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Modelling Trolleybus Networks: a Critical Review

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Abstract—The trolleybus system is already part of the urban environment of several metropolitan cities. In view of the emergence of smart cities, it appears reasonable to look at how the trolleybus grid can become a more active part of the urban's electricity network. However, the infrastructure design approaches adopted so far make the current trolleybus networks overdesigned to handle the improbable worst-traffic case scenarios. Consequently, the trolleybus electrical supply system is both underutilized and oversized. Through modelling, simulations, and a cluster of measured trolleybus and corresponding network data, various new functionalities may be explored, among which electric vehicle chargers and energization of auxiliary equipment, towards a more sustainable and smart trolleybus grid. This paper merges the authors' engineering knowledge and sources available in the literature on designing and modelling trolleybus networks and performs a critical review of them to lay the foundations for proposing possible optimal alternatives. Being the city of Bologna organized with multiple electrically powered zones with either basic or complex topologies, the respective trolleybus system has been chosen as a case study.

Keywords—catenary model, circuit modelling, electric mobility, probability-based approach, simulation, trolleybus

I. INTRODUCTION

The electrical infrastructure of a typical electric traction network consists mainly of DC traction power substations (TPSSs), i.e., uncontrolled rectifier substations, and overhead contact line (OCL) systems. To guarantee the regularity of the traction system operation, the OCLs are divided into feeding sections (FSs), or electrical zones, that are fed separately [1]. An FS is the portion of the OCL between two or more electrical disconnection points. The electrical disconnection points along the OCLs are considered to be always open circuited as they are not commonly operable except in case of emergency. Ordinary FSs are supplied bilaterally. In the event of bidirectional traffic, typically for urban traction grids the two physically parallel OCLs are connected at different regularly distributed points by equipotential bonding, or voltage equalizers, forming a double contact line (double-bifilar line in the case of trolleybuses). The equipotentiality achieved by these electrical connections tends to limit the voltage drops along the catenary by reducing the electrical resistance, especially farther from the TPSSs. While a detailed analysis of TPSSs is omitted in this paper, our work explores existing approaches (either implemented for already built infrastructures or proposed in the literature) for design, verification, and monitoring of the catenary system, to ensure service continuity and technical standards compliance. Bologna's trolleybus network is chosen as a case study and basis for comparing the modelling methods discussed here, being arranged with FSs with simple (ordinary structure of an electric railway FS) and complex topologies.

To the best of the authors' knowledge, the methodologies

effectively enacted for designing the existing metropolitan trolleybus systems have not been formalized in technical-scientific documents, although based on rules dictated by the technical expertise acquired in similar fields. Following such rules and relying on the authors' experience as researchers in the field, it was possible to reconstruct the theory behind the design of the Bologna's trolley grid.

The authors in [2],[3] described a conventional analytical method for OCL voltage drop verification employed for the electrification of railways, but also applicable for trolleybus systems. However, the modernization of urban's electricity networks makes it inevitable to perform model-based time-domain analysis. Hence, proper simulation tools are required for building and examining descriptive network models. In general, the models reported in the literature are implemented using general-purpose programming languages, such as Fortran or C (which are compiled languages), or in graphical programming environments, such as Matlab-Simulink or Modelica.

References [4]-[8] delineated a simulation tool written in Fortran aimed at correctly representing urban railway lines. This tool, named *Train-sim*, has been developed in the past century and validated for electrified subway [5] and tram [6] lines through in-field experimental tests. In [7],[8], the Fortran-language-based version is compared with Modelica-based and Simulink-based simulators for tramway systems. The modelling approach introduced in *Train-sim* involves a nodal analysis of network. A nodal analysis is also performed in [9] for trolleybus grids, intrinsically more complex than railway lines, as explained subsequently.

