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Energy Storage Management in Support of Trolleybus Traction Power Systems

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Abstract—This paper presents an energy management strategy for a battery-based stationary energy storage system (BESS) capable of supporting the operation of trolleybus power networks while adhering to the DC network's current and voltage requirements, as well as considering the limitation of the C-Rate, to avoid stress on the battery itself. This work also proposes the dimensioning of this BESS and the comparison of different battery capacities based on a Matlab/Simulink-based model able to simulate a one-day operation of the transit trolleybuses. This manuscript illustrates the effect of the proposed management and the chosen battery through comparisons of the voltage and current profiles along the line. The simulation results show an increase in the voltage level and a decrease in the line current along the catenary with the use of the BESS, indicating that the battery can be a solution to improve the operation of trolleybus systems, even though it is not usually used for this type of network.

Keywords — *IMC trolleybuses, DC catenary network, stationary energy storage, battery sizing, energy management.*

I. INTRODUCTION

In many countries, the strong request for people mobility has grown in the last years and will continue to increase in areas surrounding metropolitan cities. Currently, urban areas account for over half of total passenger transport activity, serving a global urban population that exceeded 3.9 billion in 2015. By 2050, the urban population is expected to increase by another 2.5 billion people, reaching 66% of the total global population [1]. As an example, in terms of CO₂ emissions per passenger-kilometer, railways are the most energy-efficient mode of passenger transportation and their electrification is continuously growing [1], [2]. In the urban environment, the electrification of the means of transport also tends to grow, as well as its integration with renewable energies and various technologies.

In the context of urban mobility, electric-powered mass transit, such as metro, trams, trolleybuses, and full electric buses (eBuses) are broadly used in several cities worldwide, and there is plenty of room for scientific research aimed to increase the transport capacity of the system, the energy efficiency, and lowering operational costs. Trolleybuses are comparable to other light rail modes such as tramways and metro in terms of electrification and passenger transport capacity. Unlikely ordinary buses, trolleybuses require an overhead power supply system.

An example of transport mobility enhancement from an eco-sustainable point of view and public mobility demand is happening in the city of Bologna, Italy. It will be soon in operation, together with the traditional trolleybus fleet, the so-called In-Motion-Charging (IMC) trolleybus; a hybrid between traditional trolleybus and eBuses. The IMC system relies on the overhead contact line (OCL) to recharge the battery while the vehicle travels through the electrified section

of the route. The vehicles run on battery for the rest of the journey, where there is no contact line [3].

In general, this technological trend for green transport solutions requires stronger infrastructures to support vehicles operation. In the case of the IMC trolleybus, it is expected that its operation will have a significant impact on the existing powering network because the charging of the onboard battery requires higher current levels. The natural solution would be a reinforcement of the DC catenary with the construction of more powerful conventional or reversible substations or the inclusion of reinforcing feeders that connect a substation to the weak points of the network. The first solution takes time and physical space, which are in general not easily available in city centers, while the second one introduces several technical challenges in the installation of new conductors, especially in densely urbanized areas.

Supercapacitors (SCs) stationary energy storage systems (ESS) are commonly used to support the DC catenary of urban transportation systems, like metro, tramways, and traditional trolleybuses objecting to better usage of the braking energy [4]-[9]. Batteries tend to be more used in railway systems to reduce voltage drop in the middle of the line [10] or to help during a train departure through auxiliary battery substations built close to a traction power substation [11].

The use of battery energy storage systems (BESSs) placed in specific points of the catenary represents an innovative and interesting solution for 600-750 V DC power supply networks. However, its usage has not been widely investigated so far, and just a few examples have been presented in the literature [12]. In the direction of the Smart Trolley System [13] a great integration of renewable energy sources (RESs), ESSs, electric vehicle (EV) charging points, and eBuses is expected in the near future [14]-[17]. A BESS helps with the intermittent characteristic of RESs (mainly wind generation), provides energy during peak operation hours of the day, and also reduces operative costs.

