Short-circuits at 25 kV, 50 Hz contact line system of Czech Railways

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Abstract: The paper deals with the short-circuit analysis of 25 kV, 50 Hz contact line system at Czech Railways. The analysis respects the filter-compensation equipment installed at ČD supply substations. The results were obtained by the detail computer analyses of the individual traction circuits.

Key-Words: Filter-Compensation Equipment, Supply Substation, Harmonics, Transient Effect, Short-Circuit, Contact Line, Vacuum Circuit Breaker.

1 Introduction

Interference between electric equipments (i.e. electromagnetic compatibility) is discussed a lot at present. Thus Czech Railways need to use Filter-Compensation Equipment (FCE) into 25 kV, 50 Hz traction substations. This equipment is utilized for power factor corrections and to reduce current harmonics caused by electric locomotives with diode converters. FCE operations bring transient effects that are necessary to analyze. Therefore requirements to find a solution of the problem missing out at the present days were arisen.

The main objective is to explain transient effects which arise during real operating and failure states of traction supply system and also FCE. Firstly, detail analysis of traction circuit is carried out then design of these transient effects is conducted by computer simulation from which individual modeling traction circuit are designed. These tractional models present input data for simulations by PSpice version 9.1. Critical states are deduced from current and voltage knowledge which present simulative program output. Electric values gained by analysis of these states are used as input parameters for design of traction circuit protections.

This protection design is able to utilize for traction substation design with FCE. Simulation diagrams can be used as a main tool for particular project of traction substation with FCE of protection settings process.

2 Filter-Compensation Equipment

2.1 Reasons for using FCE at Czech railways

Harmonics are generated with rectifier by single-phase locomotives. Harmonics spectrum (i.e. harmonics numbers N), which depends on types of connection rectifiers, is formulated by equation:

$$N = (p \cdot n) \pm 1 \quad [-] \tag{1}$$

Where p ...... pulse number of rectifier $[-]$
n ...... integer number 1, 2, … n.

Locomotive is current harmonics source of all odd numbers which begin the 3rd harmonic component. Thus this locomotive can be considered as current generator of odd harmonics legitimately.

The harmonics flow through contact line, independently on impedance of external supply mains, and then they flow through series alternate impedance of supply transformer where are changed only by transmission ratio of this supply transformer. According to Ohm's law are originated voltage harmonics on input alternate impedance of external supply mains. Harmonic currents of various frequencies cause voltage drop on mains impedance and supply voltage deformation [1] and [2].

Direct results are especially
- Rise of network losses
- Drop of supply active power thereby efficiency drop

These direct results can bring the others problems at specific network configuration
- Creation of network resonance which usually produces raised current or voltage
- Faulty function of protections, measuring equipments and registering equipments
- Interference of telecommunication equipments and control circuits

2.2 FCE Charakteristics at Czech Railways

Requirements on FCE are given according to [3], [4], [5] and [6]:

- Adjust to inductive power factor of fundamental harmonic of traction consumption of single-phase locomotives to required value of contractor (i.e. $DPF = 0.95 - 1.00$ inductive) in connecting point of supply substation at guarantee of sufficient compensating power.
- Minimize to transfer of current harmonics of the 3rd, 5th number and perhaps even the 7th harmonic to corresponding components in voltage of connecting point of supply substation were under required values which are required by contractor.
- Guarantee to input impedance of supply substation as complex (i.e. including contact line capacity and traction consumption of single-phase locomotives) for system operating frequency of centralized ripple control of contractor was high than required value (i.e. prevent level drop of this operating frequency 216,67 Hz in connecting point of supply substation).

These conditions have to be realized in all traction load range of supply substation according to principle single-way supplying of contact line section.