Modelica and Simulink are block-diagram environments that allow modelling multidomain systems and deploying without writing code. Authors in [8] have managed to build a railway system simulator in Simulink with the same model architecture and equations implemented in Modelica; besides, the relevant literature available on Simulink models appears to be relatively vaster: hence, this paper does not deal with Modelica. As is understandable, the equivalent electric circuit topology depicting the OCL varies with the movement of the vehicles, which draw a certain amount of electric current; hence, the vehicles split the circuit into branches of variable resistance. One of the main challenges encountered in simulating overhead contact systems is the representation of such time-varying electrical resistance. Simulink provides a block implementing a variable resistor (Variable Resistor blocks) as a current source driven by a voltage measurement. However, this model presents strong criticalities as the vehicle current absorption is typically modelled with a controlled current generator [10]-[13]. Hence, its direct connection with Variable Resistor blocks would form a current-sources-only cut-set, which originates singularities according to the circuit theory. A possible solution is explained in [11], in which the variable resistor is built with a controlled voltage source. Authors in [12],[13] developed a catenary model

based on switchable series-connected resistors for imitating variable resistors. Reference [14] applies the same concept for trolleybus lines, even though the respective vehicle model includes the non-linearities of the electric drive system, which may lead to excessively burdensome simulations.

That said, the variability of the number of vehicles typical of the trolleybus system FSs may compromise the modular extensibility of the aforementioned models. In addition, certain FSs of that sort have more complex morphologies, i.e., they are characterized by the simultaneous presence of single- and double-bifilar OCLs, unsymmetrical TPSSs in the case of bilaterally supplied FSs (both in terms of power delivery and position of the respective outgoing feeders, normally of different lengths, with respect to the FS structure), unevenly arranged voltage equalizers, and reinforcing line feeders. The modular model of trolleybus networks proposed in [15] is a potential candidate to address these points.

In the present work, the effectiveness of the already cited modelling approaches is investigated in relation to the features noted above, highlighting the possible limitations of each when applied to trolleybus grids. In Section II, the conventional analytical approach for electric traction infrastructure design is reported. Section III deals with the main literature on the simulation tools for catenary modelling, distinguishing between textual programming-based and block-based models. In Section IV, a comparison of the modelling methods analysed is provided, followed by relevant considerations. Lastly, conclusions are drawn in Section V.

II. CONVENTIONAL ANALYTICAL APPROACH

The calculations adopted for dimensioning the current trolleybus electrical infrastructure in Bologna follow a method based on the evaluation of the line electrical parameters at the FS macro-level, i.e., each FS is associated with a unique OCL current, temperature, and voltage value. Such values are derived according to precautionary assumptions, which the present work will examine in the next paragraphs.

A. Monitoring of Overloads and Overheating

Let us first understand how the conventional method estimates possible overloads and overtemperatures in the overhead lines. Owing to thermal limits on the conductors of the electric traction OCLs, it is considered that the single 100 mm² raw-copper wire should not carry more than 451 A. Since the standard identifies a continuous operating condition, the vehicle average current absorption is to be used for monitoring possible overloads, which is given by:

$$I_m = \frac{1}{t_{bs}} \int_0^{t_{bs}} i dt, \quad (1)$$

where i is the line current absorbed by the trolleybus and t_{bs} is the mean time between stops (dwell times at stops included).

The conventional design method resorts to the calculation of a unique total average current I_M , which accounts for the assumed number of vehicles within the affected FS:

$$I_M = \sum_j I_{m,j} n_j, \quad (2)$$

where $I_{m,j}$ is the vehicle average current for the trolleybuses of j -th type and n_j is the number of trolleybuses of j -th type inside the FS.

Based on the FS configuration, Table I collects the formulas for deriving the OCL pole current, to be compared with the ampacity threshold imposed by the abovementioned standard. The following simplifying hypotheses explain why the single-wire current is obtained as a divisor of I_M in specific cases:

TABLE I. OCL POLE CURRENT FOR OVERLOADS ANALYSIS

FS power supply	Single-bifilar	Double-bifilar
Unilateral	I_M	$I_M/2$
Bilateral	$I_M/2$	$I_M/4$

- i. Each bilaterally supplied FS is symmetrical in relation to the two TPSSs, i.e., the line feeders leaving the TPSSs are assumed to be of identical length (i.e., same voltage drop) and the TPSSs themselves, with the same rated voltage, equally share the power delivered to the FS. Therefore, each TPSS supplies half of the line current;
- ii. The two catenary lines of the FSs with bidirectional traffic are assumed to be electrically in parallel, i.e., the corresponding positive and negative poles are theoretically connected at infinite points along the whole OCL length; this implies that the two bifilar lines in parallel would carry the same current at any location.