The inclusion of a BESS requires an adequate management system to control its charging and discharging cycles maintaining compatible levels of current and voltage. In general, Li-ion batteries are used in DC railways for regenerative braking management, and their current is regulated through a DC/DC converter [18]. Current-based control methods regulate the current of the ESS, and voltage-based control methods regulate the voltage in the connection point of the catenary. A comparison between the two control methods has been performed in [19] and four voltage and current control functions for a bilateral DC/DC converter connected to DC railways networks are described in [20]. Optimal operating point control methods for Li-ion batteries are presented in [21], [22]. The maximum discharging current is controlled according to the State of

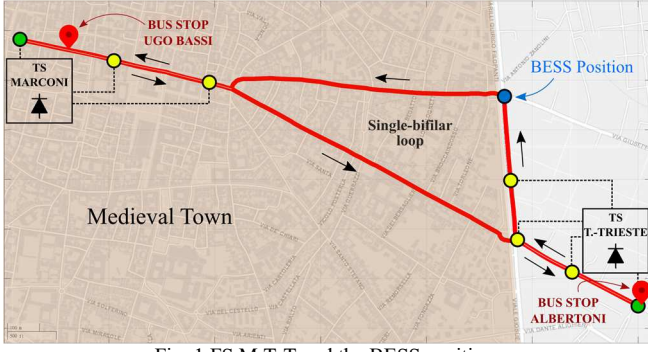


Fig. 1 FS M T-T and the BESS position.

Charge (SoC) and the internal resistance of the battery aiming to maximize the stored energy. Reference [11] presents an optimization method to define the size, position, and control parameters of an auxiliary battery substation used for 3kV DC railways. The proposed algorithm evaluates an SoC value to achieve a fair balance between the ESS faculty to support the DC system during trains acceleration and the ability to recover much of the braking energy.

This paper proposes an energy management system for a mid-line BESS that considers the DC network's current and voltage limitations, as well as the battery's maximum charging/discharging rate. This ensures standards compliance while preventing high-stress battery operations. Additionally, a BESS dimensioning is proposed based on a daily operation of the trolleybus system considering a scenario where the OCL works in a high-demand condition with the operation of sole IMC vehicles. The impact of the proposed BESS management has been estimated based on the effect on the voltage and current profiles in the OCL.

II. THE RESEARCH CONTEXT

A. The Bologna's trolleybus fleet

The current trolleybus fleet in the city of Bologna consists of 18 m standard articulated trolleybuses. Moreover, the municipality has planned to expand the fleet with vehicles suitable for IMC operations and include new trolleybus lines. This work analyzes a conservative but foreseeable scenario where feeding section (FS) Marconi Trento-Trieste (referred to as FS M-TT) runs five trolleybus lines, with IMC vehicles only.

B. The power supply system infrastructure

FSs are parts of the bifilar OCL between two or more electrical sectioning stations in Bologna's trolleybus DC electrical infrastructure. FSs are fed independently by a traction substation (TS) typically situated at one extreme point, or bilaterally by two TSs placed at the ends or in intermediate places. The TSs provide a no-load voltage of 800 V to the trolleybus network using standard 12-pulse rectifiers. The rated voltage level of the DC catenary system in Bologna is set to 750 V and the maximum allowable voltage variation is ± 250 V. Therefore, the voltage in the network should permanently remain within the 500-1000 V range [23]. Overvoltage is generally caused by the recovered braking energy injected into the OCL by standard trolleybuses. However, considering IMC vehicles only, the braking energy is entirely stored in onboard trolleybus batteries, hence the voltage never exceeds 800 V.

As visible in Fig. 1, FS M-TT contact lines span roughly 4400 m from TS Marconi (TS M) in Bologna's medieval historic center to TS Trento-Trieste (TS T-T) in the city periphery. Fig. 1 arrows indicate the trolleybuses' travel

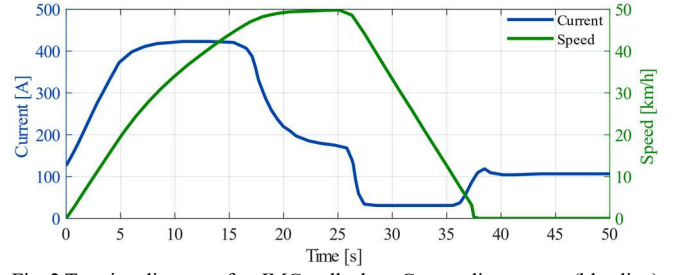


Fig. 2 Traction diagram of an IMC trolleybus. Contact line current (blue line) and vehicle speed (green line).

direction, green and yellow circles represent the location of feeders and reinforcing feeders respectively. The blue circle at about 800 m from TS T-T (2800 m from TS M) represents the BESS location. The chosen position statistically experiences a significant voltage drop caused by the presence of the single-bifilar loop. The battery position also coincides with an unaffected location regarding cultural and geographical constraints, outside the medieval town.