Filter-Compensation Equipments are designed under above these conditions that way

FCE, which is shown (Fig. 1), contains two parallel series LC branches of the 3rd and the 5th harmonic with parallel connecting decompensation branch. LC branches tuning is not made on order number of harmonic exactly but it is made on low-order of value as $n_3 = 2.90 - 2.95$ and $n_5 = 4.98 - 5.00$. The requirement on sufficient total input impedance ($Z_{vstup} = 500 - 900\ \Omega$) for operating frequency f_{HDO} are realized by the suitable option of C_3 and C_5 values in branches this is to certify they are dependent on each other. The 5th harmonic LC branch is connected by disconnecting switch, thereby is carried out filtration requirement it has to be started at the lowest number of harmonic. FCE structure provides addition of the 7th harmonic LC branch.

Decompensation branch includes reducing transformer, thyristor phase controller and decompensation chokes. Decompensation is made by decompensation choke which is controlled. Thus control is realized with inductive power factor $DPF = 0.98$ of input power which is measured in connection point supply substation. Creation of additional harmonics (i.e. primarily the 3rd harmonics) into voltage of 27 kV busbar is raised by partial controlling of controller of decompensation branch. Sum of both the 3rd harmonics controller and network would be got to congestion of the 3rd harmonic LC branch. Thus LC branch tuning for FCE is made under frequency 150 Hz.

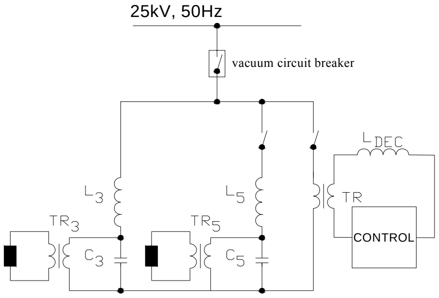

Fig. 1: FCE connection diagram

3 Configuration 25 kV, 50 Hz traction supply system

General configuration 25 kV, 50 Hz traction supply system at Czech Railways is done by [7]:

- Supply line 110 kV from contractor
- Supply substation
- Contact line

4 Transient effects solution

Transient effects are analyzed at linear systems, so that we usually solve equations system which describes following effect. It was necessarily to avoid building of physical model which would be high financial-intensive or lost of process monitoring ability and behaviour of circuit at operation conditions at solution of transient effects. Thus it was chosen simulation program PSpice (ver.9.1). This program utilizes substitution diagrams of simple connections of traction circuit as input data. These diagrams are made from substitution models of simple elements of traction circuit.

Now it is necessarily to say about the main disadvantage of computer simulation which is opposite of advantages. The program does not work with real elements but it works with models, so results can be as exact as exact elements models and describe only the effects which present using models. Creation of quality models, which represent real devices well, is the most important and the most complicated problem of simulations of electronical circuits. The simulators can describe external fields effect (e.g. electromagnetic field, thermal field), especially inhomogeneous fields, only in limiting rate.

4.1 Substitution of homogenous line by two-port network

Supply line and contact line have the same character of homogenous line with distributed electrical parameters and they can be considered as long electric line, see [1]. This long line can be substituted two-port network as π-element or T - element with distributed electrical parameters or electrical long line with parameters which are:

- Series specific resistance R_s $[\Omega \cdot km^{-1}]$
- Series specific inductivity L_s $[H \cdot km^{-1}]$
- Parallel specific capacity C_s $[F \cdot km^{-1}]$
- Parallel specific drop G_s $[S \cdot km^{-1}]$

Validity of substitute is cited in [8]. Thereinafter hold generally two general equations (2) and (3) for homogenous line with distributed electrical parameters, see (Fig. 2).