Of course, if an FS satisfies both hypotheses i and ii simultaneously, the OCL pole current is given by a quarter of I_M .

Keeping the maximum current in the conductors within the specified limits is a primary objective in the design of OCLs, which could otherwise be damaged by excessive heating. The standard EN 50119 states that the maximum temperature rise in the OCL conductors should not lead to conductor temperatures above 80 °C in steady-state conditions [1]. With a good approximation, the OCL pole temperature θ_{OCL} is governed by the following differential equation:

$$\tau_{th} \frac{d\theta_{OCL}}{dt} + (\theta_{OCL} - \theta_{OCL,0}) = C\sigma^2 = C \left(\frac{I_{OCL}}{S_{OCL}} \right)^2, \quad (3)$$

where τ_{th} is the thermal time constant of the system, $\theta_{OCL,0}$ is the initial temperature, C is the heat constant (°Cmm⁴/A²), σ (A/mm²) is the electric current density, I_{OCL} is the OCL pole current, and S_{OCL} (mm²) is the cross-section of the OCL conductor. To verify the compliance with the aforementioned standard, the analysis is limited to the evaluation of the steady-state temperature $\theta_{OCL,ss}$, obtained from (3):

$$\dot{\theta}_{OCL} = 0 \rightarrow \theta_{OCL,ss} = C\sigma^2 = C \left(\frac{I_{OCL}}{S_{OCL}} \right)^2 + \theta_{OCL,0}. \quad (4)$$

Generally, the thermal transients of the OCLs are governed by a time constant τ_{th} that has a much longer duration than current start-up transients. As a consequence, $\theta_{OCL,ss}$ may be studied with reference to the vehicle average current absorption, which means that in the conventional approach we resort to the overall average current I_M . According to the FS configuration, I_{OCL} in (4) is expressed with the relative formula in Table I.

B. Probability-Based Calculation of the Line Voltage Drop

Given the electrical resistance per unit length and the distance between TPSSs, it is possible to calculate the voltage drops corresponding to a certain line current consumption. This voltage varies according to the position of the vehicles and the currents absorbed by them. The correct functioning of the electrical infrastructure requires that the line voltage does not fall below a value that the standards set at two-thirds of the nominal voltage (the rated value is 750 V in EN 50163 [16]); hence, it is necessary to verify the maximum voltage drops corresponding to the heaviest load conditions.

In the following paragraphs, we will consider a line section of length L , without intermediate branches, neglecting for simplicity the internal voltage drops of the TPSSs and therefore considering the voltage at the supply busbars constant when the load varies.

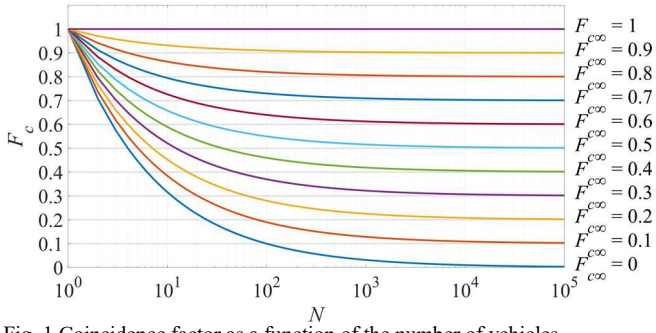


Fig. 1 Coincidence factor as a function of the number of vehicles.

1) Probabilistic derivation of the current consumption at the feeding section macro-level

As a precautionary hypothesis, to determine the maximum voltage drop along the catenary the vehicle starting current I_s is used, i.e., the mean value of the current taken by the traction inverter during the starting period, and it is obtained as follows:

$$I_s = \frac{1}{t_s} \int_0^{t_s} i dt > I_m, \quad (5)$$

where t_s is the start-up time duration (time to maximum speed).

