Transient Effects at Power-Supply System of the Czech Railways from EMC Viewpoint

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Abstract. *The paper deals with the behavior of the traction power-supply system 25 kV, 50 Hz at the Czech Railways. Electrical conditions on a contact line affect electrical conditions in a feeding station. This relation represents galvanic coupling from EMC viewpoint. Explanation of transient effects during short-circuits at the contact line can be considered as the main problem. These effects can arise during a failure in a traction circuit. Therefore, the attention is turned to an adjustment protection design of the traction circuit. Simulation diagrams were created. The design can be utilizable for a feeding station with Filter-Compensation Equipment, which is designed for the EMI reduction.*

Keywords

Power-supply system, power supply line, Filter-Compensation Equipment, feeding station, contact line, transient effect, harmonic branch, short-circuit.

1. Introduction

At present, electromagnetic compatibility (EMC) is widely discussed. Therefore the Czech Railways need to use Filter-Compensation Equipments (FCE) in feeding stations. This equipment is utilized for power factor corrections and for reducing current harmonics caused by electric locomotives with diode converters.

Transient effects during short-circuits at a contact line are the main problem. These effects can occur during a failure in a traction circuit. Firstly, a traction circuit was analyzed in detail. A traction model was created for each individual traction circuit. The models present input data for a simulation program in PSpice. The output data of the simulation program represent voltage and current waveforms. The critical states are deduced from the knowledge of individual waveforms. Input parameters for adjusting protections of the traction circuit were gained by the analysis of these states.

1.1 FCE Characteristics at Czech Railways

Filter-Compensation Equipment (FCE) [1], [2], [3], [4], which is shown in Fig. 1, has two series LC branches of the 3rd and the 5th harmonic, and a decompensation branch. The tuning of the LC branches is not adjusted to the number of the harmonics exactly but is performed for lower of value such as n_3 = 2.90–2.95 and n_5 = 4.98–5.00. This adjustment of LC branches is necessary because harmonics from the power supply line could overload these LC branches (confirmed by measuring). The device has to have an adequate total input impedance (i.e. Z_{input}= 500 to 900 Ω) for the control frequency $f_{ripple\ control}$ (i.e. 216.7 Hz) which is used by the electric power supply. This condition is met by a suitable selection of C_3 and C_5 values in the LC branches. This is to certify LC braches depend on each other.

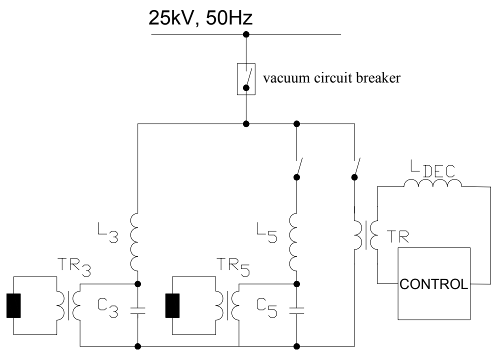

Fig. 1. FCE connection diagram.

The decompensation branch consists of a reducing transformer, a thyristor controller and decompensation chokes, see [5], [6]. The decompensation is done by decompensation choke, which is controlled. The control is done to the inductive power factor *DPF* = 0.98 of the input of electrical power, which is measured in a connection point of a feeding station. The whole FCE is switched off by a vacuum circuit breaker. The 5th harmonic LC branch and the decompensation branch have only a disconnecting switch, which is connected in the circuit for the operation maintenance. The structure design of FCE provides the possibility of the 7th harmonic LC branch but the installation of this branch is not required at the present.

1.2 Configuration of Power-Supply System of 25 kV, 50 Hz

The general configuration of 25 kV, 50 Hz system at the Czech Railways consists of [7]

- 110 kV power supply line;
- Feeding station;
- Contact line.

2. Solution Method

Transient effects are analyzed at linear systems, which are described by an equations system. Necessarily, building of a physical model has to be avoided due to the high costs, limited process monitoring abilities and the behavior of circuit transient effects. Therefore the simulation program PSpice (ver.9.1) was chosen. PSpice utilizes substitution diagrams of simple connections of a traction circuit as input data. These diagrams are obtained from substitution models of simple elements of a traction circuit.

Now, it is very important to state the main disadvantages of a computer simulation. The program does not work with real elements but it works with models. So, results can be as exact as elements' models and describe only effects which present the used models. A creation of quality models, which represent real devices well, is the most important and the most complicated problem of simulations of electronic circuits.

Therefore, models were developed for all the parts of the power-supply system in the following way.