III. THE SIMULATION MODEL

A. The DC network and IMC vehicle model

The catenary stretches depicted in Fig. 1 have been modeled by virtue of the approach adopted in [24]. Referring to the same figure, thanks to its modularity property, such an approach allows a proper circuitry representation of the elements composing the trolleybus electrical infrastructure. Hence, the model not only includes the representation of TSs (modeled through the Thevenin equivalent circuit with a diode in series) and OCL (composed of identical resistive blocks), but also allows flexibility in introducing reinforcing feeders or voltage stabilizers at any location of the line.

As for the trolleybus modeling method, the distance separating two stops, as well as the vehicle dynamics in between them, plays an important role. In the city of Bologna, this distance averages to about 340 m and it is covered at an average speed of 25 km/h in about 50 s. Fig. 2 traction diagram correlates speed and current absorption with respect to the time between stops. The vehicle accelerates at a rate of 1.1 m/s^2 until it reaches a maximum speed of 50 km/h. After reaching the maximum speed the vehicle breaks for 12 s and remains for 10 s at the bus stop for passenger transferring. During the standing time, the current is limited due to thermal constraints at the contact shoes. The braking energy is saved in onboard batteries during decelerations, resulting into a minimal OCL current absorption.

B. The trolleybuses motion simulation

In the mind of having a reasonable approximation of a daily operation of the trolleybus network, this work considers the current timetables of the trolleybuses running along the FS M-TT from 00:00 up to 23:59. In this zone, buses run in two different travel directions. The first one starts at the bus stop Ugo Bassi, next to TS M, and ends at Albertoni near TS T-T, passing through the south route for approximately 2000 m. The second direction goes from Albertoni up to Ugo Bassi, but it stretches for about 2400 m through the north side of the route. With reference to above traction diagram, first and second directions are composed of roughly six and seven 340 m movement cycles respectively. To simulate a realistic situation, multiple routes of a trolleybus movement cycle have been considered.

Adverse factors such as traffic and pedestrians make the real current profile of the trolleybus different from the

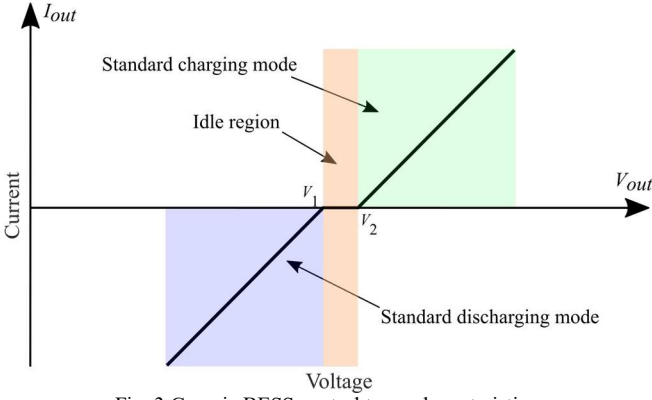


Fig. 3 Generic BESS control trans-characteristics.

reference one. The trolleybuses may also not accurately meet the scheduled times due to delays. All these random factors have not been considered in the simulation model.

C. The battery and the DC/DC converter models

The main battery parameters considered in the present work are the capacity (usually expressed in Ah), the voltage, and the C-Rate. The battery model considered in this work is the Li-ion battery available in Simulink (Mathworks).

The power converter that connects the battery to the catenary system is a boost DC/DC converter whose averaged behavior can be fairly described by the following equations:

$$V_{in} = V_{out}(1 - d), \quad (1)$$

$$I_{out} = I_{in}(1 - d). \quad (2)$$

Equation (1) relates the input V_{in} and the output voltage V_{out} with the converter duty cycle d , whereas (2) associates the input I_{in} and output current I_{out} .

IV. THE PROPOSED ENERGY STORAGE MANAGEMENT

The BESS works in different operating modes, in which the output current in the DC/DC converter is controlled as a function of the line voltage and the battery SoC. The current in the output of the converter is limited in relation to the characteristics of the conductor of the bifilar line, while the current in the input of the converter (battery side) is limited by the battery C-Rate.