The evaluation of the OCL voltage drops affecting each FS is performed by estimating a total starting current accounting for the number of vehicles within each FS per each vehicle type. As it is requested to calculate the maximum voltage drop, the representation of a worst-case scenario results of interest. Such a scenario is characterized by trolleybuses working in the phase of highest line current absorption, i.e., the start-up phase. With reference to the procedure adopted by Rusck [17] (re-examined in [18]), the start-up time durations of vehicles of the same type are assumed to be normally distributed. Given the j -th trolleybus type, the start-up coincidence (or simultaneity) factor that a very large number of vehicles would have is calculated as follows:

$$F_{c\infty,j} = \frac{t_{s,j}}{t_{bs,j}}, \quad (6)$$

where $t_{s,j}$ is the start-up time duration for the trolleybuses of j -th type and $t_{bs,j}$ is the mean time between stops for the trolleybuses of j -th type. Ideally, given a set of an infinite number of similar vehicles, this factor represents the probability of each vehicle to be in the starting phase, at each instant. Because the time between stops is always larger or equal to the start-up time duration, the calculated simultaneity factor always varies between 0 and 1.

Since an FS may be characterized by the presence of different trolleybuses at the same time, we must resort to the mean coincidence factor, obtained as follows always with the hypothesis of a large number of vehicles for each j -th type:

$$F_{c\infty,m} = \frac{\sum_j F_{c\infty,j} n_j}{\sum_j n_j} = \frac{\sum_j F_{c\infty,j} n_j}{N}, \quad (7)$$

where N is the total number of buses inside the FS.

In practice, when dealing with a common finite number of vehicles present within an FS, the expression of the start-up coincidence factor becomes [17]-[22]:

$$F_c = F_{c\infty,m} + \frac{1 - F_{c\infty,m}}{\sqrt{N}}. \quad (8)$$

Therefore, from (8) the total starting current drawn by the vehicles inside the FS is calculated as follows:

$$I_s = F_c \sum_j I_{s,j} n_j = \left(F_{c\infty,m} + \frac{1 - F_{c\infty,m}}{\sqrt{N}} \right) \sum_j I_{s,j} n_j, \quad (9)$$

where $I_{s,j}$ is the starting current drawn by a trolleybus of j -th type.

Focusing, for the sake of simplicity, on the case of trolleybuses with identical characteristics, i.e., $F_{c\infty,m} = F_{c\infty}$, the

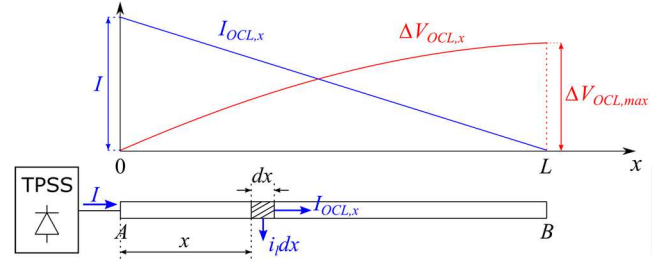


Fig. 2 Unilateral power supply, uniformly distributed load.

relation between the simultaneity factor and the number of vehicles for different values of $F_{c\infty}$ is depicted in Fig. 1. Note that the horizontal axis has a logarithmic scale. The figure shows that the coincidence factor decreases with the increasing number of considered trolleybuses, as it becomes less probable that they are in their start-up phase simultaneously. For a very large number of vehicles ($N \rightarrow \infty$) the coincidence factor F_c is very close to the respective value taken by $F_{c\infty}$.

2) Voltage drop evaluation with unilateral power supply

a) Uniformly distributed load

Let us refer to Fig. 2 for the evaluation of the maximum OCL voltage drop in the case of unilaterally supplied FSs.

If the number of trolleybuses becomes very large (this is the typical case of a high-traffic trolleybus line, with low-powered vehicles following one another closely), we are approaching, at the limit, the theoretical situation of uniformly distributed load, corresponding to a specific current absorption (assuming vehicles having equal characteristics):

$$i_l = \frac{I}{L}, \quad (10)$$

where I is the total current delivered by the TPSS at line end A .

The load absorption in a line segment of length dx equals:

$$dI = i_l dx. \quad (11)$$

At a distance x from the TPSS, the OCL current is given by:

$$I_{OCL,x} = I - xi_l = (L - x)i_l. \quad (12)$$

The elementary voltage drop is obtained as follows:

$$d(\Delta V_{OCL,x}) = r_l I_{OCL,x} dx = r_l (L - x) i_l dx, \quad (13)$$

where r_l is the OCL electrical resistance per unit length.

