Simulation of electrical power supply system in railway infrastructure

An integration with rolling stock in Sweden

Emilio Rodríguez Martínez, Diego Galar Pascual
Division of Operation, Maintenance and Acoustics
LTU (Luleå University of Technology)
Luleå, Sweden
emilio.rodriguez@ltu.se, diego.galar@ltu.se

Nava Raj Karki
Department of Electrical Engineering
T.U. (Tribhuvan University)
Kathmandu, Nepal
nrkarki@ioe.edu.np

Stefan Niska
Trafikverket
Luleå, Sweden
stefan.niska@trafikverket.se

***Abstract*—A Matlab model of the electrical power supply system of a 15 kV AC and 16.7 Hz, the most common in the Swedish railway infrastructure, is proposed. Within the validated models of rolling stock and infrastructure an integrated model is implemented. The train can be integrated in different position of the track to verify the behaviour of the supply system from an electrical point of view. Its output can be also used as an input for a design of an electromagnetic model in high frequencies. Specifically, our aim is to identify how the rolling stock and infrastructure, mainly in the low frequency, affects to other components due to the harmonic currents on the track. In a first approach the model is only intended to cover stationary conditions, not transients. After the design of the model, a measurement campaign in the north of Sweden to validate the model was carried out and compared with our results. These measures were also used in the implementation of a real source.**

Index Terms— Railway, power supply, EMI impact, train operation.

I. INTRODUCTION

The specification of power supply characteristics is based on the physical layout of the route, the location of the passenger stations, the topography of the track route including the curves to be encountered and their physical characteristics. This information together with the required acceleration and speed of the train as a function of position along the track can be used to determine the tractor effort requirement of the train as a function of position.

Different operating scenarios are assumed starting with the number of trains per hour to run, in what station a train should stop, what are the speed limits at various lengths of the route, the required acceleration and deceleration, and so on. All these acts are to determine location of the trains at any instant of time. Having those snapshots, the concerned engineer determines the power requirements at the different points on the tracks (where the trains are). This information provides the interface between the overall system and the power supply system energizing the trains. The specifications of the electrification system constitute a subset of the overall specifications, for example, voltage specifications are specified by international standards such as BS EN 50163 [1] and IEC 60850 [2].

The international railway community always aspires to explore any possible common consensus between the requirements of individual country and the wider generic phenomena capable of causing similar interactions in all the member countries. Existing assessments may be narrowly defined or even be specific to a single train or infrastructure component.

Directive 2008/57/EC on the interoperability of the railway system within the European Community [3] defines the railway as a series of subsystems:

- Infrastructure
- Control command and signaling
- Power
- Rolling stock
- Operation and traffic management
- Maintenance
- Telematics.

However, the national railway system in every country consists of two physical parts: the static part (infrastructure, control command and signaling and power) and the mobile part (rolling stock, telematics).

All this subsystems must be independent on the power supply and can be tested in our model.

Regarding the first one, it is needed to study the capacity and number of Auto Transformers (AT) and converters. The power requirement of each train on each track and the location of each train is calculated using the speed and the traction effort and therefore capacity and number of the power supply units is established in order to fulfil the demand of the vehicles.

The power lines are the ten wires detailed in the next sections. In few literatures, the messenger wire and the catenary wire are called the catenary system or the Overhead Catenary System (OCS). The rails are used as return conductors also. The configuration of the system specifies the coordinates, material and diameter of each conductor (horizontal and vertical distances, usually from the centre of the track) and also what type of conductors are to be used.

On the other hand, the mobile part can be further sub-divided into two categories defined by its power source; electric or non-electric. The electrically powered mobile part must comply with all the physical requirements of the non-electric mobile part e.g. gauge, loadings, platform height and so on but must also be compatible with the electrical systems. Unlike the physical aspects, the electrical aspects do not have an easily defined or constrained interface with the rest of the world and hence they are potentially more difficult to assess. The rolling stock electromagnetic emissions are a major concern for train manufacturers and railway infrastructure operators [4] in Europe and elsewhere.

