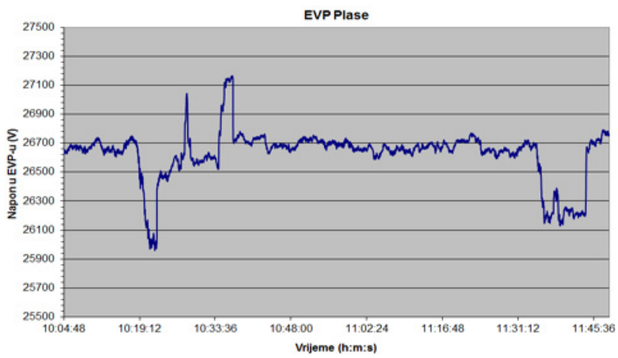


Figure 3. Voltage in ETS Plase

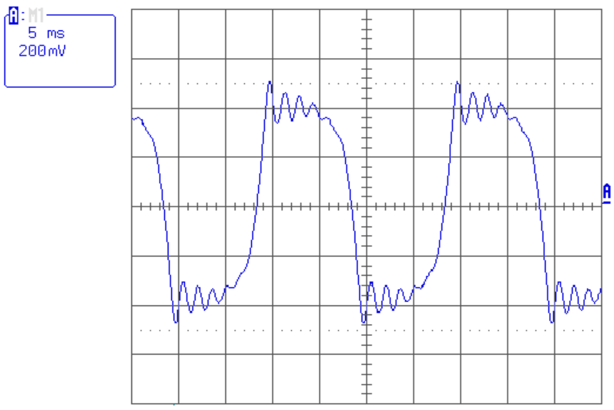


Figure 4 . Measured current waveform during the drive of locomotive equipped with diode rectifiers (100 mV=80 A)

Current waveforms shown in Fig. 3 are typical for diode locomotive series 1141. Current locomotive contains a substantial proportion of higher harmonics: 3.h - 24.2% 5.h - 12.2% 7.h. - 6.8%, 9.h. - 4.8%, 11.h - 5.7% 13.h - 7.0% 15.h. 1.7% .. (percentage of higher harmonics in relation to the fundamental harmonic 50 Hz is shown). Such current in impedance contact network, electric-traction transformers and 110 kV networks creates nonsinusoidal voltage drops which distorts voltage supply and affects the quality of electricity. So unless unbalanced load (connected to two phases of 110 kV network) electric traction current effects the quality of the voltage in the 110 kV network. Due to the sudden changes in load, usually caused by changing train ride regimes, the network can lead to voltage flicker (flicker).

Power supply scheme of ETS Plase is shown in Fig. 4. Lengths of the railway track powering from this ETS are 8,9 km and 15,3 marked as (L1) and (L2) in Figure 5 respectively.

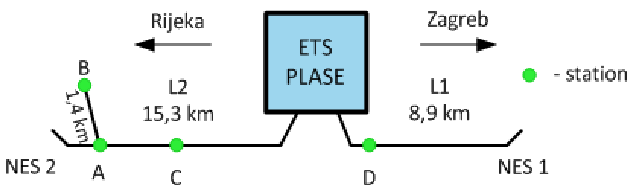


Figure 5. Power supply scheme of ETS Plase

The test freight train was travelling along the railway track, between the stations Skrljevo and Moravice, which is shown in Table 3. The train departed from the station Skrljevo at 10:19 am, and it was travelling in the area supplied from ETS Plase till 11:44 am. The measuring results recorded in that period are shown next.

Table 3. Overview of test freight train movement

`TRAIN STATION	ARRIVAL (HH:MM)	DEPARTURE (HH:MM)	DELAY (MM:SS)
Škrljevo	-	10:19	09:39
Meja	10:28	10:28	-
Plase	10:38	11:35	00:57
Drivenik	11:45	11:45	-
Fužine	11:55	12:11	00:20
Lokve	12:23	12:23	-
Delnice	12:31	12:31	-
Zalesina	12:39	12:39	-
Skrad	12:47	12:52	00:07
Brod-Moravice	13:03	13:03	-
Moravice	13:11	-	-

3.1 Drive of the freight train

The train was travelling from Rijeka direction . In the time period from 10:19 to 10:34 it was moving along the branch (L2), and after that time along the branch (L1) (direction Zagreb in Figure 5). Results of measuring current, active and reactive power as a function of time are shown in Figure 6.

