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This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

Published Version:

Paternost R.F., Mandrioli R., Barbone R., Cirimele V., Loncarski J., Ricco M. (2022). Impact of a Stationary Energy Storage System in a DC Trolleybus Network. Institute of Electrical and Electronics Engineers Inc. [10.1109/ITEC53557.2022.9813948].

Availability:

This version is available at: <https://hdl.handle.net/11585/891624> since: 2024-02-29

Published:

DOI: <http://doi.org/10.1109/ITEC53557.2022.9813948>

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Impact of a Stationary Energy Storage System in a DC Trolleybus Network

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Abstract—In the context of urban transportation electrification, trolleybus systems can be modernized by using vehicles based on the so-called In-Motion-Charging (IMC) technology. The current required by IMC vehicles is higher than traditional trolleybuses because, in addition to traction, they must also absorb the current needed to recharge the batteries on board. With the aim of reducing voltage drops in trolleybus networks even in case of high-power demands, the impacts of the inclusion of a mid-line stationary energy storage system to maintain a high voltage level and to reduce the network energy losses are analyzed in this paper. This work consists of the development of Monte Carlo-based simulations to treat as random variables the initial positions of the trolleybuses in the DC catenary system and their respective current draws. A current absorption profile of the IMC trolleybus has been used in conjunction with a model able to simulate the movement of multiple vehicles in a DC network section. According to the achieved results, it is possible to observe an improvement in the network voltage profile and an indication of energy savings.

Keywords—trolleybuses, DC catenary network, stationary energy storage, battery, Monte Carlo simulations.

I. INTRODUCTION

As a consequence of the prevalence of internal combustion engine vehicles in the European Union (EU) vehicle fleet, transport contributes to about one-quarter of the total greenhouse gasses (GHG) [1]. In the European Green Deal, EU goals aim to reduce transport GHG by at least 55% and 90% by 2030 and 2050, respectively [2]. In this context, urban public transport plays an important role, and it is expected to channel noticeable efforts and investments. Electric-powered mass-transit like trolleybuses, trams, and metro are commonly spread in European cities, and there is indeed much space and public interest for technological research objecting to the improvement of energy efficiency and the decrease of their operational cost.

Trolleybuses, differently from traditional buses, require an electrical infrastructure (i.e., the overhead lines) for the supply having similar characteristics to light railway modes, like tramways and metro. The use of a fully electric bus (eBus) fleet for urban transportation is subordinated to battery charging, making necessary the building of contact charging stations or induction charging stations at terminals [3]. This results in longer deadtime in the depots, considerable financial resources for implementation, and cumbersome routes replanning. One alternative solution is the so-called In-Motion-Charging (IMC) technology. Being a hybrid between standard trolleybus and eBus, the IMC system requires the overhead contact line to recharge the battery while moving through the electrified stretch of the route. In the remaining part of the course, where

there is no contact line, the vehicle runs on battery [4].

In the context of eco-sustainable and intermodal passenger transport, several cities worldwide are planning IMC deployment as part of their trolleybus fleet. For example, a considerable amount of IMC vehicles is expected to constitute a relevant share of the trolleybus fleet in the city of Bologna [5]. Consequently, the DC overhead infrastructure should be strengthened to support the IMC vehicles, which clearly require a higher current than the traditional counterpart. As the requirement of higher current levels can imply high voltage drops, losses increasing, overloads, and overtemperatures along the infrastructure, it could be beneficial to include a stationary energy storage system (S-ESS) along the line to keep voltage profiles close to rated levels (e.g., 750 V [6]), by providing energy during peaks hours.

Literature reports many examples of S-ESS for voltage profile improvement and energy savings. Supercapacitor S-ESSs are more used for electrified urban transportation systems, like traditional trolleybuses, to recover the braking energy (high-power and low-energy requirements). Applications for trolleybuses networks can be found in [1], [7] - [9], as well as tramway and metro systems are exemplified in [10] - [13]. As explained in [14] - [16], batteries are mainly used in DC railway systems. The design of a hybrid S-ESS composed of supercapacitors and batteries for railways applications is presented in [17]. In the case of IMC trolleybuses, the braking energy can be directly recovered into the onboard vehicle's battery, so high-power S-ESSs (e.g., supercapacitors) are not needed, and batteries can be instead adopted to optimize the DC network from an energy-intensive point of view.

This paper aims to analyze the benefits in the voltage level and current distribution thanks to an S-ESS properly placed in the most overloaded section of the Bologna trolleybus network. The possibility of enhancing the DC network system efficiency operation due to catenary losses reduction is also evaluated. To perform the analysis, simulations have been carried out based on a Monte Carlo method that deals with the randomness of the trolleybus positions and their respective current draws. The electrical network and the moving trolleybuses have been modeled in Matlab/Simulink environment according to the model developed in [18]. To the best of the author's knowledge, there are no works in literature coupling an IMC trolleybus current absorption profile with Monte Carlo-based simulations together with a model able to simulate the movement of different trolleybuses within the urban infrastructure.