This situation causes waste of time and resources for train manufacturers when integrating rolling stocks and signalling systems. And with tested trains in use, problems may still arise occasionally. Then, the technical solutions are not straight forward. The duration of the field testing employed to solve this kind of problems and to go through the certification process may vary between 3 months and 12 months costing between 25 k€ to 1.5 M€ [4]. Further, the railway infrastructure operators suffer the railway infrastructure availability reduction caused by the rolling stock electromagnetic incompatibility with the safety critical signalling systems and may cause an estimated reduction of 10% of the availability in the most crowded lines. [5]

II. GENERIC SCHEMATIC DIAGRAM

Our model corresponds to a track section from the exit of the converter to the end of one single track line, the most typical case in Sweden. See Fig. 1 and Fig. 2.

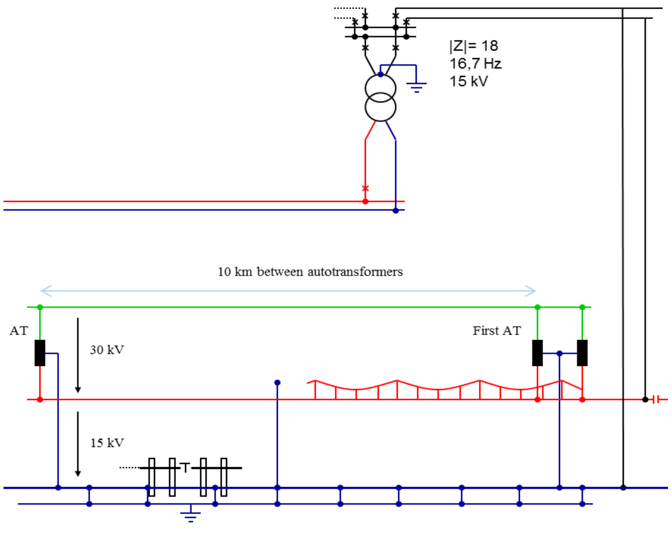

Figure 1. Power supply system from the exit of the converter to the end of the track.

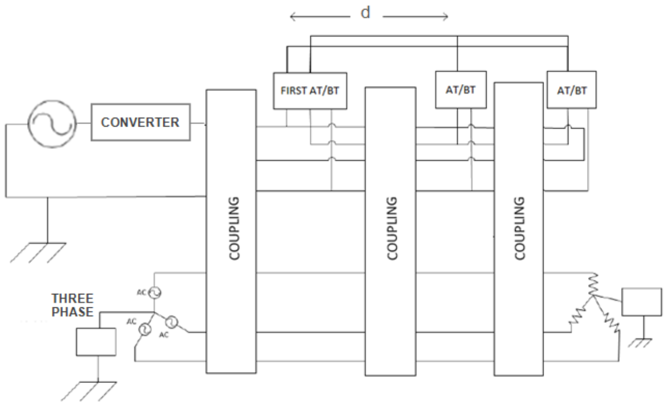

Figure 2. Generic schematic diagram valid for most of the power supply system railway infrastructures.

A typical AC railway power feeding system receives the electricity supply at the substation. For technical reasons, like feeding reliability, protection, rotation of phases, and so on, any feeding section is isolated from the others and supplied with only one power substation/converter. A feeding section is 100 kilometres long maximum to ensure its correct performance. Conventionally, the power substation/converter is connected to the feeder transformers 10 kilometres apart from each other to ensure the power supply to the transmission lines. These cables feed the system and run along the tracks hanged from the poles.

A generic simplified schematic diagram valid for most of the power supply system railway infrastructures is shown below.

The main blocks in all infrastructures are: the converters, the transformers (AT or BT) and the transmission lines with their couplings.