2.1 Substitution of Homogeneous Line by Two-Port Network

The power supply line and the contact line are of the same merits as the homogeneous line (distributed electrical parameters). Power lines can be considered as a long electric line [8]. This long line can be substituted by a two-port network as a π-element or T -element with distributed electrical parameters, or an electrical long line with parameters, which are the series specific resistance R_s, the series specific inductivity L_s, the parallel specific capacity C_s and the parallel specific leakage G_s. Validity of the described substitution is verified by the German Railways measurements [9]. Thereinafter, we obtain two general equations (1) and (2) for the homogeneous line with the distributed electrical parameters

$$-\frac{dU}{dx} = I\left(R_S + j\omega L_S\right), \tag{1}$$

$$-\frac{dI}{dx} = U\left(G_S + j\omega C_S\right). \tag{2}$$

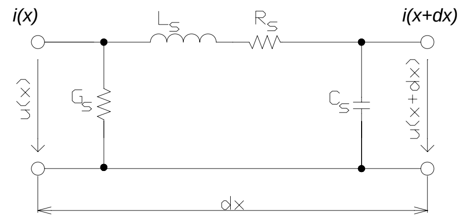

Fig. 2. Section of homogeneous line.

2.2 Substitution of the Power Supply Line

In this case, we preferably consider the 110 kV power supply line as the line with the inductivity L_s and the capacity C_s (i.e. the line leakage G_s and the line resistance R_s are ignored). The fact, which makes this simplification possible, is mentioned in [8]. The specific electrical parameters of the power supply line of 110 kV depend on the design and used materials of the line. Possibly, the capacity C_s can be also ignored, because an error can be assumed to be small. Hence, the line is substituted by one series inductivity with the value of L_{110} = 2 mH.

2.3 Substitution of the Contact Line

The contact line is the electrically homogenous line with the distributed electrical parameters, and can be presented as a long electrical line, see [9], [10], [11]. This assumption is true if sections of the contact line, which are outside of the railway station (i.e. open line), are longer in comparison with sections of the contact line of the railway station. The model of the homogenous line has also four parameters (Fig. 3): the series specific resistance R_{CL}, the series specific inductivity L_{CL}, the parallel specific capacity C_{CL}, and the parallel specific leakage G_{CL}.

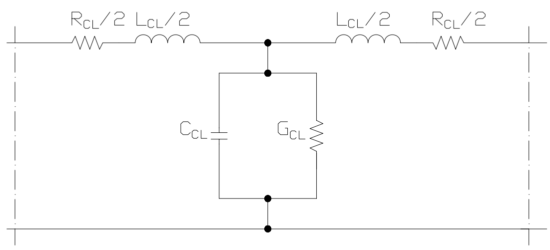

Fig. 3. Substitution diagram of the contact line.

The specific leakage G_{CL} of the contact line and the specific leakage G_{CL} of others lines, which are connected with the contact line, are left out in calculations. The reason is a very good isolation in the case of this contact line. This possibility is given by the properties of the used line insulators. The specific leakage gets very high values, see [12], [13].

The specific resistance R_{CL} and the specific inductivity L_{CL}, which depend on the frequency, enter into a calculation. Currents, which pass through a conductor, are pushed out on a conductor surface (i.e. skin-effect) by the increasing frequency. Then the useful section of the conductor (i.e. the effective section of conductor) is decreased and the specific resistance R_{CL} is increased. The current is decreased by skin-effect, so a loop area decreases, too. The specific inductivity L_{CL} decreases until the definite frequency, where it remains constant. The specific capacity C_{CL} is made by the capacity of all conductors that have the traction voltage. This capacity is measured between a returned line, which is represented by earth, and the contact line. Its numerical value will depend on the number of conductors, heights, external diameters and also configuration of neighboring of electrified railway track (such as tunnels, railway cuttings, railway embankments, stations).

The values for the substitution diagram of the lossy homogeneous line with the distributed electrical parameters of the contact line (i.e. 100 Cu + 50 Bz) are:

- The contact line length l_{CL} = 53.2 km;
- The series specific resistance R_{CL} = 0.4 Ω/km;
- The series specific inductivity L_{CL} = 1.0 mH/km;
- The parallel specific capacity C_{CL} =1 5 nF/km (without an intensive line);
- The parallel specific leakage G_{CL} ≈ S/km.

2.4 Substitution of the Traction Transformer

The 110 kV/27 kV traction transformer can be replaced only by one series inductivity L_{TT} in the area of energetic harmonics. The inductivity L_{TT} is given by the short-circuit voltage of the traction transformer and the series resistance R_{TT}, which represents active losses. The values of the alternate series inductivity depend on the used tap of the transformer because a transformer ratio can be a little bit different for each transformer. These transformers have a wide regulation range of the output voltage (i.e. 2 × 8 taps) which can be changed under power. Current harmonics pass through the traction transformer and they are changed only by the used winding ratio. The values for the traction transformer (nominal power 10 MVA) and short-circuit active losses (53 kW) are:

- The series inductivity L_{TT} = 24 mH;
- The substitute resistance R_{TT} = 0.39 Ω.

