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Published Version:
Barbone R., Mandrioli R., Ricco M., Paternost R.F., Lo Franco F., Grandi G. (2022). Flexible and Modular Model for Smart Trolleybus Grids. Institute of Electrical and Electronics Engineers Inc. [10.1109/CPE-POWERENG54966.2022.9880904].

Availability:
This version is available at: https://hdl.handle.net/11585/899776 since: 2024-02-29

Published:
DOI: http://doi.org/10.1109/CPE-POWERENG54966.2022.9880904

Flexible and Modular Model for Smart Trolleybus Grids

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***Abstract*—The reduction of climate-changing emissions is vital, especially in urban areas. To reach this goal, the decarbonization of the public transport sector is crucial. Dynamic conductive power transfer through catenary systems is potentially a carbon-neutral solution. This paper focuses on trolleybus grids, already established in several metropolises, which are re-emerging as a smart city-oriented electrified transport system. A better integration of trolleybus grids with renewable sources, energy storage, and the existing electric network of the urban area is necessary to increase the efficiency of the system and optimize energy flows, favouring the transition towards smarter and greener cities. Moreover, trolleybus systems may act as a DC backbone for charging stations powering private electric vehicles, thus contributing to a closer interconnection between public and private mobility. A modular model of the electric traction grid in Matlab-Simulink is explored to simulate the actual complexity of novel trolleybus network topologies. By means of graphical and numerical results illustrating the behaviour of the main electrical line parameters, the model flexibility towards the inclusion of smart city-oriented technologies, such as stationary battery energy storage systems and electric vehicle chargers, is verified in this work. The trolleybus electrical infrastructure of the city of Bologna was chosen as a case study.**

***Keywords*—battery energy storage systems; catenary model; circuit modelling; electric mobility; electric vehicle charging stations; trolleybus; urban transport**

I. INTRODUCTION

The reduction of greenhouse gas (GHG) emissions, of which transport vehicles constitute a major source, is one of the greatest global challenges through 2050 [1]. To achieve this goal, it is necessary to revolutionize mobility, starting from the urban context, as cities produce more than 70% of worldwide GHG emissions [2]. In the direction of sustainable urban mobility, catenary-powered mass transit, such as metros, trams, and trolleybuses, are broadly spread in many metropolises all over the world. Focusing on trolleybus networks, the introduction of in-motion-charging (IMC) vehicles may contribute to make the related electrical infrastructure greener and smarter. Such innovative vehicles are trolleybuses powered by the two-wire catenary and equipped with an on-board battery to extend the journeys to non-powered stretches allowing the replacement of currently employed internal combustion engines. Nevertheless, technical obstacles can be encountered due to increased absorption of electrical power by the IMC vehicles to guarantee both the energy for traction and the energy for charging the on-board battery ESS (BESS) for the off-wire travelling. The transition to this new technology leads to further electrical load applied on the overhead catenary, hence higher voltage drops at the critical line points as well as conductors overheating. Moreover, the infrastructure burden would grow further to satisfy commuters' demand of higher frequency cyclic schedules. Therefore, to avoid running into possible disruptions to users in the worst case, the entire electrical infrastructure needs for appropriate support. For this purpose, the clever integration of renewable energy sources (RESs) and stationary ESS within the trolleybus network may be the right way forward.

The trolleybus grid may also represent a great chance to favour the deployment of electric vehicles (EVs), forasmuch as the network itself could work as a DC backbone for EV charging stations (EVCSs), i.e., catenary-to-vehicle (C2V) operation. Furthermore, with a proper management of the power flows, vehicle-to-catenary (V2C) operation could be investigated too, possibly enabling additional support to the catenary network.

In this direction, research has been already made on railways [3-6]. The authors in [3] presented electrical protection requirements for interconnecting bidirectional EVCSs to railway traction systems, also including backup storage and photovoltaic (PV) systems as support. The research in [4] dealt with the potential of braking energy from trains to feed via railway catenary the electrical infrastructure for charging a fleet of EVs. In the microgrid, a battery storage is adopted for voltage stability purposes. The use of railway infrastructures for powering fast charging stations located in nearby highway service areas was analysed in [5]. The authors in [6] studied the feasibility of providing power to EVs in train station parking lots obtained from a PV system and train regenerative braking. The proposed DC microgrid also embeds an ESS.