Integrating (13) along the line section of length x gives:

$$\Delta V_{OCL,x} = \int_0^x r_l (L - x) i_l dx = r_l i_l x \left(L - \frac{x}{2} \right). \quad (14)$$

Equation (14) shows that $\Delta V_{OCL,x}$ varies quadratically as a function of x , and it assumes the maximum value at line end B (see Fig. 2), i.e., for $x = L$, as expressed in the following formula:

$$\Delta V_{OCL,L} = \Delta V_{OCL,max} = r_l i_l \frac{L^2}{2} = r_l L \frac{I}{2}. \quad (15)$$

b) Evenly spaced concentrated loads

In practice, the catenary is burdened with a finite number of trolleybuses, which can be treated as concentrated loads absorbing the currents I_1, I_2, \dots, I_N , at distances $x_1 < x_2 < \dots < x_N$ from the TPSS at point A . The maximum voltage drop corresponding to the x_N abscissa can be determined as follows by superposition of effects:

$$\Delta V_{OCL,max} = r_l \sum_{h=1}^N x_h I_h. \quad (16)$$

Since the exact position of the vehicles is not known, they are evenly spaced from an electrical perspective with respect to the supply points, and as far as possible from them so as to represent a more precautionary scenario. For example, if the

load is concentrated on a single point, this point is considered to be the farthest end from the TPSS; while if the load is concentrated on two points, half is considered to be on the farthest end from the TPSS and half in the centre; and so on.

In this work, the computation of the maximum OCL voltage drop is performed based on a plus-factor ranging between 1 and 2, which depends solely upon the number of vehicles N inside the FS. The plus-factor is represented in Fig. 3 for both unilaterally (k_u) and bilaterally (k_b) fed FSs. By increasing the number of vehicles, the plus-factor decreases, as the load is shared among more line points.

In the case of unilaterally supplied FSs, the voltage drop plus-factor is determined as follows:

$$k_u = 1 + \frac{1}{N} = \frac{N+1}{N} \quad \forall N \in \mathbb{N}. \quad (17)$$

The plus-factor based method provides a compact expression for evaluating the voltage drop, replacing the summation typical of the superposition principle (see (16)), which results cumbersome when the number of trolleybuses is relatively large. The maximum voltage drop hence is expressed as follows:

$$\Delta V_{OCL,max,u} = k_u \Delta V_{OCL,max} = \frac{N+1}{N} r_l L \frac{I}{2}, \quad (18)$$

where I takes the value of the total starting current I_s . Note that for a very large number of vehicles, being k_u closer to 1, $\Delta V_{OCL,max,u}$ assumes the result expressed by (15), i.e., we approach the condition of uniformly distributed load.

3) Voltage drop with bilateral power supply

Let us assume that for both TPSSs, located at the A and B extremities of the line section, the voltage is equal to $V_{OCL} = V_{OCL,A} = V_{OCL,B}$.

a) Uniformly distributed load

Let us refer to Fig. 4 for the evaluation of the maximum OCL voltage drop in the case of bilaterally supplied FS.

Similarly to the one-sided supply, the current consumption per unit length (i_l) is given by (10). According to the assumption i in Section II.A, each TPSS delivers a current equal to $I/2 = i_l \cdot L/2$. At a distance x from the TPSS, the OCL current is given by:

$$I_{OCL,x} = \frac{I}{2} - x i_l = \left(\frac{L}{2} - x\right) i_l. \quad (19)$$

The small amount of voltage at the line segment of length dx is equal to:

$$d(\Delta V_{OCL,x}) = r_l I_{OCL,x} dx = r_l \left(\frac{L}{2} - x\right) i_l dx, \quad (20)$$

which, once integrated over the entire OCL section, gives:

$$\Delta V_{OCL,x} = \int_0^x r_l (L-x) i_l dx = r_l i_l x \left(\frac{L}{2} - \frac{x}{2}\right). \quad (21)$$