For the sake of simplicity, the conductor continuous ampacity is set to 451 A following the procedure reported in [25] annex A, although this standard has been recently superseded by [26]. Considering BESS positioning close to the middle of the line, battery current could be fairly assumed to be equally shared between the two OCL stretches. As a result, the proposed management system sets 900 A as the maximum injected/drawn current limit.

A. Standard charging and discharging modes

The BESS is in the discharging mode if the line voltage is below the lower threshold value V_1 , corresponding to a high-load situation with many vehicles in operation. Hence, the battery supports the catenary using the stored energy ($\text{SoC} > \text{SoC}_{\min}$). Instead, if the line voltage exceeds the upper threshold value V_2 , the battery stores energy ($\text{SoC} < \text{SoC}_{\max}$), reducing the line voltage. The battery current is zero in the idle range between V_1 and V_2 ; voltage level is let free to float as in standard trolleybus networks [11]. Charging and discharging modes are depicted in Fig. 3 as a generic curve with the sole scope to illustrate battery behavior.

Charging and discharging modes are ruled by:

$$\text{charging} \rightarrow I_{out} = s_2(V_{out} - V_2), \quad (3)$$

$$\text{discharging} \rightarrow I_{out} = s_1(V_{out} - V_1), \quad (4)$$

whose V_1 and V_2 , and their corresponding discharging and charging slopes (s_1 and s_2) should be customized according to the FS characteristics, BESS position, desired control behavior, ampacity, and so on. Equations (3) and (4) dictate the converter output current when no C-Rate limitation is considered.

B. Limited charging and discharging modes

Objecting not to operate the battery under high stress, the maximum battery C-Rate is set to 2C. Therefore, replacing (1) in (2) and setting $I_{in} = 2C$, the maximum I_{out} for charging and discharging take the form:

$$\text{charging} \rightarrow I_{out} = \frac{2CV_{in}}{V_{out}}, \quad (5)$$

$$\text{discharging} \rightarrow I_{out} = -\frac{2CV_{in}}{V_{out}}. \quad (6)$$

For the charging process of the battery, the intersection between (3) and (5) leads to the voltage value:

$$\text{charging} \rightarrow V_{out} = \frac{V_2}{2} + \frac{1}{2} \sqrt{V_2^2 + \frac{8CV_{in}}{s_2}}, \quad (7)$$

from where the converter output current I_{out} starts to be ruled by (5) due to the C-Rate limitation. Similarly for the discharging process, the intersection between (4) and (6) leads to the voltage value:

$$\text{discharging} \rightarrow V_{out} = \frac{V_1}{2} + \frac{1}{2} \sqrt{V_1^2 - \frac{8CV_{in}}{s_1}}, \quad (8)$$

under which (6) starts to rule I_{out} .

To ensure that (8) always results in real values, following inequality must hold:

$$V_1^2 - \frac{8CV_{in}}{s_1} \geq 0. \quad (9)$$

meaning that maximum discharging limitation occurs only if the battery capacity is lower than:

$$C = \frac{s_1 V_1^2}{8V_{in}}. \quad (10)$$

Charging and discharging could be additionally limited by voltage thresholds set by standards and OCL ampacity.

V. SIMULATION RESULTS

This section reports the simulation results showing impacts of the proposed control system on OCL and BESS.

From the OCL point of view, BESS action produces a voltage increment while reducing catenary current when a great amount of trolleybuses are in operation. On the other hand, the proposed control ensures that the battery never exceeds the maximum C-Rate 2C.

The control curve requires to be customized so that the BESS influences the DC network in the desired way with reference to the standard operations without BESS; here indicated as base

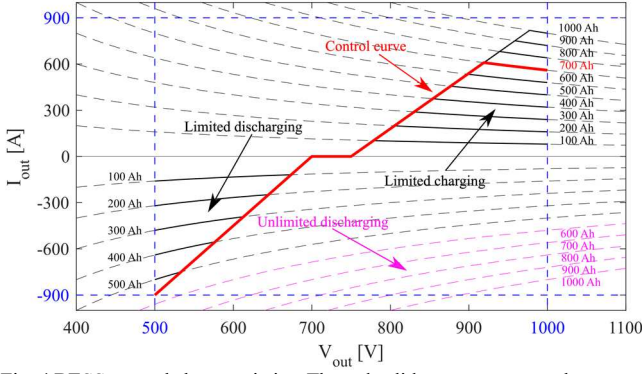


Fig. 4 BESS control characteristics. The red solid trace represents the control curve with a 700 Ah battery. The black solid lines illustrate charging and discharging C-Rate limitations. Unlimited discharging is depicted with pink dashed lines. Blue bonding constitutes OCL current and voltage limitations.