Specifically for urban transport networks, examples of DC microgrids integrating RESs, EV charging points, and ESSs can be found in [7-9]. In [8], the idea of a smart trolleybus system arises to modernize the current trolleybus grid in Solingen. The authors in [9] propose the integration of EVCSs with trolleybus catenary systems through multi-port converters.

The desired integration of smart city-oriented technologies within the DC grid makes paramount the use of flexible circuit modelling strategies, useful for assessing novel interventions in current topologies without undue difficulty. As discussed in [10], the modelling approaches available in the literature are either based on excessively simplifying assumptions or do not enable the suitable versatility to each specific application requirement. Hence, the development of modular circuit models of trolleybus networks might prove the viability of the smart city transition. The modularity property of a multi-vehicle motion-based (MVMB) model in Matlab-Simulink was also shown in [10], the use of which is actually extendable to any other electric transport system relying on dynamic conductive power transfer, where the ability of the model itself to replicate the actual line morphology was demonstrated. The present work shows how the flexibility of the MVMB model modular could be demonstrated by applying different topological changes to the catenary network and showing consistent results in terms of voltage, current, and temperature distributions all over the line. With an eye on smart trolleybus grids, the system configuration changes intended in this paper relate to the incorporation of BESSs, which also constitute a viable alternative to reinforcement power cables, and EVCSs into the network.

II. MULTI-VEHICLE MOTION-BASED MODEL OF THE CATENARY IN SIMULINK

In the following, catenary-powered electric traction systems are understood to mean DC traction power substations (TPSSs), i.e., uncontrolled rectifier substations, and 750 V DC overhead contact line (OCL) supply systems [11]. To guarantee the regularity of the trolleybus operation, the OCLs are divided into feeding sections (FSs) [12]. FSs are electrically insulated OCL sections, implying that there is not a single point of origin that electrifies the entire grid. Typical FSs are fed bilaterally. Among them, those of basic structure are characterized by bidirectional traffic, whereby usually the two physically parallel bifilar OCLs are connected at different points by equipotential bonding, or voltage equalizers, forming a double-bifilar line. The equipotentiality achieved by these electrical connections tends to limit the voltage drops along the catenary by reducing the equivalent resistance, especially farther from the TPSSs. Nevertheless, it is not uncommon to deal with FSs of major complexity, as in the case of trolleybus networks.

In this work, multi-vehicle motion-based modelling is intended as simulating the trolleybus network behaviour as a function of the variation in vehicle position in time, also giving versatility in choosing the number of vehicles. To such an end, a thorough study of the catenary system has proven to be essential, while detailed analysis of electrical substations, as well as of the vehicle traction system, is beyond the scope of this paper. Indeed, each TPSS is simply represented with the Thevenin equivalent circuit (open-circuit voltage of 800 V and equivalent series resistance of 68 mΩ) with a diode in series (reasonable assumption for emulating twelve-pulse parallel rectifiers) and, as explained in the next paragraphs, a controlled current generator is designated for modelling the trolleybuses.

A. Catenary Modelling

The idea behind the Simulink model of the OCL is to represent the dynamism of the trolleybus. In this respect, the method followed in the present work concerns the introduction of Subsystem Reference (SR) blocks in Simulink. As analysed in [10], by connecting more referenced subsystems together it is possible to extend the catenary model to the wanted length and morphology. Fig. 1 displays an example of OCL model. All relevant data are serially propagated between contiguous blocks, enabling the space distribution of the electrical parameters, such as line voltages, currents, and temperatures.

Each referenced subsystem includes a 20 m span of the OCL. Being the length of a typical articulated trolleybus of approximately 18 m, the chosen span model length appears to be appropriate for discretizing the vehicle position. Nonetheless, the SR strategy is very flexible from this viewpoint, allowing for adjusting the span according to the required discretization accuracy. The span circuit is represented in Fig. 2. The catenary span is modelled with resistors and a time-varying controlled current source, which represents the trolleybus current absorption, and it is turned on only if the position of the trolleybus itself corresponds to that specific SR block. A given profile is assigned to the trolleybus position and current, which are set as input to the catenary model.