Here too, $\Delta V_{OCL,x}$ varies with quadratic law as a function of x , but this time it takes the maximum value at the midpoint of the OCL section, i.e., for $x = L/2$. The following result is achieved:

$$\Delta V_{OCL,L/2} = \Delta V_{OCL,max} = r_l i_l \frac{L^2}{8} = r_l L \frac{I}{8}. \quad (22)$$

b) Evenly spaced concentrated loads

In the case of bilaterally supplied FSs, the precautionary assumption of evenly spaced trolleybuses along the catenary is still valid. This time, if the load is concentrated on a single point, that point is considered to be in the centre of the FS; whereas if the load is concentrated on two points, half of it is considered to be at one-third of the FS and half at two-thirds; and so on. The voltage drop plus-factor is hence obtained as (see Fig. 3):

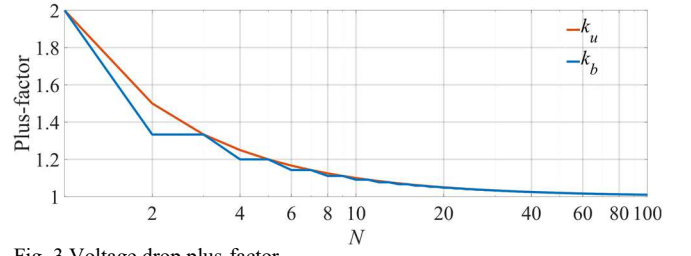


Fig. 3 Voltage drop plus-factor.

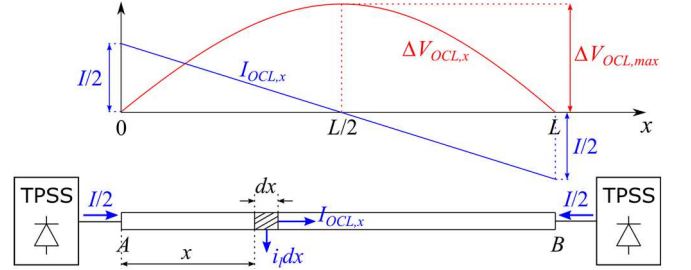


Fig. 4 Bilateral power supply, uniformly distributed load.

$$k_b = \frac{(-1)^N + 3 + 2N}{(-1)^N + 1 + 2N} \quad \forall N \in \mathbb{N}. \quad (23)$$

Therefore, an expression for the maximum line voltage drop is provided below:

$$\Delta V_{OCL,max,b} = k_b \Delta V_{OCL,max} = \frac{(-1)^N + 3 + 2N}{(-1)^N + 1 + 2N} r_l L \frac{I}{8}, \quad (24)$$

where $I = I_s$. Similarly to the previous case, for a very large number of vehicles $\Delta V_{OCL,max,b}$ assumes the result expressed by (22).

III. THE SIMULATION TOOLS

A. Textual Programming-Based Catenary Models

Before delving into the increasingly popular block-based programming, some words about catenary models relying on text-based coding are worthwhile. Let us analyze the simulation tool named *Train-sim*, written in Fortran language, and employed for modelling DC railway systems so far. *Train-sim* consists of two computational codes: *Train-perf* and *Train-el*.

The *Train-perf* calculation code takes the line features and the electromechanical characteristics of the vehicles as input data, and outputs the motion profiles of the vehicles themselves. Different traffic scenarios can be determined.

The *Train-el* code builds an equivalent electrical network for each simulation time step, based on the corresponding vehicle positions given by the *Train-perf* tool. It then solves load flow analysis by assuming the TPSSs, vehicles, and voltage equalizers as electrical nodes, while the resistive branches between such nodes represent the traction circuit stretches with their equivalent resistances. By adopting classic iterative numerical methods (e.g., Newton-Raphson), the software provides the output powers from each TPSS, the OCL voltage profiles, and the currents flowing through the line feeders. The vehicles are modelled as constant power loads. If the current absorption attempts to exceed the maximum permitted value, such a value is imposed as a constraint during the iterative calculation of the non-linear equations, until the voltage seen by the vehicle decreases.