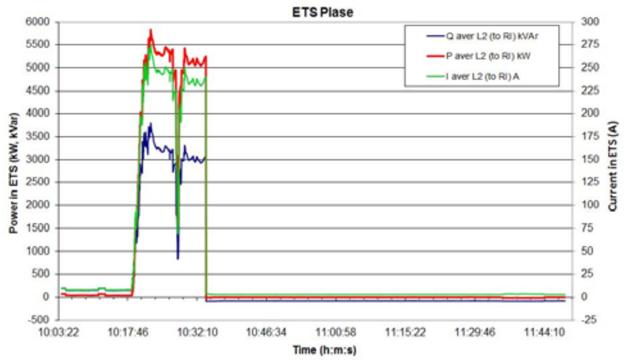


Figure 6. Active, reactive power and current in ETS Plase supplying the branch L2

Very small power consumption of 45 kW can be noticed during the first period of measurement, starting at 10:03 am, up to the moment of the train departure, which is 10:19 am. The reactive power consumption is higher with the average value of 147 kVAr, and current is 7.7 A. At that time, the train was stationed at the station Skrljevo supplying the auxiliary drives (heating/cooling, compressors, pumps, fans, etc.). Oscillation of current, active and reactive power is due to the periodic inclusion/exclusion of a certain auxiliary propulsion system.

The test freight train which was pulled by two locomotives, consumed the maximum current of 274.9 A from the network, the maximum active power in the amount of 5.82 MW and the maximum reactive power of 3.8 MVAr, when accelerating up to the prescribed limit. Considering the rather high consumption of reactive power regulation is recommended by the capacitors embedded in ETS Plase.

The train enters the supply branch L1 at 10:34 am, and after a short time it begins to slow down; at 10:38 am it stops at the station Plase (Figure 7). The train is staying at the station until 11:34 am. In this time period the train takes an average current of 8,1 A, the average active power of 45 kW and the average reactive power of 164 kVAr.

At 11:34 am the train continues its journey to Moravice and begins to accelerate to the proper prescribed speed limit in this area. During acceleration the train takes from the network maximum current 280.6 A, the maximum active power in the amount of 5.93 MW and the maximum reactive power in the amount of 3.77 MVAr.

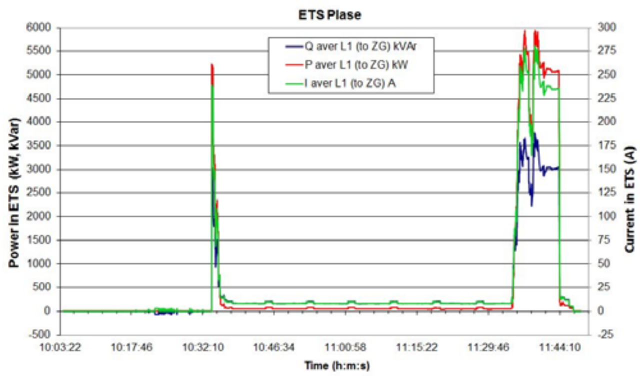


Figure 7. Active, reactive power, and current in ETS Plase supplying the branch L1

4 Comparison of simulation and measurement

The train movement simulator was used in order to calculate the electrical conditions during the movement of the test freight train

4.1 Simulation of train movement

The principle of the calculation is depicted in Figure 8.

The whole calculation runs in the time steps for the desired time period. The train movement simulator gives the exact location, as well as active and reactive power demands of the train in each time step.

Every motion of a vehicle is accompanied with resistances along the track and the tractive effort is needed to overcome these resistances. The maximum tractive effort available by a certain speed F_t is determined from the speed-tractive effort curve of an electrical train as depicted in Figure 2. The required tractive effort must be smaller or equal to the adhesive force, which is the frictional grip between the driving wheel of a locomotive and the rail. Mechanical power on the brim on the wheel is defined as the product of the tractive effort and the speed. The electrical power P_{el} which is converted to the mechanical power P_m is determined with the efficiency factor, which is a non-dimensional measure of the performance of an electrical vehicle and its value is smaller than 1. A constant value of the efficiency factor is assumed as well as the constant values of the auxiliary power P_{pom}.

The reactive power of the train is calculated with the help of a power factor, which is a function of the speed and voltage that should be known from the network analysis.