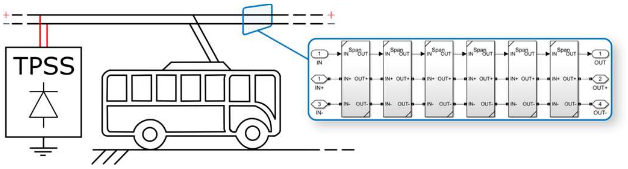

Fig. 1 Catenary modelling with Subsystem Reference blocks.

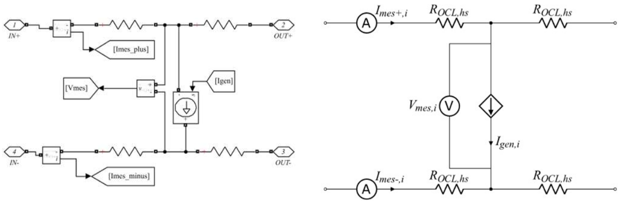

Fig. 2 Configuration of the OCL span model, showing the Simulink representation (left) and the circuit schematic drawing (right).

B. Modelling of Battery and EV Charger

As the scope of this paper is the verification of the flexibility property that characterises the MVMB model, there is no need to enter in the details of circuit modelling accuracy for the BESS and the EVCS. Instead, it is important to prove that the catenary model can monitor the behaviour of the line wherever the location of such systems and whatever their actual features.

To a first approximation, while the BESS is represented with a DC current source, the EVCS is modelled with a constant-power load (C2V), or source (V2C). The EVCS model is built with a voltage-controlled current generator: the current value is given by the ratio between the predetermined power absorption (C2V), or injection (V2C), and the voltage measured across the OCL in that point. The values of battery current and DC charger power selected in this work refer to a certain significant time instant of the simulation.

III. CASE STUDY OF BOLOGNA: SMART CITY-ORIENTED FEEDING SECTIONS

With the objective of reducing the environmental impact of public transport in Emilia-Romagna, which is still mainly powered by endothermic engines, the Metropolitan City of Bologna is working on the introduction of IMC trolleybuses into the urban transit system. Consequently, Bologna's transport operator is planning the addition of reinforcement supply point within the most in-need FSs, which must be adequate to ensure the proper introduction of such novel vehicles. The MVMB model might be adopted to this end.

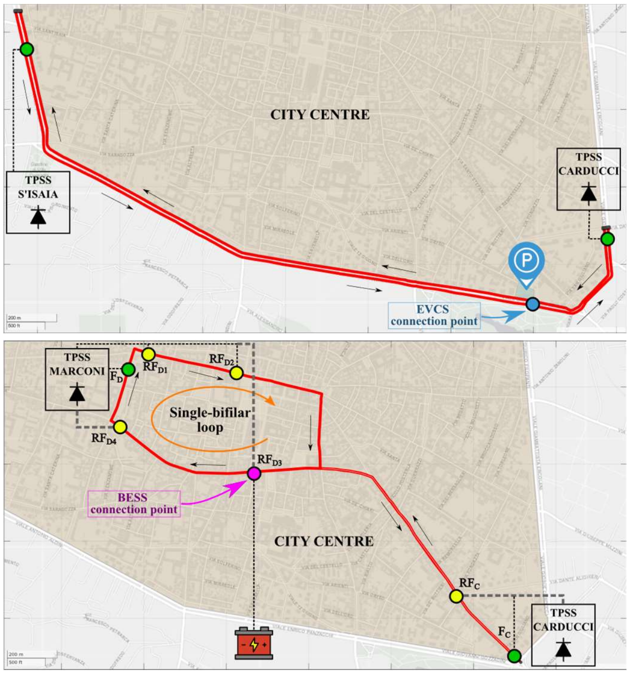

Fig. 3 Hypothetical Bologna's FSs following smart interventions, i.e., connection points to the OCL for EVCS (top, in light blue) and BESS (bottom, in magenta). The trolleybus routes (oriented by arrows) of FS 1 (top) and FS 2 (bottom) are plotted together with TPSSs and supply points (relative to line feeders in green and to reinforcing feeders in yellow). Planned reinforcing feeders are marked in grey.

