A Simulation Tool for the Design of the Electrical Supply System of High-Speed Railway Lines

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Abstract-The design of the electrical supply system of high-speed railway lines involves the selection of the single phase system (one or two active conductors: 1x25kV or 2x25 kV), the design of the catenary, and the location and sizing of the substations and the autotransformers in case of a 2x25 kV system. The electrical system should be designed so the train voltages are in the admissible range and the conductor currents and transformer powers are smaller that their rated values. This paper presents a simulation tool for the design of the electrical supply system of high-speed railway lines. The tool is composed of two main modules: (1) the simulator of the railway line and (2) the electrical system simulator. The railway line simulator determines the position and power consumption of each train at each time step provided the line operation policy. The electrical system simulator solves the AC network at each time step and provides the catenary and train voltages, the conductor currents and the transformer power flows.

Keywords- high-speed railways, electrical supply system, traffic simulator, electrical simulator.

I. INTRODUCTION

The development of high-speed railway lines starts in France at the beginning of the 80's when the line Paris – Lyon was opened [1] (the first section Lyon – St. Florentin was opened in 1981 and the full line Paris - Lyon was opened in 1983). The French developments have been followed by other ones in Germany, Italy and Belgium.

The first Spanish railway line (Madrid – Seville) was opened in 1992. It is approximately 450 km long, the nonstop trip takes 2:30 hours and the trains travel at a maximum speed of 300 km/h. The technical and economic success of that line has encouraged the Spanish government to start new projects: Madrid – Barcelona – French border (800 km), Madrid – Valencia (350 km) and Madrid – Valladolid (200 km). These projects are also supported by the European Union under the framework of the Common Transportation Policies. The line Madrid - Barcelona – French border is currently under construction. The different sections will be progressively opened in the next years: Madrid – Lleida (450 km) in 2002, Lleida – Barcelona (200 km) in 2004 and Barcelona – French Border (150 km) in 2006. This line has been designed to allow a commercial speed of 350 km/h (which means top speeds up to 385 km/h) so the trip Madrid – Barcelona will take 2:30 hours.

The main components of a high-speed railway line are (i) the civil work, (ii) the electrical supply system, (iii) the control system and (iv) the rolling stock. This paper presents a simulation tool of the electrical supply system of railway lines oriented to its design.

The paper is organized as follows. Section II describes the typical configurations of the electrical supply system of high-speed railway lines. Section III formulates the design problem: design variables and constraints to be considered. Section IV overviews the simulation tool. Section V and VI describe respectively the two main components of the tool: the traffic simulator and the electrical simulator. Section VII illustrates the capabilities of the tool. Section VIII offers the conclusion of the work.

II. ELECTRICAL SUPPLY SYSTEM OF HIGH-SPEED RAILWAYS

The electrical supply system of a high-speed railway line provides electric power of the desired characteristics (AC, single phase, 25 kV) to the trains from the high-voltage network. The main components of the system are the catenary and the substations that feed the catenary from the high-voltage network. Fig. 1 displays a typical configuration of the system. Each transformer is connected to two phases of the three-phase system. Each section of the line is independently fed by a traction substation. In case that a substation is out of service, the adjacent substations respectively feed the two parts of the corresponding section.

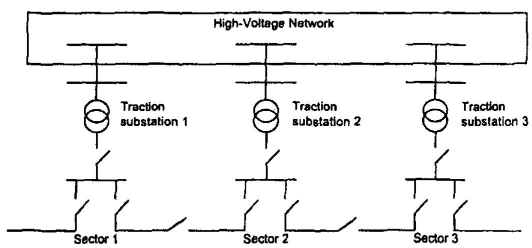

Fig. 1. Electrical supply system of a high-speed railway line.