Subsequently calculations continue in order to determine acceleration, along with speed and distance. The procedure is repeated for the next time interval – calculation step.

. 4.2 Comparison of simulation with measurements

The first comparison is made for the train running from Rijeka direction ; the train was moving along the branch (L2) in the time period from 10:19 to 10:34. The maximum value of the active power (P) engaged by the train from the power grid is 5.84 MW, Figure 9. The deviation of 0.3 % could be observed comparing this value with the maximum value of the measured active power. The maximum deviation of calculated and actually measured values of active power on the reference branch L2 is 17.2 %.

The maximum computed value of reactive power is 3.65 MVAr that makes a deviation of 3.2 % compared to the measurement. The maximum deviation between the measurement and simulation of reactive power at the reference branch L2 is 13.8 %.

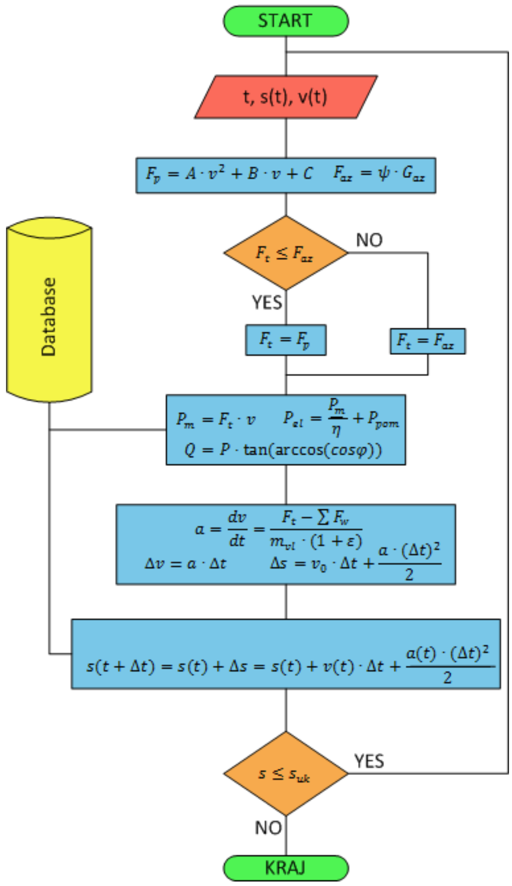


Figure 8. Flowchart for the train movement simulator

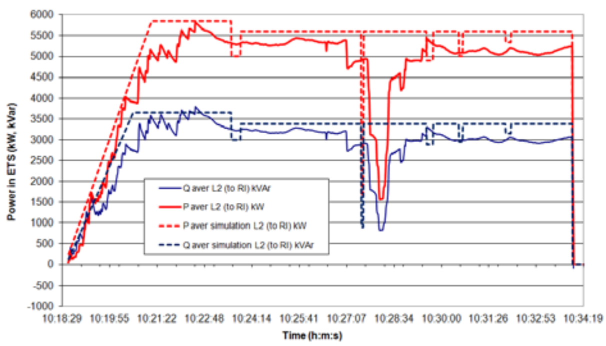


Figure 9. Comparison of measurement and simulation results of the freight train moving along the supply branch L2

A time lag between the simulation and measurement results could be noticed in Figure 9. This occurs due to the different speeds of the train in the simulation and in the reality. In simulation the train accelerates to the planned speed on a certain section using the maximum power available at the time, but in reality this is not always the case. Deviations between simulation and measurement results can also occur due to non-compliance of the planned speed and schedules on individual sections (human train driver).

During motion of the train along the supply branch (L1) the maximum value of the active power taken from the grid is 5.84 MW. The maximum value of active power measured on the reference branch is 5.93 MW, which means that the maximum deviation between the simulated and measured values is 1.52 %. The maximum deviation values of active power between simulated and measured results in some sections amounts to 17.8 %.

The maximum value of reactive power that train takes from the network, moving along the branch (L1) is 3.73 MVAr, which represents a deviation of 3.2 % compared to the obtained measurement. The maximum deviation of simulation and measurement results for the consumption of reactive power in certain parts of the branch is 11.48 %. Figure 10. also shows the time lag between simulation and measurement results which is primarily caused by the different speeds of the train in the simulation and in reality.