The present section shows how the flexibility of the MVMB model could be exploited to integrate stationary ESSs and EVCSs within one of Bologna's trolleybus routes belonging to a specific FS in Simulink environment. Two FSs, depicted in Fig. 3, were thoroughly analysed by virtue of the peculiarities of their current configuration:

- FS "Sant'Isaia - Carducci" (FS 1): bilaterally supplied FS (two feeding TPSSs, i.e., TPSS "Sant'Isaia" and TPSS "Carducci", from which the FS designation is derived) with a basic topology (top of Fig. 3), i.e., there exists approximately a symmetry of the double-bifilar line between the supply points. Rounding to the nearest multiple of 20, i.e., assumed span length in meters, the total bifilar length is of 6240 m;
- FS "Marconi - Carducci" (FS 2): bilaterally supplied FS with a complex structure (bottom of Fig. 3), due to the simultaneous presence of a double-bifilar line (towards the TPSS "Carducci") and a single two-wire loop (in the direction of the TPSS "Marconi"), as well as the power support via several reinforcing feeders. Assuming valid the approximation made in the case above, the total bifilar length is of 4540 m.

Among the elements constituting the electrical infrastructure, particular emphasis is placed on the actual length and position of line feeders (F_A, F_B, F_C, and F_D), reinforcing feeders (currently present, i.e., RF_{D1}, and RF_{D2}, or planned, i.e., RF_C, RF_{D3} and RF_{D4}), and equipotential bonding, with reference to the OCL path within the feeding section analysed. While real data on cables and conductors were provided by TPER (Trasporto Passeggeri Emilia-Romagna) and reported in [10], Google Street View was exploited to determine the corresponding spatial coordinates, as well as the location for the insertion of the ESS and EVCS. In the following paragraphs, the hypothesized infrastructural interventions in the perspective of smarter urban mobility are discussed.

TABLE I
CONSIDERED POWER RATINGS OF DC EV RECHARGING SYSTEMS

Definition	Power output
Slow-to-fast DC recharging point threshold value	50 kW
Fast DC recharging point	120 kW
Level 1 - ultra-fast DC recharging point	175 kW
Bottom limit of level 2 - ultra-fast DC recharging point	350 kW

A. *EV charging station in FS "Sant'Isaia - Carducci"*

This paragraph comprises the analysis of the line electrical parameters in the case of the power connection of an EVCS to the traction catenary. Both catenary-to-vehicle (C2V) and vehicle-to-catenary (V2C) applications are considered.

Since, coming from TPSS "Carducci" in the direction of TPSS "Sant'Isaia", there is the parking area of Piazza del Baraccano next to the trolley line, such a location could be ideal for the insertion of an EVCS, as depicted in Fig. 3. To avoid excessive current/temperature spikes, the EVCS is connected to both two-wire lines in both directions of travel.

Table I lists the power output levels assigned to the EVCS in this work, i.e., realistic values belonging to the classification of recharging systems valid in the European Union, which range between slow (which also finds application in wireless power transfer-based charging systems [13]) and ultra-fast DC chargers. As the actual power profile of the vehicle being connected to the charging station does not concern the aim of this paper, an extreme scenario is considered in which the EV constantly draws (C2V) or inject (V2C) the maximum power output of the recharging system (in a given time instant of simulation).

B. *Stationary battery ESS in FS "Marconi - Carducci"*

Thanks to the modularity property of the MVMB model, any FS morphology intricacy could be handled. This is the case of the FS 2, which is supplied by many reinforcing feeders spread all over its topology. However, the addition of new feeding cables does not allow smart optics services, such as power flow control, and they require obstructive construction sites. Interventions oriented to smart urban mobility may involve the introduction of stationary BESSs. Battery-based auxiliary substations [14], or other support mid-line BESSs in critical network areas, could constitute a solid alternative to reinforcing feeders. In the case of voltage drops, the BESSs would act providing power to the lines. Through the MVMB model one could understand whether this solution is feasible or not. Exploiting the SR blocks, our model is generalizable for any metropolitan trolleybus network (e.g., Minsk, San Francisco, and so on), most of which operate at voltages lower than 750 V DC (typically 600 V DC), making the integration of stationary energy storage even more important to tackle the presumably higher voltage drops. Moreover, the BESSs could manage the power flows to avoid overloads, and lead to a better handling of the traffic jam conditions.