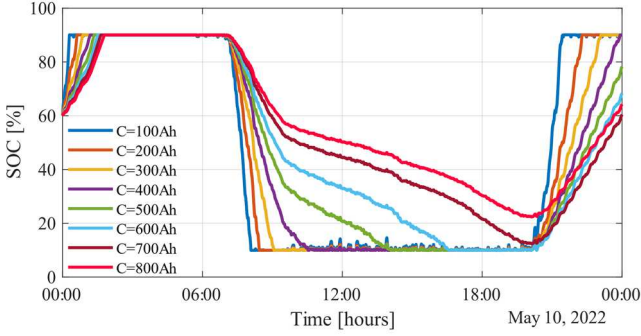


Fig. 5 Simulation of the 24 h trolleybus system operation for different battery capacities considering the proposed energy management system.

case scenario (BC scenario). To adequately design the control curve, the BC scenario covers network operation between 7:00 to 10:00. Being the latter the most energy demanding period, the BESS is expected to provide the most significant contribution. From the analysis of the BC scenario, the control curve parameters V_1 and V_2 have been set to 700 V and 750 V respectively, resulting in a charging process that occurs from 750 V to 1000V and a discharging one that occurs from 500 V to 700V. With a view to limiting I_{out} at the maximum OCL ampacity (900 A), charging s_2 and discharging s_1 slopes are computed and set to 3.6 A/V and 4.5 A/V respectively.

Fig. 4 illustrates the converter output current considering the charging/discharging limitation for a battery voltage equal to 400 V. Dashed lines result from (5) and (6) by considering different capacities, from 100 Ah to 1000 Ah. The solid traces characterize the control curve considering the effect of the C-Rate limitations according to the battery capacities. Specifically, the red solid line illustrates the control curve for a battery capacity of 700 Ah. As visible from the blue dashed box, Bologna's DC OCL voltage and current limitations bound the control characteristic operative region. For the scenario addressed in this paper, Fig. 4 indicates that the discharging process is no longer limited for batteries capacities above 560 Ah (as argued in (6)). Indeed, pink dashed traces never intersect with the standard discharging mode curve. In contrast, even with high-capacity values, it is possible to observe charging process current limitations due to OCL ampacity. In case of battery fully charged or discharged, I_{out} is set to zero when operating in charging and discharging quadrants respectively; the OCL is left free to float as in conventional trolleybus grids.

A. Choice of the battery capacity

As visible in Fig. 5, simulations have been performed with battery capacities varying from 100 to 800 Ah to determine

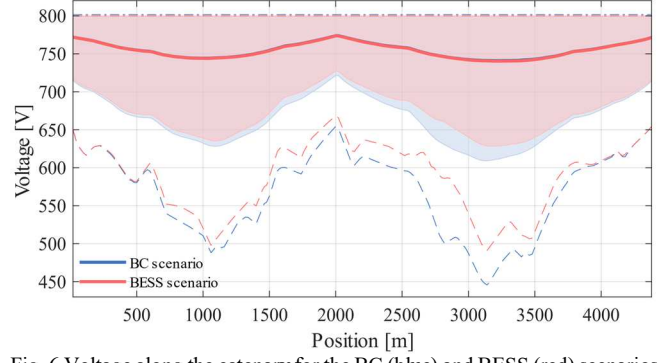


Fig. 6 Voltage along the catenary for the BC (blue) and BESS (red) scenarios for the 24 h simulation. Voltage maximum and minimum (dot-dashed lines), mean (solid lines), and 95% central inter-percentile range (filled areas).