Furthermore, the maximum recuperable powers during the braking phase of the vehicles are computed. If the system allows it, the catenary can accept all the power produced during regenerative braking, according to the solution of the system equations. If the voltage increases, the recoverable energy transferred to the OCL (the portion of energy

TABLE II. COMPARISON OF THE CATENARY MODELLING TECHNIQUES AND REQUIRED FEATURES

Modelling methods	Variable number of vehicles	Complex FS morphology	User-friendliness
Conventional analytical approach	✓	✗	✗
Nodal analysis-based	✓	✓	✗
Variable resistor imitation	✗	✗	✓
Modular motion-based	✓	✓	✓

dissipated on the braking rheostat rises) up to zero, i.e., as soon as the voltage reaches the maximum permitted value.

To enhance the review, it is worth underlining that modelling electric traction networks via nodal analysis, along with embracing iterative numerical methods for network resolution, does not manifest itself in the literature solely through the development of *Train-sim*. Dealing with trolleybus grids, of particular interest is the catenary model examined in [9], which relies on the backward-forward sweep iterative method [24]. The authors in [9] also analyse common simplifying assumptions made in the literature on prior trolleybus grid models. To generalize, the broad variety of network elements (treated as electrical nodes) manageable by nodal analysis-based models make them particularly suitable for simulating complex catenary grid scenarios, although the intuitive dynamic graphical interface lack pushes us to look for other modelling strategies.

B. Simulink-Based Catenary Models

In the following, we focus on electric traction network modelling in Simulink decoupled from the dynamic vehicle representation, namely, the catenary behavior may be reasonably simulated by assuming the vehicles as controlled current sources. These current sources are positioned at certain points in the line circuit, thus splitting the FS into OCL branches. Hence, the circulation of the vehicles is emulated by changing the OCL equivalent circuit configuration, i.e., the electrical resistances associated with the corresponding OCL branches vary with time based on the motion profiles of the vehicles themselves. As mentioned in Section I, if such modelling strategies are applied, there is no built-in block in Simulink viable for representing the line resistance variability according to the vehicle position. Two published techniques for emulating the functioning of the variable resistor in railway grids are reported below. Then, this paper shows a modelling approach that, exploiting its modularity property, aims at the displacement of the current sources rather than focusing on catenary resistance variability. Such an approach was applied to trolleybus networks.

1) Model based on imitation of line resistance variability

The first strategy consists in inserting a current-controlled voltage source within the OCL section run by the vehicle [11], which is connected in series with an ammeter measuring the line current. By keeping track of the vehicle position, the voltage value assumed by the controlled generator is evaluated as the product of the OCL resistance per unit length, the distance between the vehicle itself and the adjacent TPSS feeding that section, and the measured OCL current. The coefficient of proportionality between the voltage source value and the ammeter reading is the amount of resistance to be attributed to the variable resistor. Nevertheless, it should be stressed that such a formulation requires management of the initial conditions to avoid an unphysical representation, e.g., the short circuit of the entire OCL if the initial voltage is set to zero, as well as it experiences criticalities in the event of null resistance, e.g., when the vehicle is in the vicinity of the TPSS.

The second technique introduces switchable series-connected resistors for imitating variable resistors [12],[13]. The resistors network is included in a subsystem handled by a designated control logic. The subsystem presents switches in parallel to each resistor of the series, whose values are discretized within different order of magnitude ranges. Once again, by monitoring the vehicle movement, the line resistance between its position and the contiguous feeding point is given by the corresponding distance multiplied by the OCL resistance per unit length. Based on the vehicle location, the control system switches the resistor network to reach the estimated value with a certain accuracy.

2) Model based on current absorption displacement

As the imitation of catenary resistance variability may limit the flexibility of the adopted modelling approach, a valid alternative consists in changing current source positions representing the vehicle absorptions. Such an idea is realizable by resorting to modular models, as shown in [15]. The respective model is composed of identical resistive blocks (resistances are fixed) representing segments of the OCL. Within each of these blocks, a time-dependent current source is connected in the midpoint. Through a properly programmed logic, the motion of the vehicle absorption is simulated by turning on the current generator at the block in which the vehicle itself is located. Obviously, the equivalent line resistance seen by the turned-on current source changes according to the location of the corresponding resistive block, hence the same scope of variable resistor-oriented models is achieved.

IV. MODELLING TECHNIQUES COMPARISON AND DISCUSSION

Table II clarifies whether the analyzed techniques for modelling the catenary achieve certain features, here examined one by one. Obviously, the most adequate method depends on the scope of the model [25].