TABLE II

CASES OF PLANNED REINFORCING FEEDERS UNDER ANALYSIS FOR FLEXIBILITY VERIFICATION

Cases	RF_C	RF_{D3}	RF_{D4}
Case 1	✓	✗	✓
Case 2	✓	✗	✗
Case 3	✗	✗	✗

TABLE III

VEHICLE CURRENT ABSORPTIONS CONSIDERED IN THE MODEL

Feeding section	Starting current	Average current
FS “Sant’Isaia - Carducci” (FS 1)	237.6 A	149.8 A
FS “Marconi - Carducci” (FS 2)	209.4 A	184.9 A

The MVMB model allows to study the effects of BESSs on the trolleybus grid. Three batteries were selected, corresponding to 100, 300, and 500 A in terms of current injections in a specific time instant of the simulation, as per a simplistic model devised for explanatory purposes only (see Section II-B). These values were chosen based on the currents through the feeding wires sensed in the circuit model. As shown in Fig. 3, the battery is connected to the catenary in a point of the single-bifilar line, which is subject to lower voltages as highlighted in [10]. This connection point coincides with that of one of the planned TPSS “Marconi” reinforcing feeders (RF_{D3}) (at 1400 m from the line disconnector of TPSS “Carducci”, element representing the starting point of the circuit model of the OCL), and potentially represents a critical network point. In the following, the FS 2 is studied with reference to the currently intended network configuration, designed with an uncontrollable feeding system that involves the installation of RF_C, RF_{D3} and RF_{D4} for supporting the IMC-integrated DC grid. The absence of the RF_{D3} represents the first case analysed. In the second case, the behaviour of the line is tested also without the reinforcing feeder RF_{D4}, which is likewise part of the feeding equipment directly connected to the single-bifilar loop. Lastly, the third case considers the further omission of the feeding cable RF_C, connected to the double-bifilar line, and powered by TPSS “Carducci”. Table II summarizes changes applied to the feeding system configuration in the three examined cases.

IV. DISCUSSION OF RESULTS

For both FSs considered here, different simulations were performed assuming the trolleybus positions vary linearly with time. The number of trolleybuses within the portion of the route analysed (five and nine vehicles for the FS 1 and FS 2, respectively) as well as the values of the vehicle current absorptions were set according to [10]. For the sake of simplicity, it is hypothesised that trolleybuses belonging to the same FS are identical, consequently so are their corresponding current draws, which are reported in Table III. As explained in [10], it is reasonable to refer to the vehicle starting current when studying the OCL voltage and the vehicle mean current when analysing OCL currents and temperatures. The line voltage, positive-pole current, and positive-pole steady-state temperature are shown all over the FS at a significant time instant in which the trolleybuses are scattered with a certain criterion explained in the abovementioned article. As is known, when sizing an infrastructure the related parameters should comply with standards, dedicated to electric traction systems in this context. In particular, the foregoing electrical parameters must stay within specific limits dictated by two standards provided by European Committee for Electrotechnical Standardization (CENELEC) [11-12]. Reference is made to [10] for the proof that the MVMB model allows for a reasonable verification of the standards, without directly intervening on the real system. Since the values assigned to the EVCS and BESS parameters are indicative for the mere purpose of model flexibility analysis, the present work does not address standard compliance.