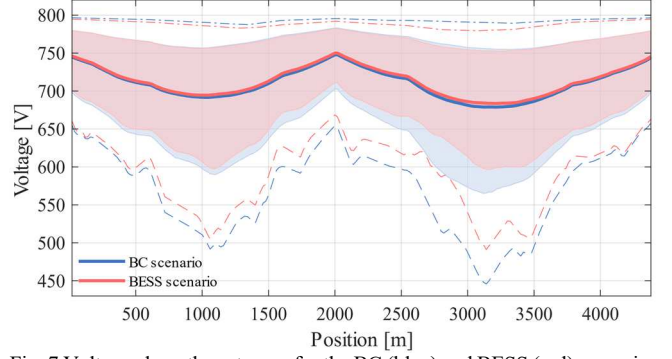


Fig. 7 Voltage along the catenary for the BC (blue) and BESS (red) scenarios for the 3 h simulation. Voltage maximum and minimum (dot-dashed lines), mean (solid lines), and 95% central inter-percentile range (filled areas).

the optimal value. The battery SoC is limited by the control between the range $10\% < \text{SoC} < 90\%$. At the simulation starting time (00:00), the battery SoC is initialized at 60%, making it possible to observe one entire cycle of charging and discharging for one-day simulation (up to 23:59). The 20:00 to 07:00 interval (11 h covering night and early morning) is left for the battery charging since, because subjected to the fewer number of trolleybuses. The choice of the battery capacity to be used in the system can be done by observing the traces in Fig. 5. As anticipated before, 07:00 to 10:00 is the most overloaded period. Indeed, it is possible to see batteries having capacity lower than 600 Ah hitting the 10% SoC limit too soon – if not at the operations beginning – experiencing a complete battery discharge. On the other hand, a capacity of 800 Ah appears oversized, since the minimum SoC that it reaches is about 23%, well above 10%. In conclusion, the analysis on the here specific scenario has been done considering a battery with a capacity of 700 Ah; battery operations are here indicated as BESS scenario. The adopted control curve coincides with the red curve displayed in Fig. 4.

B. The impact on the system voltage profile

Voltage levels have been acquired with a 20 m spatial discretization over a full-day and 07:00 to 10:00 sessions. By means of a 1 Hz sampling rate, 86400 and 10800 data points have been collected for the 24 h and 3 h simulations respectively.

Voltage mean, maximum, minimum, and its 95% inter-percentile computed every 20 m are illustrated in the OCL voltage distributions of Figs. 6 and 7 for the 24 h and the 3 h sessions respectively. BC scenario is depicted in blue while BESS scenario is represented in red. The two extremities (0 m and 4400 m) where the voltage levels reach the maximum point coincide with TS M location. On the other hand, mid-line voltage peak corresponds with TS T-T position.

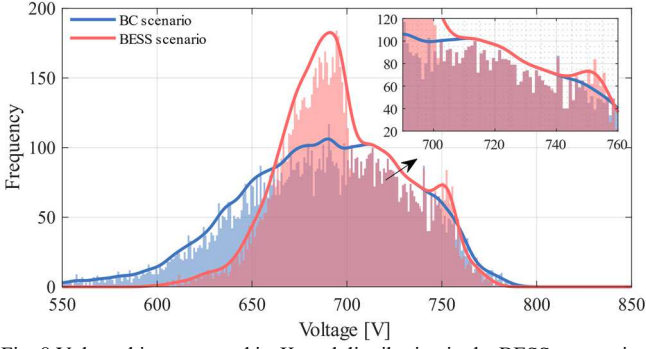


Fig. 8 Voltage histogram and its Kernel distribution in the BESS connection point for the BC (blue) and BESS (red) scenarios from 7:00 to 10:00.

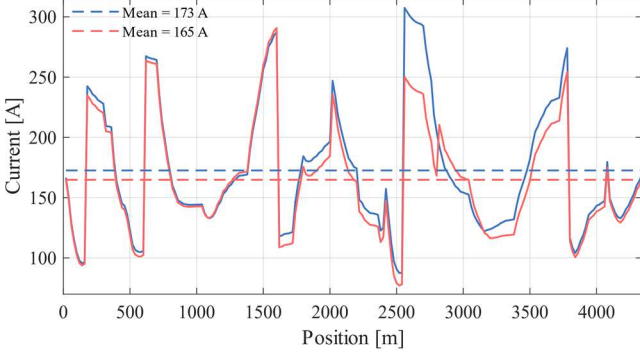


Fig. 9 Current RMS (solid traces) and its mean value (dashed lines) along the OCL for the BC (blue) and BESS (red) scenarios from 7:00 to 10:00.