The Swedish railway supply is a catenary/pantograph system at 15 kV AC and 16.7 Hz and the rail is connected to ground. The transformer mostly used is the BT (Booster-Transformer), but in all new lines that are building in Sweden it is only the AT (Auto-Transformer) that is used, with a distance around 10 km between them.

The required data for this model is:

Distances: Between poles, transformers, converters and connections of the rail to ground.

Converter: Input and output frequencies and voltages as well as the R and L in series with this source.

Transformer: Operating power, voltages and frequency. Regarding the losses, it is necessary to specify the power losses obtained from the open circuit test and short circuit test, the voltage drop obtained from short-circuit test and the magnetization current from open circuit test. It is important to obtain the contact impedances and impedances of the AT.

Transmission lines: Voltage levels, coordinates in the pole, shapes/diameters and electrical data, as material conductivity.

As commented in the introduction, a Matlab model of the train, Fig. 3, can be integrated in any point of the track between rail and catenary to run the simulation and get the resulting signals of the integration.

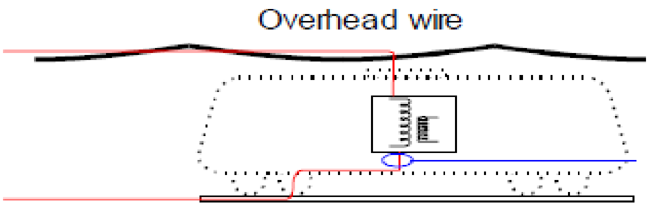

Figure 3. Schematic diagram of the train.

III. MODELLING OF THE DIFFERENT MAIN BLOCKS.

A. Converter

The function of the converter it to transform the domestic supply (3 phases, 50 Hz, 70 - 220 kV) to the railways supply (1 phase, 16.7 Hz, 15 kV).

As it will be shown in the description of the pole and the transmission lines in the Table 3, there is a positive and a negative feeder and the electric potential is 30 kV voltage. A first good approximation of the converter was a linear transformer with -15 kV and 15 kV, but after the measurement campaign we could reproduce a customized source. This customized source was produced by means of the Fourier series of the superposition of the 8 first harmonics of those signals, given in Tables 1 and 2. The Fig. 4 and Fig. 5 show the commented measures performed in the Swedish railway infrastructure.

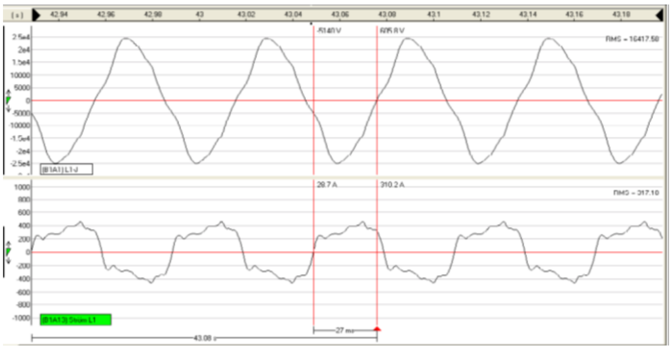

Figure 4. Phase shift between the voltage and the current measured in Swedish railway power supply system before the converter with the train in the track.

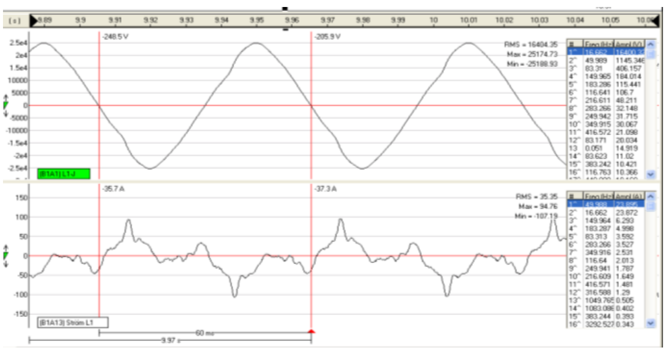

Figure 5. Phase shift between the voltage and the current measured in Swedish railway power system before the converter without train in the track.