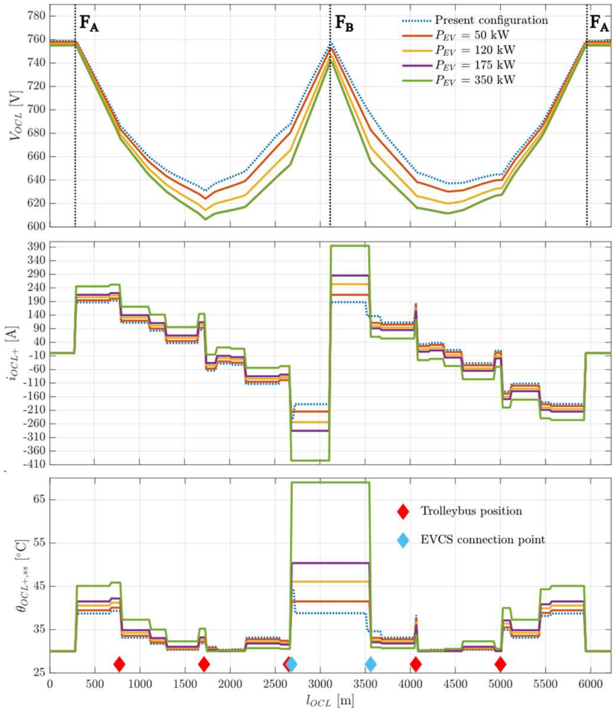

Fig. 4 Distributions of OCL voltage (top), positive-pole current (middle), and positive-pole steady-state temperature (bottom) along the FS 1 for C2V operation. Feeder positions are marked with dashed lines.

C. *Line behaviour of the updated FS “S’Isaia - Carducci”*

In the following, the distribution of the main electrical parameters of the OCL is depicted for the FS 1, stressing the differences between the current line morphology and its behaviour after the introduction of an EVCS with different power levels (see Table I).

1. *Catenary-to-vehicle operation*

In the C2V operation, the EVCS draws power from the catenary network. The power values are listed in Table I. Fig. 4 shows the profiles of the OCL voltage, current, and temperature. As expected, by increasing the power taken from the EV charger, the line voltage drops accordingly. The graph behaviour in the point of connection of the EVCS with the OCL is similar to that in presence of a trolleybus (V-shaped valley). Instead, the line current and temperature tend to increase, especially at the EVCS location.

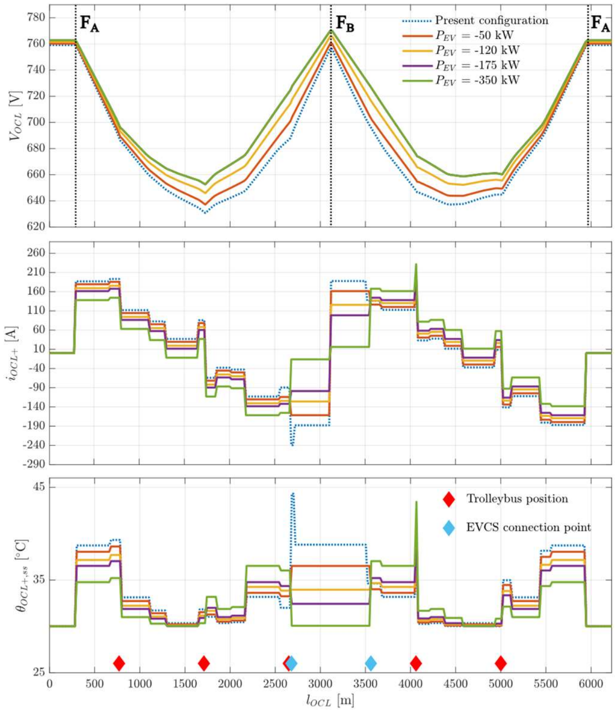

Fig. 5 Distributions of OCL voltage (top), positive-pole current (middle), and positive-pole steady-state temperature (bottom) along the FS 1 for V2C operation. Feeder positions are highlighted with dashed lines.