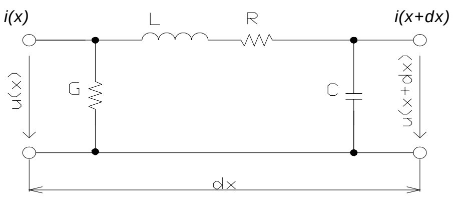

Fig. 2: Section of homogenous line

$$-\frac{dU}{dx} = I(R + j\omega L) \qquad (2)$$

$$-\frac{dI}{dx} = U(G + j\omega C) \qquad (3)$$

4.2 Substitution of Supply line

In this case it is preferable to respect 110 kV supply line as line with inductivity L_s and capacity C_s (i.e. ignored line drop G_s and line resistance R_s). The fact, which is given this simplification, is that mention specific electrical parameters of supply line depend on construction and used materials of line largely, see [1]. Capacity C_s can be also possible ignored because error would not assume great values. Substitution of supply line is converted on one series inductivity with value $L_{110} = 2\ mH$.

4.3 Substitution of contact line

Contact line is elecrical homogenous line with distributed elecrical parameters and it can be presented as long elecrical line, see [9] and [10]. This precondition can be taken because sections of track contact line are longer in comparison with sections of station contact line. Model of homogenous line, see (Fig. 3), with four parameters which are:

- Series specific resistance R_{CL} $[\Omega \cdot km^{-1}]$
- Series specific inductivity L_{CL} $[H \cdot km^{-1}]$
- Parallel specific capacity C_{CL} $[F \cdot km^{-1}]$
- Parallel specific drop G_{CL} $[S \cdot km^{-1}]$

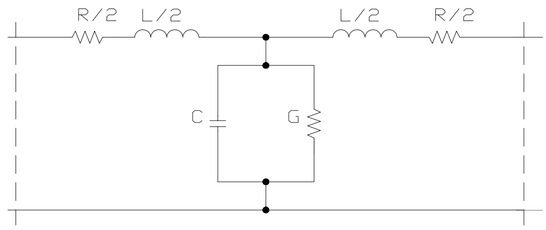

Fig. 3: Substitution diagram of contact line

Specific drop G_{CL} of contact line and specific drop G_{CL} of others lines, which are connected with contact line, are left out by calculations because it has very good isolation in the case of contact line. This possibility is given properties of using line insulators and elimination of possibility of their surface pollution by ending of stream traction, so specific drop runs into very high values and enables simplification; see [11] and [12].

Specific resistance R_{CL} and specific inductivity L_{CL}, which are frequency dependent, are come in by calculation. Current, which flows through conductor, is pushed out on conductor surface (i.e. skin-effect) by rising frequency. Then useful section of conduction (i.e. effective section of conduction) is dropped and specific resistance R_{CL} is risen. Current, which depths to earth, is decreased by skin-effect, so loop area decreases too and specific inductivity L_{CL} drops until definite frequency, where it stays constantly. Specific capacity C_{CL}, which is made by capacity of all conductors have traction voltage, is measured up returned line which is represented earth largely. Its numerical values will depend on number of conductors, their height, their external diameter above all and also configuration of neighbourhood of electrified railway track (tunnel, railway cutting, railway embankment, station etc.).

Values for substitution diagram of losses homogenous line with distributed elecrical parameters of contact line (i.e. 100Cu + 50Bz) are:

- Contact line length $l_{CL} = 53.2$ km
- Series specific resistance $R_{CL} = 0.4\ \Omega \cdot km^{-1}$
- Series specific inductivity $L_{CL} = 1.0\ mH \cdot km^{-1}$
- Parallel specific capacity $C_{CL} = 15\ nF \cdot km^{-1}$ (without intensive line)

- Parallel specific drop $G_{CL} = 0\ S \cdot \mathrm{km}^{-1}$

4.4 Substitution of 110 kV / 27 kV transformer

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

- Series inductivity $L_{TT} = 24\ mH$
- Substitute resistance $R_{TT} = 0.39\ \Omega$

4.5 Substitution of Filter-Compensation Equipment

Device of supply substation Modřice was chosen for FCE substitution diagram, see [13]:

The 3rd harmonic LC branch

- Total condenser capacity $C_3 = 8.5\ \mu F$
- Resonance choke inductivity $L_3 = 137\ mH$
- Choke resistance $R_{L3} = 1.43\ \Omega$
- Inherent resonance frequency $f_3 = 147.5\ Hz$