Table 1. Amplitude and phase of the harmonics in current.

Harmonic Overtones (16.7 Hz)	Amplitude (mA)	Phase(Degree)
1x	427.91	249.45
2x	0.24	297.95
3x	11.48	77.39
4x	0.31	166.48
5x	42.17	209.13
6x	0.49	260.18
7x	25.53	11.10
8x	0.61	337.60

Table 2. Amplitude and phase of the harmonics in voltage.

Harmonic Overtones (16.7 Hz)	Amplitude (V)	Phase(Degree)
1x	28900.00	94.78
2x	23.79	148.58
3x	2000.00	133.32
4x	14.00	316.82
5x	874.12	221.14
6x	2.46	52.27
7x	156.50	334.00
8x	3.46	337.60

Fig. 6 and Fig. 7 show the differences between the original sources and the simulated sources, for current and voltage respectively with the train in the track.

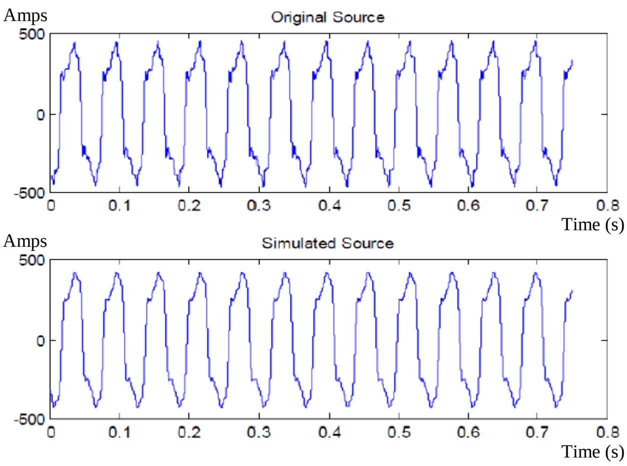

Figure 6. Measured and simulated current comparison.

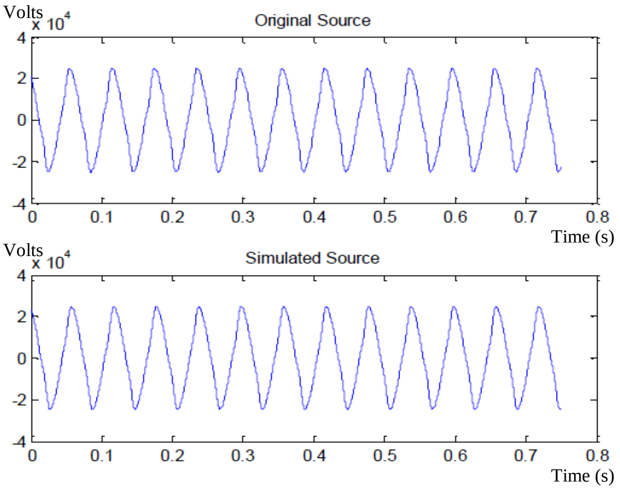

Figure 7. Measured and simulated voltage comparison.

B. Transformers

They are used to assure the power supply to the transmission lines. As the Auto-Transformers are used in the Swedish railway infrastructure, it is relevant to present the equivalent electrical circuit used to model the auto transformer as shown in the Fig. 8.

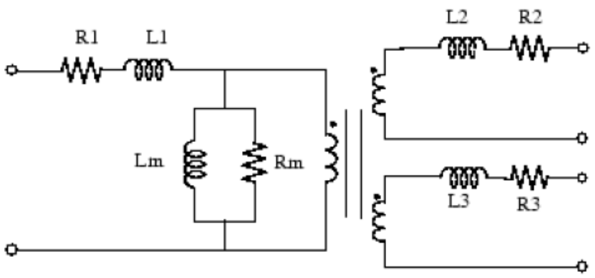

Figure 8. Electric circuit diagram of the autotransformer.