The catenary can be equipped with either one or two active conductors resulting respectively in the so called 1x25 kV or 2x25 kV systems (in case that the catenary voltage is 25 kV). Fig. 2 and Fig. 3 show respectively the basic topology of 1x25kV and 2x25 kV systems. Regarding the 1x25 kV system, the catenary is simply fed by a single-phase two winding transformer. The topology of the 2x25 kV system is more complex: the catenary is fed by a single-phase three winding transformer and autotransfomers connect the positive and the negative phases [2]. The autotransformers allow to transmit power at 50 kV whereas the trains are fed at 25 kV.

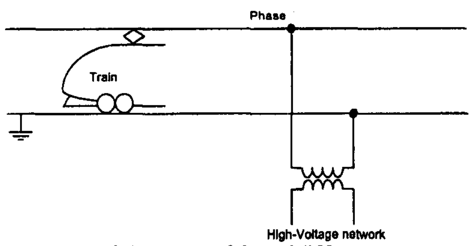

Fig. 2. Topology of the 1x25kV system.

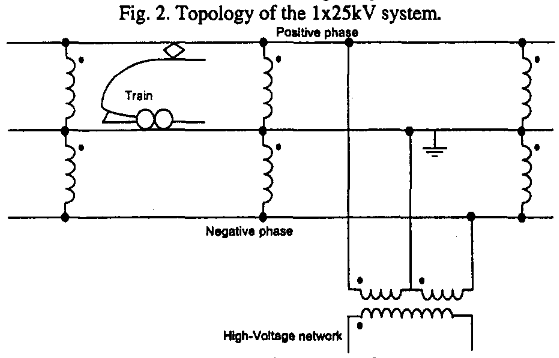

Fig. 3. Topology of the 2x25kV system.

III. DESIGN OF THE ELECTRICAL SUPPLY SYSTEM OF HIGH-SPEED RAILWAYS

The problem of designing the electrical supply system of a high-speed railway line consists of determining the values of the design variables so the required technical constraints are fulfilled.

A. Design variables

The design variables define the configuration of the system, the size of its components and impose constraints to external systems. Therefore, three groups of design variables are set up:

1) Topological variables: variables which define the topology of circuits, that is (i) type of feeding system of each sector, (ii) location of each traction substation and connecting bus to the high-voltage network, (iii) location of each switch and (iv) location of each autotransformer.

2) Gauge variables: variables which set the size of every element of the system, such as (i) transformers and autotransformers ratings, (ii) number and type of physical conductors of the catenary, and (iii) specifications of each grounding connection.

3) External variables: variables of the external systems that have to be modified to fulfill the external system requirements (i.e. parallel dc lines of conventional railways).

B. Technical constraints

The technical restrictions to be checked are (i) train voltages (which must be within the UIC range), (ii) current in physical conductors, (iii) power flow in transformers and autotransformers, (iv) maximum admissible step and touch voltages, (v) induced voltages in parallel lines, and (vi) maximum unbalance introduced in the three-phase high-voltage network.

C. Solution procedure

The problem of designing the electrical supply system of a high-speed railway line is solved iteratively (see Fig. 4). The starting point consists of determining the electrical consumption scenarios from traffic simulations. Then, values are assigned to the design variables, the electrical simulations are performed and the constraints evaluated. If the constraints are not fulfilled, the user assigns new values to the design variables. The tool has been designed in such a way that this process can be done easily.

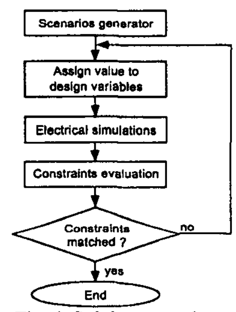

Fig. 4. Solving procedure.

IV. OVERVIEW OF THE SIMULATION TOOL

The simulation tool consists of computing modules and user-friendly interfaces to handle input and output data. The main computing modules are the traffic simulator and the electrical simulator [3].