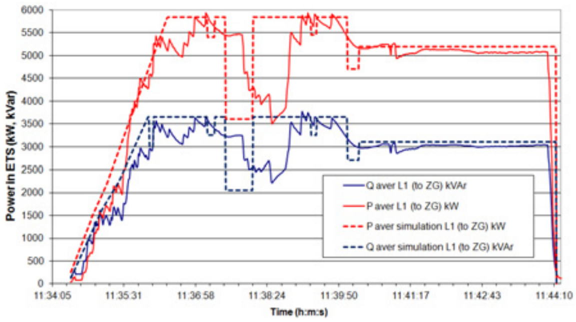


Figure 10. Comparison of measured and simulated results of the test freight train running along the supply branch L1

5 Influence of electric traction on telecommunication cables

The proximity of electric traction lines and telecommunication networks has become more and more frequent because of the continual increase in energy consumption and communication requirements.

A telecommunication cable, even below ground, following an AC electric traction line over a certain distance is subjected to significant interference. This interference consists of an inductive, a conductive and a capacitive component. Inductive interference, generated by the magnetic field, is present during both normal operating conditions and fault conditions. Conductive interference arises when an electric traction line injects a large current into the earth during a fault and the telecommunication cable is located near this fault [5]. Capacitive interference, which is generated by the electric field, influences only cables above ground, having no earth-connected sheath.

According to the International Telecommunication Union's guidelines [6] [7], there are two categories for induced voltages to be considered: normal conditions and fault conditions.

Under normal operation cables to which the members of public may come in contact with can have an induced voltage of up to 60 V rms with reference to earth. Cables that are not accessible by the public are allowed to have up to 150 V rms under normal operating conditions provided that only technicians can access them.

Electrical faults, due to insulation breakdown, leads to an excessive short-circuit current flowing through a contact line conductor. This creates a powerful changing magnetic field, which in turn generates a greater induced voltage on adjacent telecommunication cables. Under these conditions the induced voltage of up to 430 V is regarded as the allowable limit. Higher voltage values have been allowed provided that the probability of the occurrence is low and protection fault clearing time is very quick. If the above two conditions are met the allowable induced voltage can go up to 1000 V rms if the protection operates within 350 ms to 500 ms. In cases where the fault clearing time is less than 350 ms, the allowable limit is 1500 V rms.

Determination of induced voltages in telecommunication cables is a basic analysis required for all new railway systems, as well aswhen important changes to old railway systems are undertaken. Calculations and simulations are needed, not only because the analysis is carried out before system construction, but also because of the increasing complexity of traction systems with various victim circuits, different configurations and the need for a sensitivity analysis for some parameters.

Figure 11 shows the spatial configuration of the electric traction contact conductor and 3,6 km long underground telecommunication cable.

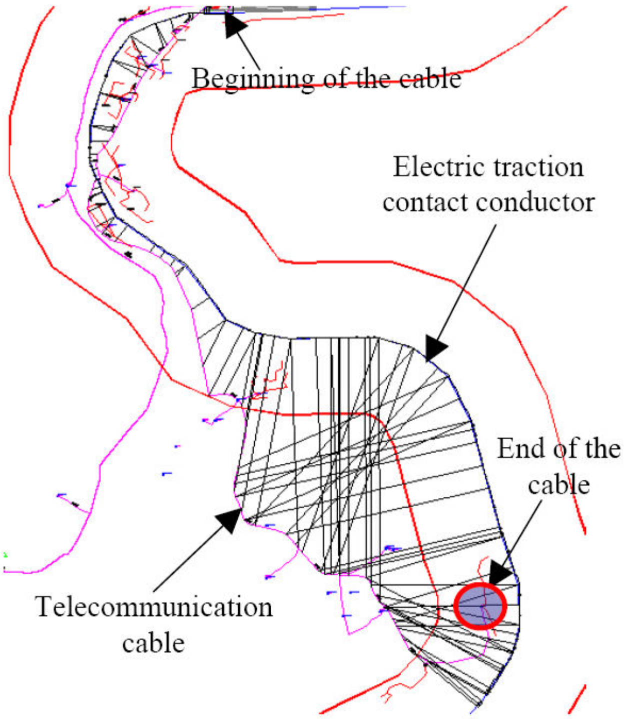
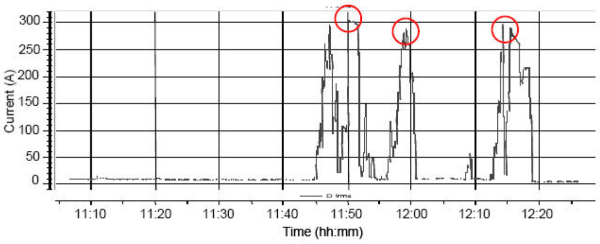