For the calculation of its values it was designed the Matlab application Auto-Transformer Parameter Calculator, Fig. 9.

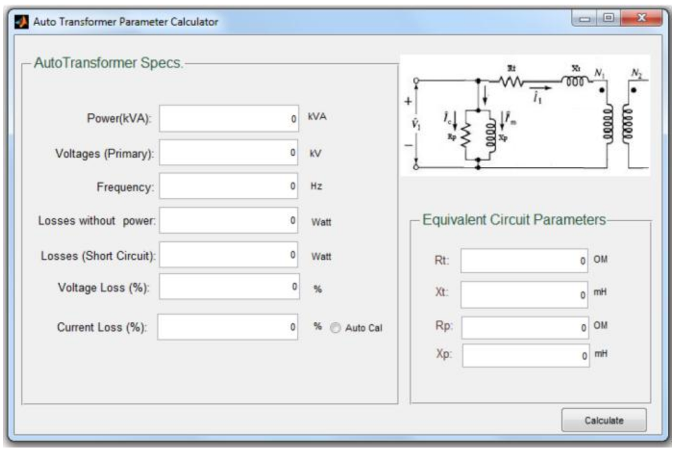

Figure 9. Matlab implementation for the calculation of the autotransformer parameters.

This application performs the computing necessary to calculate the equivalent parameters of the Auto-Transformer. The inputs for this code are the next characteristics of the Auto-Transformer: power, voltage in the primary, frequency, losses without power, losses in short circuit, the voltage loss and the current Loss. And the outputs are the equivalent parameters for a two-coil transformer within the next characteristics:

$$R_t = \frac{Losses\ (Short\ circuit) x\ Voltage^2}{500\ x\ Power^2}\ [\Omega] \quad (1)$$

$$X_t = 1000\ x\ \frac{\frac{Voltage\ Loss\ x\ Voltage^2}{100\ x\ Power}}{2\ x\ \pi\ x\ Frequency}\ [mH] \quad (2)$$

$$R_p = \frac{Losses\ without\ power}{500\ x\ Voltage^2}\ [\Omega] \quad (3)$$

$$X_p = 1000\ x\ \frac{\frac{Current\ Loss\ x\ Power}{100\ x\ Voltage^2}}{2\ x\ \pi\ x\ Frequency}\ [mH] \quad (4)$$

C. Coupling between transmission lines

The catenary system represents the messenger wire and the contact wire. The contact wire (the wire touching the pantograph) should be as horizontal as possible so that the contact pressure between the contact wire and the pantograph is more or less uniform. However, a wire supported at the two ends on poles will assume a catenary shape represented by hyperbolic function. Hence, a wire, called the messenger wire is supported at the two ends at the poles with the help of insulators and the contact wire is attached to the messenger wire by hangers of varying lengths to keep the contact wire as horizontal as possible. Figure 11 shows a schematic diagram of a Swedish pole with ten conductors in a single track configuration. For greater accuracy, each wire is modelled separately and no bundling of conductors was performed.

This single track has been modelled as a black box that comprises of all conductors between two poles (60 m. distance) and represented as a 10 inputs / 10 outputs system where the lines are interacting according to coupled inductions and mutual capacitances. In the case of the transmission lines, it is needed to model the coupling between them. Fig. 10 shows the block which represents this coupling between the transmission lines from one auto-transformer to the next one.

The mutual impedances have been calculated using readily available formula and presented in the tables below. To model the line in SimPower, the mutual inductance element is used.

The image method was used to calculate these parameters with a the image at a distance h below the rails' level of 1 meter, so it can be assumed that under h the electrical ground is really zero.