The traffic simulator builds the scenarios of electrical system (location and magnitude of the train loads) by simulating the movement of each train. The electrical simulator determines magnitudes of the high-speed power system for each scenario. In addition to the computation of voltages, currents and power flows, other studies can be performed such as unbalance introduced in the high-voltage network, step and touch voltages, or induced voltages along parallel lines. The two simulators are uncoupled [4]. In other words, the movement of the trains is not affected by the steady state of the electrical system (this is possible thanks to the control capabilities of the power electronic converters of the trains).

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V. TRAFFIC SIMULATOR

The traffic simulator determines, for every time step, the position and the active and reactive power consumption of every train. This simulation is performed in two steps: firstly, the movement of every type of train between two consecutive stations is calculated. Secondly, the entire traffic is built up using the timetable that determines each train departure from each station.

A. Movement of a train between consecutive stations

The movement of a train between two consecutive stations is determined by Newton's second law:

$$\sum_i F_i = F_t - F_p - F_c - F_a = M\frac{dv}{dt} \quad (1)$$

where M is the mass of the train, v is the speed of the train, F_t is the traction force of the train, F_p is the resistant force due to the slope of the railway line, F_c is the resistant force due to the curvature of the railway line, F_a is the force that models the aerodynamic resistance. The traction force is a piece-wise linear function of the speed. The resistance force due to the slope of the line is proportional to the mass of the train and the slope of the line. The resistance force due to the curvature is also proportional to the mass of the train and inverse to the curvature radius. The aerodynamic resistance force contains three terms: one constant, other proportional to the speed and the remaining one proportional to the square of the speed.

The solution of equation (1) provides the position, speed and acceleration of the train. The solution takes into account the speed and acceleration constraints. Once, the movement of the train has been solved, the active power consumption is determined as:

$$P_e = \frac{P_m}{\eta_{e,m}} = \frac{F_t \cdot v}{\eta_{e,m}} \quad (2)$$

where $\eta_{e,m}$ is the efficiency of the electrical-to-mechanical power conversion.

The reactive power is determined from the train power factor. The train power factor is modeled as a piece-wise linear function of the speed. Regenerative braking can be considered through an efficiency coefficient η_r, which expresses the part of the power returned to the line.

$$S_r = (P_e + j \cdot Q_e) \cdot \eta_r \quad (3)$$

B. Traffic

The simulation of each train movement between two consecutive stations is done assuming that starting time and starting station are the temporal and spatial origins. Once it has been obtained, the departure timetable is used to compose the movement of the trains' sequence. This is done by reproducing the movements with different time and space origins as shown in Fig. 5.

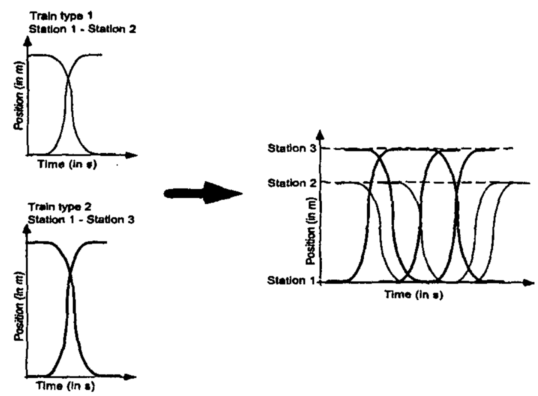

Fig.5. Procedure to build up the line traffic.

It should be noted that in the adopted model, trains do not interact with other trains. In other words, the timetable must reflect overtakes, waiting states, and all necessary behaviors to allow an efficient exploitation of the railway line.

VI. ELECTRICAL SIMULATOR

The electrical simulator contains a set of tools to perform the studies required to evaluate a design of the electrical supply system of a high-speed railway line. The main computations are the train voltages, conductor currents and transformer power flows. In addition, unbalance introduced in the high-voltage network, induced voltages along parallel lines, and step and touch voltages in the proximity of the grounding connections can be determined. An utility to compute the line parameters of the catenary has also been added due to the specific features of the catenary as a power distribution line [5].