Figure 11. Spatial configuration of the electric traction contact conductor and aunderground telecommunication cable

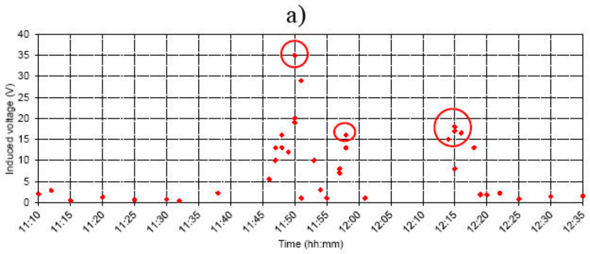
Measurement of the induced voltage at the end of the telecommunication cable was conducted using a digital voltmeter according to scheme shown in Figure 12. Simultaneously, measurement of the electric traction current was carried out in a traction substation using power quality monitoring instrument Dranetz Power a Xplorer PX5.

Figure 12. Electrical scheme for measurement of voltage induced on a telecommunication cable

Measurement results are depicted in Figure 13. There is a temporal coincidence of increased traction current with the increase of induced voltage at the end of the cable. The highest measured induced voltage was 35 V for a traction current of 280 A. At that moment the entire cable length was under the influence. Calculation of induced voltage was performed for this case.



a)



b)

Figure13. a) Current through the electric traction contact conductor; b) Voltage induced at the end of the telecommunication cable

The induced voltage U_{ind} on a telecommunication cable is given by

$$U_{ind} = 2\pi f \cdot M \cdot I \cdot l \cdot r \tag{1}$$

where f is the frequency of the inducing current, I is the inducing current, l is the length of exposition between the contact conductor and telecommunication cable, M is the mutual inductance between the contact conductor and telecommunication cable and r is a screening factor ($0 \leq r \leq 1$), which is to be calculated as the product of the screening factors of the inducing system r_i and of nearby cables r_c. The telecommunication cable was divided into 75 segments (black lines in Figure 11) in order to determine the mutual inductance M. Calculated induced voltage versus the contact line length is shown in Figure 14.

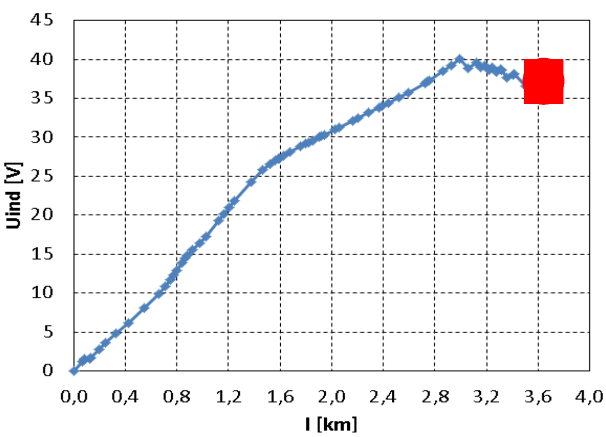


Figure 14. Induced voltage at the end of the telecommunication cable

Induced voltage at the end of the cable is 37 V which is close to the measured result, which is 35 V.

6 Conclusion

The section of railroad track from Moravice to Rijeka in Croatia was put into test-operation in the end of 2012. After changing the rail powering system the control measurements were conducted, and the test freight train was driven along the section and measurements of electrical quantities were conducted at every electric traction substation as well as measurements of the influence to the nearby telecommunication cables.

The results of measurements during the drive of the test freight train are analysed and compared with simulation results of the developed software.

The test freight train with two pulling locomotives, when accelerating up to the prescribed speed limit engaged from the network the maximum current of 274.9 A, the maximum active power in the amount of 5.82 MW and maximum reactive power amounting to 3.8 MVAr.

Also, the influence of the freight train to nearby telecommunication cables was observed. The highest measured voltage induced by a traction current of 280 A was 35 V.

The conducted investigation helped to check and improve the simulation tools used for the purpose of design and operation of electric traction facilities.

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