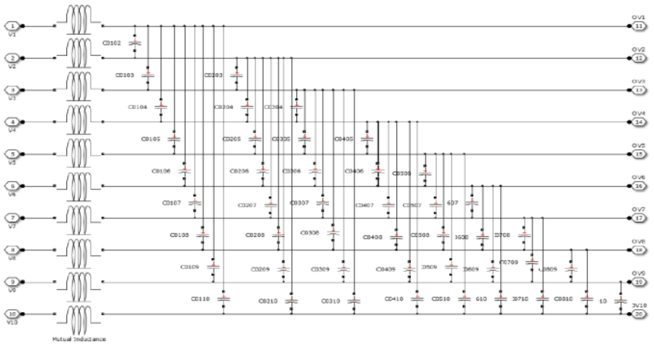

Figure 10. Detail of the coupling block.

On the other hand, proposed design is based on 'The Bothnia Track' design [6], with the characteristics of the cables and rails numbered in the Fig. 11 are detailed in the Table 3.

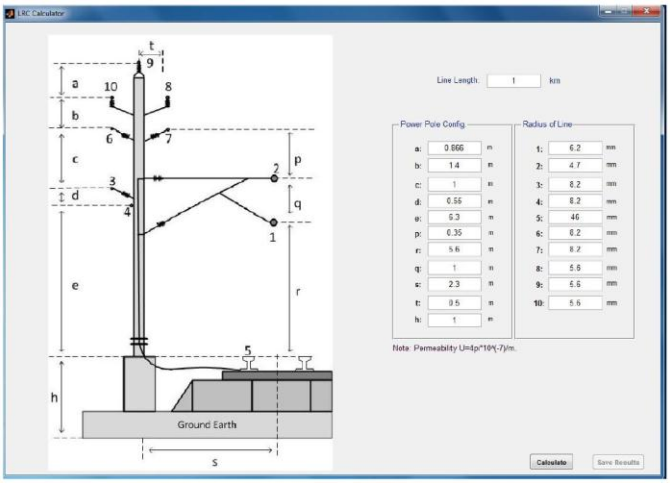

Figure 11. Matlab application for the calculation of the coupling between transmission lines.

Table 3. Characteristics of the transmission lines.

Conductor Number/ Voltage frequency	**X, mm**	**Y, Mm**	**Area, mm²**	**Radius, mm**	**Material/ conductivity, 10^6 S/m (theoretical values)**
1 catenary +15kV, 16.7 Hz	3000	5600	120	6.2	Cu 57
2 Carrier line +15kV, 16.7 Hz	3000	7300	70	4.7	Bronze 28
3 Neg. feeder -15kV, 16.7 Hz	-600	6850	212	8.2	Al 28.5
4 Return line Ground	-210	6300	212	8.2	Al 28.5
5 "Single rail"	3000	0	6648	46	Fe(steel) 8.5
6 Neg. feeder -15kV, 16.7 Hz	-600	7850	212	8.2	Al 28.5
7 Support Feeder +15kV, 16.7 Hz	600	7850	212	8.2	Al 28.5
8 Top feeder 22kV, 50 Hz	500	9250	99	5.6	FeAl 31
9 Top feeder 22 kV 50 Hz	0	10116	99	5.6	FeAl 31
10 Top feeder 22 kV 50 Hz	-500	9250	99	5.6	FeAl 31

Finally we need the impedance of each transmission line to build the resistance matrix directly with the real part of the impedance and the inductance matrix as follows.

The catenary has impedance: 0.125 + j0.343 Ω/km [7]. The resistance is directly 0.125 Ω/km and assuming the frequency 16.7 Hz it is possible to obtain an inductance of 3.3 mH/km by means of the following formula:

$$L_{ii} = \frac{Im(z)}{2\pi f} \quad , \tag{5}$$

where Im(z) represents the electrical inductive reactance and f the frequency 16.7 Hz.

In the case of the rail the resistance is R = 4.976 Ω/km and the self-inductance L = 0.964 mH/km and so on.