A. Line parameters

The configuration of the catenary of a high-speed railway line is shown in Fig. 6. The catenary contains several physical conductors that can be grouped into three groups: positive, negative and ground wires.

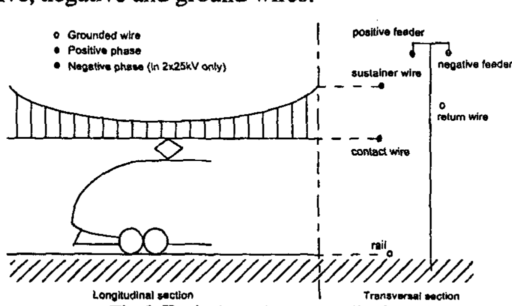

Fig.6. Typical conductor distribution.

The positive wires are the positive feeder, the sustainer wire and the contact wire. There is only one negative wire and it is usually called negative feeder. The ground wires are the rail, the collector wire and the return wire.

The line parameters routine determines the series impedance and shunt admittance matrices of the physical conductors and the equivalent conductors configurations [6]. The earth-return effect on the serial impedance matrix is calculated using Carson formulas. The shunt admittance matrix only represents self and mutual capacitances. The equivalent conductor representation is obtained by reducing the physical conductor representation assuming that the conductors of the same group have the same voltage and the current through the equivalent conductor is the sum of the currents through the physical conductors.

B. Load flow analysis

The load flow analysis of the electrical supply system of a high-speed railway line determines for each time step the train voltages, the physical conductor currents and the transformers and autotransformers power flows. The load flow solution is obtained using an equivalent conductor model of the electrical system. Once the bus voltages of such system have been determined, the currents of the physical conductors can be computed.

Fig. 7 and Fig. 8 show respectively the equivalent conductor model of a section of 1x25kV and 2x25kV electrical systems. The model of the traction substations includes the traction transformer model and the Thevenin equivalent of the high–voltage network. It should be noted that the traction transformer in case of the 2x25kV systems is a three-winding one. The autotransformers of the 2x25 kV system are modeled as –1:1 transformers connected between the positive and the negative equivalent conductors. Due to the rated voltage of the catenary, the line model considers only the series impedance component.

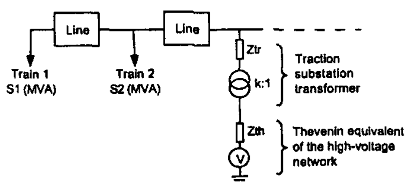

Fig. 7. Simplified 1x25kV topology.

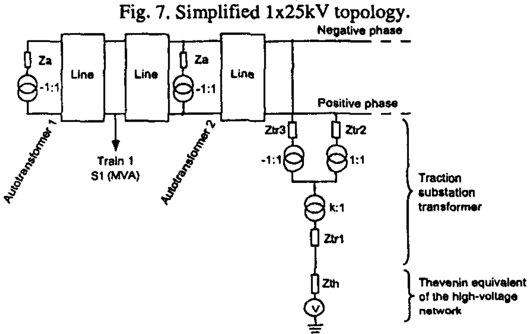

Fig. 8. Simplified 2x25kV topology.

The load flow is solved using the Newton-Raphson method. The physical conductor currents of each line section are calculated from the bus voltages as:

$$\mathbf{I}_{ph} = (\mathbf{Z}_{ph} \cdot L)^{-1}\left(\mathbf{V}_{i,ph} - \mathbf{V}_{f,ph}\right) \tag{4}$$

where $\mathbf{I}_{ph}$ is the vector of physical conductor currents, $\mathbf{Z}_{ph}$ is the physical conductor series impedance matrix, L is the length of the branch, $\mathbf{V}_{i,ph}$ and $\mathbf{V}_{f,ph}$ are respectively the voltages of the initial and final buses of the branch. Once the magnitude of the physical conductor currents I_t and the transformer and autotransformer power flows S_t have been determined at every time t, the moving root mean square currents in the physical conductors $\bar{I}$ and the moving average power flows $\bar{S}$ through the transformers and autotransformers, during a time window sized N, are computed as:

$$\bar{I} = \sqrt{\frac{1}{N}\sum_{t=1}^{N} I_t^2} \tag{5}$$

$$\bar{S} = \frac{1}{N}\sum_{t=1}^{N} S_t \tag{6}$$

C. Unbalanced voltages

The electrical system of a high-speed railway line is a single-phase load, connected between two phases, for the three-phase high-voltage network. Therefore, the railway line introduces an unbalance to the network. The unbalance in each bus of the network is measured as the ratio between the inverse and the direct sequence voltages:

$$U(\%) = \frac{V_2}{V_1} \times 100 \tag{7}$$

The direct and inverse sequence voltages can be computed exactly using a three-phase load flow program [7]. A good approximation of the unbalance can also be obtained using a linear model of the network: generators are represented as voltage sources and loads as impedances. Assuming that the direct and inverse sequences are uncoupled, they are represented by their admittance matrices:

$$\begin{bmatrix} \mathbf{Y}_{11,gg} & \mathbf{Y}_{11,g\ell} \\ \mathbf{Y}_{11,\ell g} & \mathbf{Y}_{11,\ell\ell} \end{bmatrix} \begin{bmatrix} \mathbf{V}_{1,g} \\ \mathbf{V}_{1,\ell} \end{bmatrix} = \begin{bmatrix} \mathbf{I}_{1,g} \\ \mathbf{I}_{1,\ell} \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} \mathbf{Y}_{22,gg} & \mathbf{Y}_{22,g\ell} \\ \mathbf{Y}_{22,\ell g} & \mathbf{Y}_{22,\ell\ell} \end{bmatrix} \begin{bmatrix} \mathbf{V}_{2,g} \\ \mathbf{V}_{2,\ell} \end{bmatrix} = \begin{bmatrix} \mathbf{I}_{2,g} \\ \mathbf{I}_{2,\ell} \end{bmatrix} \tag{9}$$

where the subindexes g and ℓ indicate respectively the generator and the load buses. If the generator direct sequence voltages are fixed $\mathbf{V}_{1,g}$ and the generator inverse sequence voltages are zero $\mathbf{V}_{2,g} = \mathbf{0}$, then equations (8) and (9) become:

$$\mathbf{Y}_{11,\ell\ell}\mathbf{V}_{1,\ell} = \mathbf{I}_{1,\ell} - \mathbf{Y}_{11,\ell g}\mathbf{V}_{1,g} \tag{10}$$

$$\mathbf{Y}_{22,\ell\ell}\mathbf{V}_{2,\ell} = \mathbf{I}_{2,\ell} \tag{11}$$

The conditions that describe the phase-to-phase unbalance can be formulated according to equations (12) and (13).

$$\mathbf{K}_{\mathbf{V}_{1,\ell}}\mathbf{V}_{1,\ell} + \mathbf{K}_{\mathbf{V}_{2,\ell}}\mathbf{V}_{2,\ell} = \mathbf{Z}_{\ell}\mathbf{I}_{1,\ell} \tag{12}$$

$$\mathbf{I}_{2,c} = \mathbf{K}_{\mathbf{I},c}\mathbf{I}_{1,c} \tag{13}$$

where $\mathbf{Z}_{\ell}$, $\mathbf{K}_{\mathbf{V}_{1,\ell}}$, $\mathbf{K}_{\mathbf{V}_{2,\ell}}$, y $\mathbf{K}_{\mathbf{I},\ell}$ are diagonal matrices. The nonzero elements of $\mathbf{K}_{\mathbf{V}_{1,\ell}}$, $\mathbf{K}_{\mathbf{V}_{2,\ell}}$, y $\mathbf{K}_{\mathbf{I},\ell}$ depend on which phases the load is connected to. If the unbalance conditions and the sequence equations are combined, the solution of linear system (14) provides the direct and the inverse sequence voltages.