The 5th harmonic LC branch

- Total condenser capacity $C_5 = 2.4\ \mu F$
- Resonance choke inductivity $L_5 = 169\ mH$
- Choke resistance $R_{L5} = 1.77\ \Omega$
- Inherent resonance frequency $f_5 = 249.9\ Hz$

Instrument voltage transformers

- Substitution inductivity $L_{TR} = 6079\ H$
- Substitution resistance $R_{TR} = 9945\ \Omega$

Decompesation branch

- Reducing transformer 27 kV/6 kV, type output 4200 kVA.

Devices connect to secondary winding of reducing transformer

- Air-core choke, we receive decompensation branch total inductivity at site 27 kV $L_{DEC} = 0.596\ H$ and decompensation branch resistance $R_{L,DEC} = 6.24\ \Omega$ with supply section $l_{CL} = 53.2$ km in the case device of supply substation in Modřice.
- Phase controller COMPACT, its control angle is calculated from values of instrument voltage transformer and instrument current transformer, so in order to values of power factor was c. $DPF = 0.98$ in connecting point of supply substation of line 110 kV. General substitution diagram of traction circuit for simulation is made from substitution values.

5 Short-circuits

5.1 Short-circuits at the end of contact line

Diagram of circuit is shown (Fig. 4) for examinant effect. Contact line is represented as open line. Short-circuits is made by traction voltage maximum.

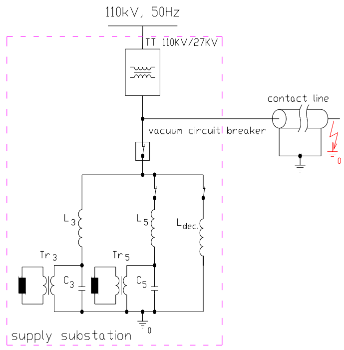

Fig. 4 Traction circuit diagram by short-circuit at the end of contact line

Voltage at the begin of the contact line section, which come out from initial values 38.9 kV, is shown in (Fig. 5). Traction line as a long line is terminated inductivity, which is represented substitutional inductivity of traction transformer $L_{TT} = 24\ mH$, at supply substation. Internal impedance of source (38.9 kV) can be considered as zero impedance. This inductivity is seemed as infinite impedance during orders time milliseconds, it is declared by [14]. Wave comes to the open end of the homogenous line it reflects with the same polarity as original wave. Wave comes to short-circuit end of homogenous line is reflected with reversed polarity than original wave. After short-circuit, it can be possible to suppose constant value of supply voltage during orders time milliseconds at supply substation which has amplitude 38.9 kV as trolley voltage.

Coefficient of reflection wave is defined by equation, see [1]

$$k = \frac{Z_{0,2} - Z_{CL1}}{Z_{0,2} + Z_{CL1}} \; [-] \qquad (4)$$

Where Z_{CL1} . impedance of line $[\Omega]$

$Z_{0,2}$ .. impedance ending element $[\Omega]$.

For short-circuited line i.e. $Z_{0,2} = 0$ is $k = -1$; Reflection wave has reversed polarity and the same amplitude.

For open line i.e. $Z_{0,2} \cong \infty$ is $k = 1$; Reflection wave has the same polarity and the same amplitude.

Existence of FCE does not assert in voltage image at supply substation output by short-circuit conditionals at the end of open contact line. Reason is substitutional inductivity of LC branch of FCE has high values which is connected to substitutional conductivity of traction transformer.

Current in contact line comes out from initial value 9.8A and peak value gets 1.2 kA. It is represented in (Fig. 5).