It is taken a distance of 10 km between Auto-Transformers and a distance of 450 km from the power source to the converter.

Using the multi-transmission line (MTL) method, the mutual inductance for any pair of transmission lines i and j can be calculated with the next formula:

$$L_{ij} = \frac{\mu_0}{2\pi} \ln \frac{D_{ij}}{d_{ij}} \quad , \tag{6}$$

where $\mu_0 = 4 \times \pi \times 10^{-4}$ H / km, D_{ij} the distance from the line i to the image of j and d_{ij} the distance from the line i to the line j. The mutual capacitance can be obtained from (6) as:

$$C_{ij} = \frac{1}{c^2 L_{ij}} \quad , \tag{7}$$

where $c = 3 \times 10^8$ m/s and L_{ij} the mutual inductance.

As in the case of the Auto-Transformer, a Matlab program was designed for the calculation of the mutual inductances and capacitances. A screen shot of the application is shown in the Figure 11.

IV. Complete MATLAB Model

The whole infrastructure system can now be represented by a single model taking into consideration that series configuration of the blocks corresponding to the cable will come out as an accurate version of the real catenary system.

The distance between the converter and the end of the line depends on the number of 10 km long coupling blocks integrated in the model. In between, several auto transformers can be found to feed the corresponding sections. These track sections have cable sets (10 input/outputs boxes) connected in series configuration (each box corresponds to 60 meters as a distance between poles).

The train model is added to the infrastructure model as a subsystem with two ports. One of the ports is connected to our catenary and the other one to our rail as a real train in the line.

The proposed railway infrastructure system modelled with Simulink offers the flexibility of integration of train anywhere along the track. The train is a harmonic current source which connects the catenary with the rails. So, the integration of the train model introduces new harmonics to this feeding frequency. This enables the system to check different scenarios when the train is close or far to the transformer with the minimum transferred power. It also allows simulating the worst scenarios for transmission lines in terms of signal propagation.

The accuracy of the integrated model is such that the train can be allocated anywhere between two poles, but the train being an active load will unfortunately contaminate the power line with harmonics. One very important verification test was to check the validity of the model for the idle currents in the absence of the train.

As it can be seen in Fig. 6 and Fig. 7, the similarities in both signals partially verifies that the model reproduces real condition in absence of active load what creates optimum initial condition to introduce the rolling stock as a subsystem of the overall railway system.

Once the train load is connected, the signals (power supplied by the converter) are entirely different and there is an obvious phase shift of 180 degrees between the voltage and current. Measured and simulated signals don't differ significantly and, therefore, the model can be assumed to be valid under certain boundary conditions.

The outcomes of this integration will be the different power signals produced by the presence of the train in different position along the track. This dynamic response containing harmonics and high power consumption will produce some undesired effects in the surrounding areas affecting electronics systems and components that can be affected from electromagnetic field as a consequence of radiated emissions produced by these conducted signals.

Therefore, the previously described model exhibits the capability to replicate the conducted emission along the track in the power systems. The conducted emission may be potentially dangerous for the safety of signalling systems and other electromagnetically sensitive components, apertures and systems.

V. Conclusions

The paper proposes a model of the power supply system in the Swedish railway infrastructure to integrate a train as an active load to carry out simulations. The implementation of the models of the rolling stock and the infrastructure were independently implemented and validated.

The infrastructure model has been tested in presence and absence of train and logical results seem to be achievable. Idle currents when empty track and reactive loads when train is present may validate the assumptions made in the model. External factors like meteorological conditions may produce anomalies in the model; therefore, system robustness should be tested regarding these issues in a future work.

This influence is more relevant in the starting of the train in the presence of another train in the same section and different track (uncommon in the Swedish infrastructure which is typically a single track system) or with the occurrence of undesired events which produce external signals, as the strike of a lightning close to the track. These events are very seldom, but the impact on the performance of the infrastructure is relevant.

Acknowledgment

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