$$\begin{bmatrix} \mathbf{Y}_{11,\ell\ell} + \mathbf{Y}_{\ell}\mathbf{K}_{\mathbf{V}_{1,\ell}} & -\mathbf{Y}_{\ell}\mathbf{K}_{\mathbf{V}_{2,\ell}} \\ -\mathbf{K}_{\mathbf{I},\ell}\mathbf{Y}_{\ell}\mathbf{K}_{\mathbf{V}_{1,\ell}} & \mathbf{Y}_{22,\ell\ell} - \mathbf{K}_{\mathbf{I},\ell}\mathbf{Y}_{\ell}\mathbf{K}_{\mathbf{V}_{2,\ell}} \end{bmatrix} \begin{bmatrix} \mathbf{V}_{1,\ell} \\ \mathbf{V}_{2,\ell} \end{bmatrix} = \begin{bmatrix} -\mathbf{Y}_{11,\ell g}\mathbf{V}_{1,g} \\ \mathbf{0} \end{bmatrix} \tag{14}$$

D. Step and touch voltages

Train currents flow from the catenary to the rails. A component of this current derives to earth through the ballast. The remaining current is derived to earth through grounding connections. The rail currents are very high due to the power requirement of high-speed trains. Since a fraction of those currents flows through the grounding connections, non-admissible voltages may appear near them [8]. The step and touch voltages analysis estimates those voltages to design the adequate safety measures.

The step and touch voltages analysis models the trains as equivalent impedances (which are determined using the voltage calculated by the load flow analysis and their consumption) and traction substations by their Norton equivalent (see Fig. 9).

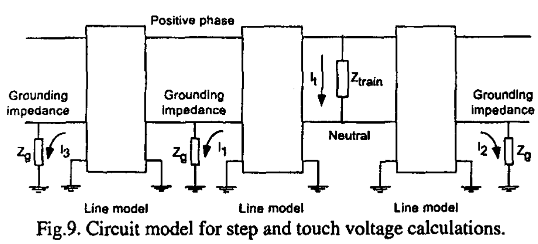

Fig.9. Circuit model for step and touch voltage calculations.

A detailed representation of the catenary sections is used in the step and touch voltage analysis: series impedance and shunt admittance matrices of physical conductors, grounding connections, connections between conductors, etc. Voltages are obtained by solving the nodal equations taking advantage of the sparse structure of the admittance matrix.

E. Induced voltages in parallel lines

Catenary currents also induce voltages in long parallel lines, like parallel catenaries of conventional railway lines. Induced voltages over admissible values can damage such lines unless corrective measures are applied. The induced voltages are computed using the equivalent conductor model of the catenary and representing the parallel line by sections of uniform separation from the catenary (see Fig. 10).

$$\mathbf{V}_{ext} = \sum_{sect}\sum_{ph} \mathbf{M}_{ph-c} \cdot \mathbf{I}_{ph} \cdot L_{sect} \tag{15}$$

where $\mathbf{M}_{ph-c}$ are the mutual induction coefficients between the catenary equivalent conductors and the external parallel conductor, and $\mathbf{I}_{ph}$ are the equivalent conductor currents and L_{sect} is the length of the section.

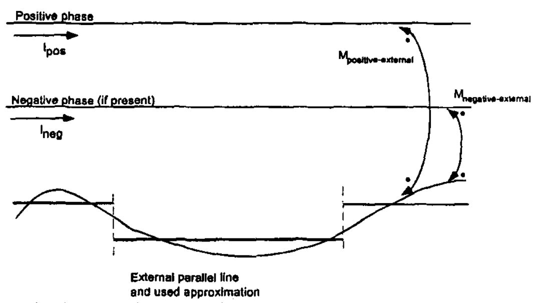

Fig. 10. Model to determine induced voltages in a parallel line.