The conventional analytical approach permitted obtaining the line parameters at the FS macro-level through relatively simple mathematical expressions. Because of their strict dependence on the number of vehicles within the FS, the conventional method allowed easy changing of such a number. Referring here to the *Train-sim* tool (but this is also valid for other nodal analysis-based techniques), it also had no difficulty in this direction, as it is only a question of modifying the quantity of electrical nodes via coding. By contrast, the catenary models in Simulink relying on variable resistor imitation did not concede flexibility in varying the number of vehicles. The number of vehicles defined how many variable resistor models will be used to simulate one FS, and it could not be assumed they were identical, as the distances between the different vehicles may have varied according to the traffic intensity and the specific speed profile of each. Instead, by virtue of its modularity property, the last model discussed here based on current source motion enabled simulating any trolleybus fleet.

As already discussed, most of the trolleybus system FSs are characterized by a greater morphology complexity if compared to railways ones. Within FSs of that typology, because of the simplifying hypotheses that characterize the conventional approach, it does not consider the presence of reinforcing feeders, the asymmetry of the TPSSs (see Section I), the possible combination of single- and double- bifilar lines, and the actual distribution of the equipotential bonding system. Moreover, FSs topology intricacy grows with the introduction of stationary energy storage systems for supporting the trolleybus grid, as well

as with the idea of using the grid itself for charging electric vehicles. Hence, the conventional method, which is already based on a maximalist scenario, appears to be excessively precautionary in the event of intricate FSs, leading to unreliable electrical parameters. Concerning the catenary models described in Section III.1, the way they were built made us deduce that the displacement of the TPSS feeders and the addition of reinforcing feeders or voltage equalizers at any point on the OCL was unrealizable. As for the *Train-sim* simulator, on the other hand, the addition of supply points or equipotential bonding also in this case was just a matter of increasing the number of electrical nodes for the network calculations: the internal code exactly defined all the OCL branches forming the FS. The model mentioned in Section III.2 also had no difficulties in this respect, always thanks to its modularity property.

Let us now focus on the user-friendliness of the studied methodologies. As regards to the conventional approach, although the respective equations may straightforwardly be implemented in electronic spreadsheets (e.g., Excel) or in diverse integrated development environments (e.g., Matlab), one may realize the lack of intuitiveness of use. Concerning the simulation tools, the man-machine interface in the *Train-sim* simulator is also not flexible, as Fortran is a programming language that involves mainly writing code. On the contrary, Simulink provides a graphical interface: hence, the catenary structure models and related parameters may be easily adjusted.

V. CONCLUSIONS

A critical review of the existing modelling techniques adoptable for trolleybus catenary systems is provided in this paper. Based on the authors' knowledge and the literary material available, it has been possible to piece together a conventional method for trolleybus electrical infrastructure design, founded on analytical calculations. The present Bologna's trolleybus grid has been planned according to such a conventional approach. However, the renovation of the urban's electricity network drives the need of employing dedicated software for evaluating the feasibility of electrified transport systems. First, the *Train-sim* simulation tool is discussed, which was developed through text-based coding and relies on nodal analysis. Second, this work reports three catenary models contrived in Simulink. The first two are based on the imitation of contact line variable resistors, while the third one is founded on the idea of keeping fixed the resistive configuration while logically allowing the displacement of the vehicle constant-current absorptions.

The four modelling strategies analyzed are compared with reference to the following purposes: elasticity in changing the number of vehicles within an FS, ability of modelling FSs with morphology of greater complexity, and user-friendliness of the man-model interface. The conventional method, although straightforward and effective in the case of FSs with basic structure, becomes inevitably incompatible with the demand of modernization of trolleybus networks. Despite the intuitiveness provided by the graphical interface of Simulink with respect to compiled languages, the variable resistor-based models reviewed in this paper may not prove suitable for dealing with complex network morphologies and allowing the variability of the number of vehicles. Hence, modular catenary models appear as good candidates for solving the issues here examined. With respect to the nodal analysis-based methods discussed, the motion-based modular model examined here was devised in Simulink environment, whose flexible man-machine interface

and the broad variety of functionalities make the model itself versatile and future-proof towards intelligent trolleybus grids.

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