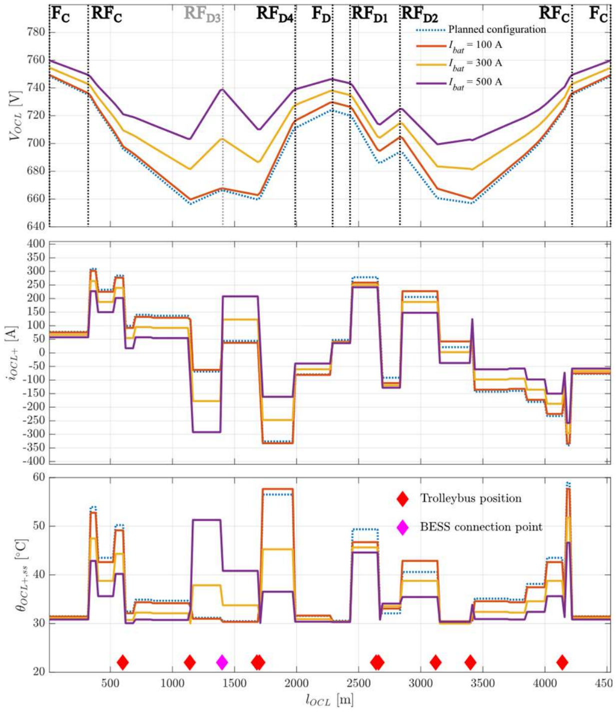

Fig. 6 Distributions of OCL voltage (top), positive-pole current (middle), and positive-pole steady-state temperature (bottom) along the FS 2 in the first case. RF_{D3} is faded in grey to mark its absence in this configuration.

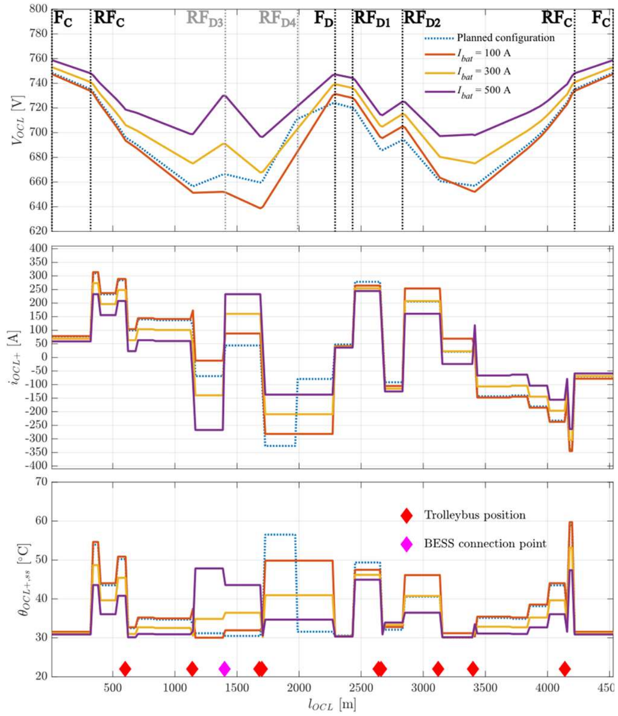

Fig. 7 Distributions of OCL voltage (top), positive-pole current (middle), and positive-pole steady-state temperature (bottom) along the FS 2 in the second case. RF_{D3} and RF_{D4} are faded in grey to mark their absence in this new configuration.