2.5 Substitution of the Filter-Compensation Equipment

The device of the Modřice feeding station was chosen for a FCE substitution diagram, see [14]:

<u>The 3rd harmonic LC branch:</u>

- The total capacity C_3 = 8.5 μF;
- The choke inductivity L_3 = 137 mH;
- The choke resistance R_{L3} = 1.43 Ω;
- The resonance frequency f_3 = 147.5 Hz.

<u>The 5th harmonic LC branch</u>

- The total capacity C_5 =2.4 MF;
- The choke inductivity L_5 = 169 mH;
- The choke resistance R_{L5} = 1.77 Ω;
- The resonance frequency f_5 = 249.9 Hz.

<u>Instrument voltage transformers</u>

- The substitution inductivity L_{TR} = 6079 H;
- The substitution resistance R_{TR} = 9945 Ω.

<u>Decompensation branch</u>

- The reducing transformer 27 kV/6 kV;
- The air-core choke;
- Decompensation branch at site 27 kV:
    - The total inductivity L_{DEC} = 0.596 H;
    - The resistance $R_{L,DEC}$ = 6.24 Ω.
- The phase controller COMPACT: its value of the control angle is calculated from the values of the instrument voltage transformer and instrument current transformer, for the values of power factor to be approximately DPF = 0.98. This value is measured in the connecting point of the feeding station and the 110 kV power supply line.

3. Simulation Results

3.1 Short-Circuits on the Contact Line at the Feeding Station

The circuit diagram for the analyzed effect is shown in Fig. 4 The contact line is represented as the open line. Short-circuits are made when the traction voltage is 38.9 kV (i.e. maximum).

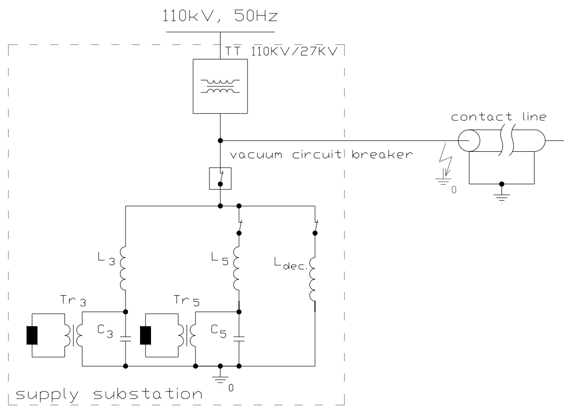

Fig. 4. Circuit diagram at short-circuit of the contact line at the feeding station.

The current in the contact line, marked as $I_{CL\_beginnig}$, comes out from the initial value of 9.8 A which represents the value of the capacitive current and passes through the contact line, see Fig. 5. The peak value of this current in the contact line is 146 A. Series inductivities of the contact line cannot be used at the shorted current due to their low values. The current is divided among parallel capacities. The total capacity of the contact line for the selected section of the contact line with l_{TV} = 53.2 km is C_{TVl} = 7.98^{-7} F. The initial value of the capacitive current is given by the value of 9.8 A for simulations. This value is higher than the value of 9.75 A given by the calculation. It is caused by an accuracy of simulation models.

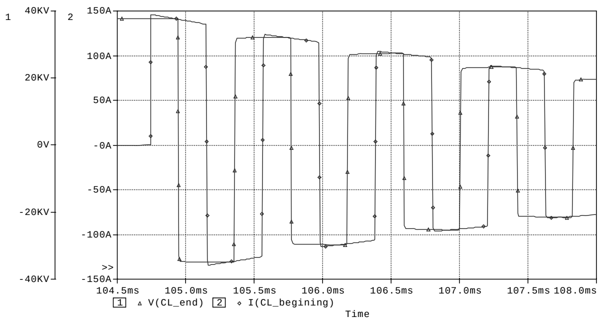

Fig. 5. The voltage waveform at the end of the contact line and the current waveform in the contact line after the short-circuit of the contact line at the feeding station.

The wave coming to the end of the contact line, which is not matched, is reflected. The time of passing wave (i.e. a delay time) to one direction for the selected section of the contact line (i.e. l_{TV} = 53.2 km) is given by the equation:

$$TD = l_{TV} \cdot \sqrt{L_{TV}.C_{TV}} = 206\ \mu s \tag{3}$$

where l_{TV} is the selected section length of the contact line, L_{TV} is the series specific inductivity of the contact line and C_{TV} is the specific capacity of the contact line.