From the results, it is possible to observe that the mean values for both scenarios are almost the same for the 24 h case (Fig 6), while for the 3 h period (Fig 7) the mean value for the scenario with battery is slightly higher. In particular, minimum voltage point in the BESS scenario results 1.5% higher with respect to the BC scenario. The voltage improvement appears clearer when observing the minimum values, which in the minimum voltage point can be quantified as an increment of about 10% (Fig 7). As visible from the inter-percentile range, the voltage distribution appears to be less dispersed especially close to the battery connection point (2800 m). Although battery effectiveness is more remarkably visible from 07:00 to 10:00 when the network is overloaded (Fig. 7), it still provides crucial support throughout the whole day (Fig. 6).

C. The catenary voltage in the battery connection point

Fig. 8 shows the histogram and the associated Kernel probability distribution of the voltage profile in the bifilar line at the point of the BESS connection for the discharging process from 07:00 to 10:00. As clearly visible, the profile gets narrower when the BESS is connected shifting the profile's lowest percentile from around 570 V to 600 V (Fig. 7). Furthermore, it is possible to demonstrate the idle region (700-750 V) correct operation by comparing the voltage histograms zoomed frame for the BC (in blue) and the BESS (in red) scenarios. As expected, a zero current is provided by the storage, resulting in the same voltage profile for both scenarios, as witnessed by the superposition area (in violet).

D. The impact on the system current profile

The current measurements in the catenary provide positive and negative values, because of the measuring instrument orientation and the vehicles' travel direction. To have a better visualization of the catenary current profile, Fig. 9 displays the current RMS value calculated in every 20 m measurement point over the 7:00 to 10:00 period. As expected, the red curve shows an overall current reduction for

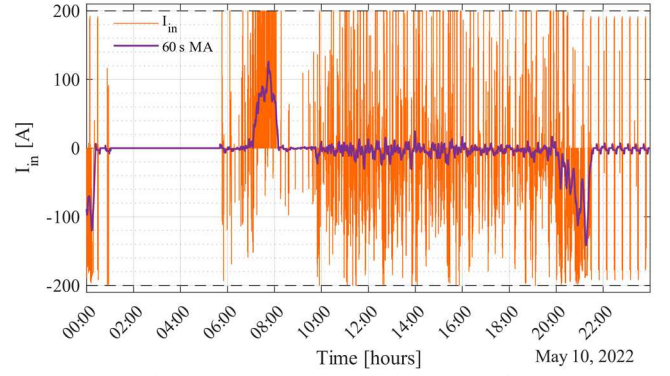


Fig. 10 Battery instantaneous current (orange trace) and its 60 s moving average (violet trace) considering a capacity of 100 Ah (2C limits ± 200 A).

the BESS scenario (red line) with respect to the BC (blue line). The place where the current reduction is more apparent is near the TS T-T (at approximately 2500 m), with a reduction of about 20% in the current level. Finally, the average of the RMS provides insights on network Joule losses associated to both scenarios. As visible in Fig. 9, BESS scenario (red dashed line) produces a 4.6% reduction in the average current RMS values in comparison with the BC scenario (blue dashed line).

E. The battery current limitation

Even though a battery with a capacity of 100 Ah is largely undersized, the network simulation with this specification is useful to verify if the current limitation imposed by the control method works. Fig. 10 illustrates the current limitation for the discharging (positive currents) and charging process (negative currents). In both situations, the current does not exceed the ± 200 A limitation (2C). The 60 s moving average (MA), represented by the violet trace, presents results in agreement with the SoC evolution shown in Fig. 5.

VI. CONCLUSIONS

The developed work proposes an energy management strategy for a battery stationary energy storage system that accounts for both voltage and current limitations of the DC bifilar line and of the battery itself (maximum C-Rate). This manuscript also proposes the sizing of this BESS for the specific case under analysis thanks to simulations of the daily operation of the trolleybus network in the city of Bologna performed in the Simulink environment. A high energy demand scenario has been examined due to IMC trolleybuses operating in the system. The proposed control method has been verified through comparisons of the voltage and current profiles along the DC network.

The results indicate that the installation of a BESS improves the DC network voltage and current profile while its control ensures that the battery does not operate under stress. As an example, the voltage increase for the minimum voltage point can be quantified as 1.5% referring to the mean value, and 10% for the minimum voltage. A decrease in the network current profile is also observed and quantified up to 20% in the vicinity of the TS T-T.

The battery specifications, such as capacity, pack voltage, and C-Rate, and the control thresholds for the idle region are not determined through an optimization process, but by an evaluation of the FS operation for the BC scenario. The application of an optimization process for the choice and control of the BESS can considerably improve the results, opening paths for future contributions.

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