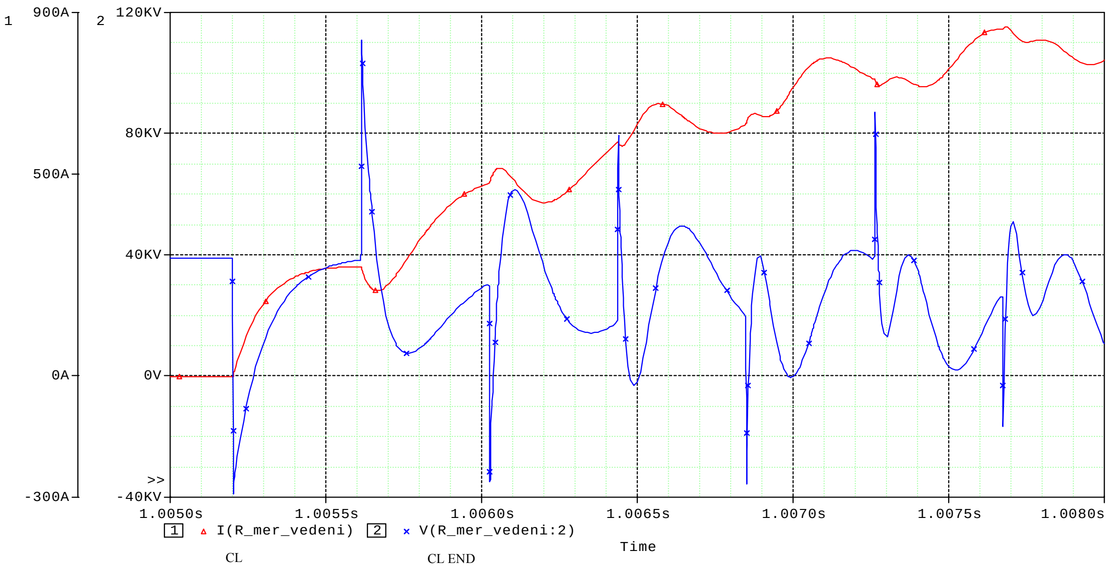

Fig. 5: Current waveform in contact line and voltage waveform at the end of contact line after short-circuits on contact line at supply substation

6 Conclusion

<u>Short-circuits on contact line at supply substation</u>

- Character of short-circuits and passage time of wave are the same for various type of FCE connection
- Current in contact line comes out from initial value 9.8A and peak value gets c. 168 A, then current falls consecutively. Effect subsides after c. 1.6 s.
- Voltage at the end of contact line section come out from initial values 38.9 kV and peak value gets c. 43.1 kV due to reflection of wave at the end of open contact line then voltage drops consecutively. Reflection of wave is got at the end of open contact line because this contact line are not mismatching. Passage time of wave takes c. 412 μs both directions (i.e. from begin of contact line to end of contact line and from end of contact line to begin of contact line) in contact line. Effect subsides after c. 1.6 s.

<u>Short-circuits at the end of contact line</u>

- Peak values of voltage at supply substation output can be got tree times of peak value of traction voltage.
- Instant of origin time, which can be triple of peak values of traction voltage theoretically (at neglect contact line loss), is given by tree times of passage time of wave which depends on length of contact line.
  - o First passage time of wave from short-circuited end of contact line to supply substation,
  - o Second passage time of wave from supply substation to short-circuited end of contact line,
  - o Third passage time of wave back to supply substation.

- Reflection of transient wave on impedance of supply substation does not depend on number of LC branches of FCE because supply substation from viewpoint of contact line consists from parallel inductivity which are
  - Substitution inductivity of traction transformer ($L_{TT} = 24\ mH$)
  - Substitution inductivity the 3rd harmonic LC branch ($L_3 = 137\ mH$)
  - Substitution inductivity the 5th harmonic LC branch ($L_5 = 169\ mH$)
- Current in contact line comes out from initial value 9.8A and peak value gets 1.2 kA.
- Voltage at the begin of contact line section come out from initial values 38.9 kV and peak value gets c. 104 kV in time c. 620 ms which depends on contact line section (in this case 53.2 km) due to reflection of wave at the end of open contact line then voltage falls consecutively.

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