The time of passing the wave in the contact line takes approx. 412 µs for both directions (i.e. from the beginning of the contact line to the end of the contact line and from the end of the contact line to the beginning of the contact line). The voltage at the end of the contact line, marked as VCL_end, comes out from the initial value of 38.9 kV. The voltage does not gain this value again. The whole effect fades after approx. 1.6 s.

The character of short-circuits and the passage time of the wave are the same for various type of FCE connection.

3.2 Short-Circuits at the End of the Contact Line

The circuit diagram for the examinant effect is shown in Fig. 6. The contact line is represented as the open line. Short-circuits are made when the traction voltage is 38.9 kV (i.e. maximum).

The current in the contact line, marked $I_{CL\_beginnig}$, comes out from the initial value of 9.8 A and its peak value gets 1.19 kA. It is shown in Fig.7.

The voltage at the beginning of the contact line, marked as $V_{CL\_beginnig}$, which comes out from initial value of 38.9 kV, is shown in Fig. 7. The voltage value gets 90.3 kV at the time approx. 620 ms, which depends on the section of the contact line (in this case 53.2 km), due to reflection of voltage surge at the end of the open contact line. Then the voltage falls consecutively.

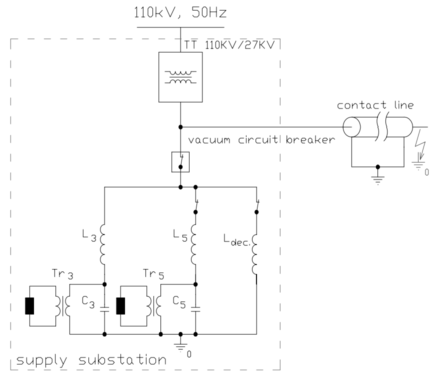

Fig. 6. Circuit diagram at short-circuit of the end of the contact line.

Theoretically, the peak values of voltage at the output of the feeding station can get triple of the peak value of the traction voltage (i.e. 116.7 kV). This value is given by triple of the time of the wave passage.

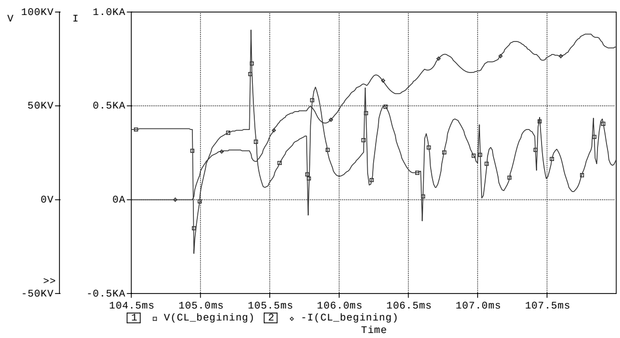

Fig. 7. The voltage waveform at the end of the contact line and the current waveform in the contact line after short-circuits on the contact line at the feeding station.

The contact line as a long line is ended by the inductivity, which is represented by the substitutional inductivity of the traction transformer L_{TT} = 24 mH. The internal impedance of the source (i.e. 38.9 kV) can be considered as zero impedance. This inductivity is seemed as the infinite impedance during few milliseconds. It is declared by [15].

The reflection of the wave on the impedance of the feeding station does not depend on the number of LC branches of FCE because the feeding station from the viewpoint of the contact line consists from parallel inductivities which are:

- The substitution inductivity of the traction transformer (L_{TT} =24 mH);

- The substitution inductivity the 3rd harmonic LC branch (L_3 = 137 mH);
- The substitution inductivity the 5th harmonic LC branch (L_5 = 169 mH).

The wave comes to the open end of the homogeneous line and is reflected with the same polarity as the original wave. The wave coming to the shorted end of the homogeneous line is reflected with the reversed polarity than the original wave. The reflected wave is of the same polarity and the same amplitude. After the short-circuit, it can be possible to suppose a constant value of voltage during few milliseconds at the feeding station.

The time of the wave passage is the sum of:

- The first passage time of the wave from the shorted end of the contact line to the feeding station;
- The second passage time of the wave from the feeding station to the shorted end of the contact line;
- The third passage time of the wave back to the feeding station.

4. Conclusion

The paper describes the solution of a part of a very complicated and complex problem. The solution required to solve short-circuits without building a physical model. Therefore the simulation program was chosen. The design of protections can be used for the feeding station design with or without a FCE. Simulation diagrams can be used as a main tool for a particular project of a feeding station of protection settings process from EMC point of view.

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