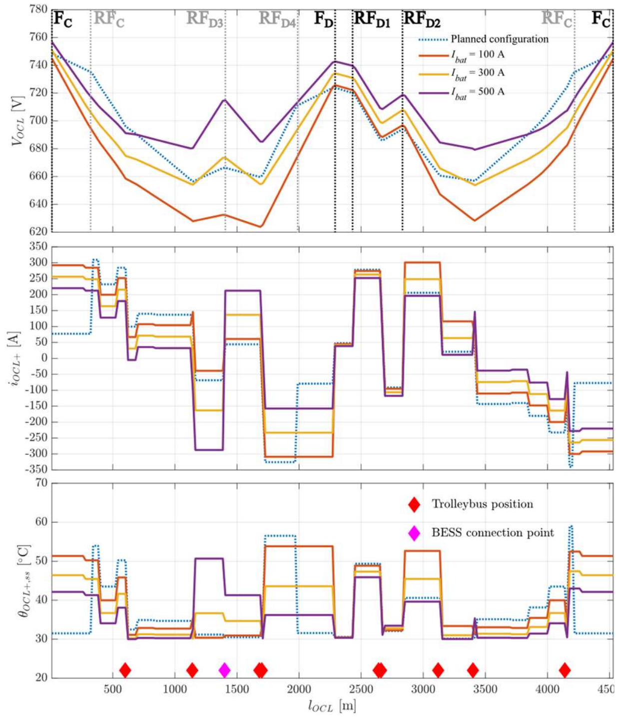

Fig. 8 Distributions of OCL voltage (top), positive-pole current (middle), and positive-pole steady-state temperature (bottom) along the FS 2 in the third case. RF_{D3}, RF_{D4}, and RF_C are faded in grey to mark their absence in this new configuration.

2. *Vehicle-to-catenary operation*

In the V2C operation, the EVCS is returning electricity to the DC grid, hence, to simulate an injection into the catenary, the same constant power values (refer to Table I) associated to the charger were changed of sign. As a result, the OCL is greater than that of the present FS configuration (i.e., FS without interventions towards smart trolley grid), and it grows along with the absolute value of the EVCS power, as depicted in Fig. 5. Moreover, the effect of the EVCS is to nullify the V-shaped valleys caused by the trolleybus current absorptions. As for the line current, the mean of the absolute value of its distribution in the case of -350 kW (i.e., 75 A), for which the lowest currents are foreseen, is clearly lower than that in the absence of the EVCS (102 A). Future work could perform the analysis of the line losses along with the calculation of the FS efficiency, for a better understanding of the benefits of EV chargers' integration.

D. *Line behaviour of the updated FS "Marconi - Carducci"*

The following subsections include a comparison between the behaviour of the primary line electrical parameters for the currently planned configuration of the FS 2 and for its structure after the addition of the BESS. Three cases were studied involving different topological choices. Remarks and considerations focus on the OCL voltage trend, which is easier to interpret.

1. *BESS instead of RF_{D3}*

The graph in Fig. 6 displays the catenary voltage, current, and temperature trends when considering the BESS instead of RF_{D3} in the same connection point to the OCL (Case 1 in Table II). Focusing on the OCL voltage, the BESS injecting a current of 100 A is distinctly sufficient to do the job of the removed feeder. Higher battery currents (300 A and 500 A) raise the voltage level all over the FS considerably.

2. *BESS instead of RF_{D3} and RF_{D4}*

In the present case, the FS topology is further modified by omitting the RF_{D4} together with the already subtracted RF_{D3} (Case 2 in Table II). Battery ratings are kept unchanged from the previous case. As Fig. 7 shows, the catenary voltage distribution is only satisfactory for battery currents of 300 A and 500 A. This confirms that power supply devices play an important role in the weaker single-bifilar loop of FS 2.

3. *BESS instead of RF_{D3}, RF_{D4}, and RF_C*

In the third and last case, the absence of the reinforcing feeder (RF_C) from TPSS "Carducci" was also addressed (Case 3 in Table II). Only the feeding cables currently present were considered. Fig. 8 clarifies the need of batteries with higher capacity for this configuration. Indeed, just the BESS delivering a current of 500 A leads to a minimum OCL voltage higher than that relative to the existing configuration.

V. CONCLUSIONS

The flexibility of the MVMB modular model of trolleybus DC catenary systems is graphically verified in this paper. By providing the distribution of the contact line electrical parameters for several possible scenarios, the MVMB model could help in investigating the integration of next-future technological features in the context of smart city evolution, such as stationary ESSs for catenary grid support and EV fast charging via the DC grid itself. The use of EV recharging points to empower the OCL network might also be envisaged. To conclude, any line topology configuration can be simulated, as the model responds reasonably in terms of line voltage, current, and temperature behaviour. As seen, the functioning of the model is independent from the accuracy of how BESSs and EVCSs are represented, and any required complexity could be added to the whole system model in retrospect. Future works may include the development of energy management strategies to optimize the BESSs and EVCSs operation within the traction network. Therefore, the MVMB model might make aware of the benefits and drawbacks of stationary batteries, given that these are currently more expensive than conventional reinforcing feeders. In addition, this model paves the way for a smart interconnection between public and private transport, certainly of great interest for commuters.

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