VII. ILLUSTRATIVE EXAMPLE

The tool will be illustrated with results of the studies of the Madrid – Barcelona high-speed railway line (Madrid – Lleida section). A traffic scenario corresponding to a Thursday of March 2015, between 12:00:00 and 15:00:00 will be considered. Two Alstom train models have been used. A realistic configuration of the electrical supply system has also been assumed.

Fig. 11 displays the minimum voltages along the catenary. It should be noted that such voltages are always over the minimum requirement (19 kV).

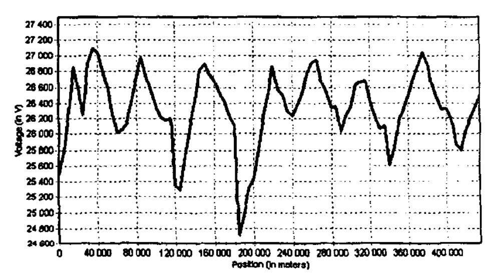

Fig. 11. Minimum voltages along the catenary.

Fig. 12 and 13 show respectively the maximum loads in the transformers (which are between 30 and 45MVA) and in the autotransformers (around 7 MVA).

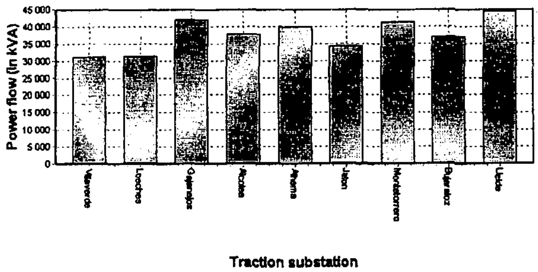

Fig.12. Transformer loads.

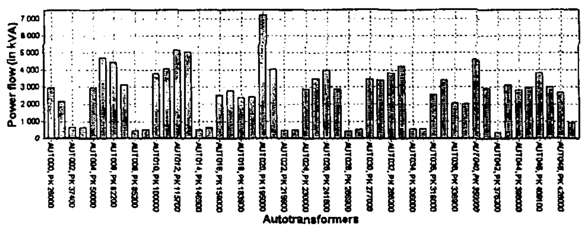

Fig. 13. Autotransformer loads.

Fig. 14 details the unbalance introduced in the current Spanish high-voltage network by the single-phase loads due to the section Madrid – Lleida of the Madrid – Barcelona high-speed railway line. A number of buses exhibit unbalances higher than 2%. It indicates that the network should be reinforced to reduce them. In fact, a program to reinforce the Spanish transmission system has been planned to reduce the unbalance to admissible values, and it will be ready when the line opens.

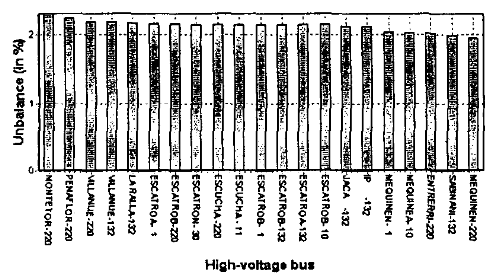

Fig. 14. Maximum unbalance introduced in the high-voltage network.

VIII. CONCLUSIONS

This paper has presented a tool to help in the design of the electrical supply system of high-speed railway lines. The main components of the simulation tool are the traffic simulator and the electrical simulator. The tool has been extensively used by SEMI to design the electrical system of the Madrid – Lleida section of the line Madrid – Barcelona – French border. SEMI has been awarded by the Spanish government with the project and the construction works of the power supplying system of this high-speed line.

In the future, automation and optimization of the design procedure will be explored: a more complete and accurate model of the high-speed power supplying would allow to find a set of optimal systems based on technical and economic criteria.

IX. ACKNOWLEDGEMENT

The development of tool described in this paper has been partially founded by the Spanish Ministry of Industry and Energy (ATYCA Initiative P63/1997 and National Fond for Scientific and Technical Research Development CDTI-970399).

Thanks are also given to Mr. Íñigo Basañez of Elecnor.

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XI. BIOGRAPHY

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