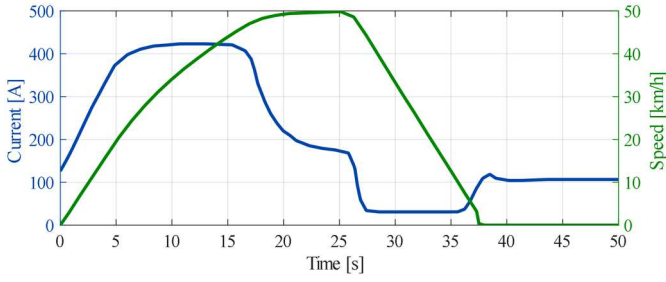


Fig. 1 Traction diagram of an IMC trolleybus. Contact line current (blue line) and vehicle speed (green line).

II. THE RESEARCH CONTEXT

A. Chosen trolleybus fleet and electrical infrastructure

The DC electrical infrastructures to feed trolleybuses are generally divided into feeding sections (FSs), which are portions of the bifilar overhead line between two or more electrical sectioning points. This work focuses on the trolleybus network in the city of Bologna, in which FSs are fed independently by two traction substations (TSs) placed at their extremities.

As per [6], TSs power the trolleybus network with a nominal voltage of 750 V through standard 12-pulse rectifiers represented by its equivalent Thevenin model detailed in [18]. This work focuses on the FS named “Marconi Trento-Trieste”, referred to as FS M-TT. Its contact lines stretch from TS Marconi (TS M), located in the medieval historic center of Bologna, towards TS “Trento-Trieste” (TS T-T), located in the city suburbs, for approximately 4400 m.

In general, the companies responsible for the trolleybuses' power supply systems, tend to design the electrical infrastructure based on a conservative high power demanding scenario of the system operation. For the city of Bologna, in a peak hour conservative scenario, at most 14 trolleybuses can simultaneously transit FS M-TT as scheduled by the local public transport company timetables. Therefore, the analysis provided in this manuscript considers 14 trolleybuses operating in the network. Furthermore, a more power-demanding situation considering only IMC vehicles is assumed.

B. IMC vehicles characteristics

An IMC current profile has been built using a Simulink model that correlates the speed and the current absorption of vehicles with respect to time over a route between two stops, which is standardized as 340 m according to the local public transport company in Bologna. The results graph is referred to as the traction diagram (TD) (Fig. 1).

With the purpose of building the TD, the path of 340 m is covered in 50 s, considering an average speed of 25 km/h. The vehicle starts moving with an acceleration of 1.1 m/s² up to reach the maximum speed of 50 km/h. After reaching the maximum speed, the vehicle starts braking and completes the process in 12 s, remaining for 10 s at the bus stop for passenger transit. It can be noticed that during the standing time, a constant current absorption is present to supply auxiliary power sources. During decelerations, braking energy is stored on onboard batteries leading to no current absorption from the contact line.

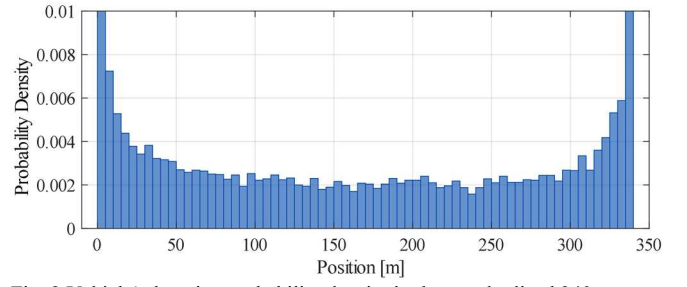


Fig. 2 Vehicle's location probability density in the standardized 340 m span.

III. THE SIMULATION MODEL

A trolleybus power system can be reasonably treated as a stochastic object because of the randomness of some variables [19]. Examples of random variables are the trolleybuses positions in the system, which can be predicted based on the scheduled arrival time in the stops provided by timetables. But, due to traffic, driving behavior, road construction, and so on, trolleybuses can be delayed.

The location of the trolleybuses and their respective current draw are the two key parameters used to provide an analysis of the DC catenary network [19]. These two variables have a random nature and can be treated as Monte Carlo input variables. In this model, the initial positions of the trolleybuses are described by their probability density function (PDF). The IMC current characteristic gives the vehicle's current (Fig. 1), and the initial current value depends on the distance of a trolleybus from the consecutive stop.

A. The probabilistic approach of the initial trolleybuses position

The following demonstration is based on the manuscript [19]. The probability of finding a vehicle between two points (x_1, x_2) is proportional to the time travel between them:

$$P(x_1, x_2) = \frac{k(x_2 - x_1)}{v_{av}}, \quad (1)$$

where v_{av} is the average speed between two points and k is a proportional coefficient. The probability is defined as:

$$P(x_1, x_2) = \int_{x_1}^{x_2} p(s) ds, \quad (2)$$

where $p(s)$ is the PDF of finding a vehicle at a given point. Symbolizing the difference $x_2 - x_1$ as Δs , one obtains:

$$P(0, \Delta s) = k \frac{\Delta s}{v_{av}} = \int_0^{\Delta s} p(s) ds. \quad (3)$$

Considering an infinitesimal space ($\Delta s \rightarrow ds$), the speed can be considered by its instantaneous value $v(s)$ instead of the average speed (v_{av}). Therefore, the function takes the form:

$$k \frac{ds}{v(s)} = p(s) ds. \quad (4)$$

Finally, the desired PDF can be found:

$$p(s) = \frac{k}{v(s)}. \quad (5)$$

The physical meaning of equation (5) is that the probability of finding a vehicle at a given point is inversely proportional to the vehicle speed (exemplified in Fig. 2). Indeed, the probability of finding the vehicle increases near the stops.

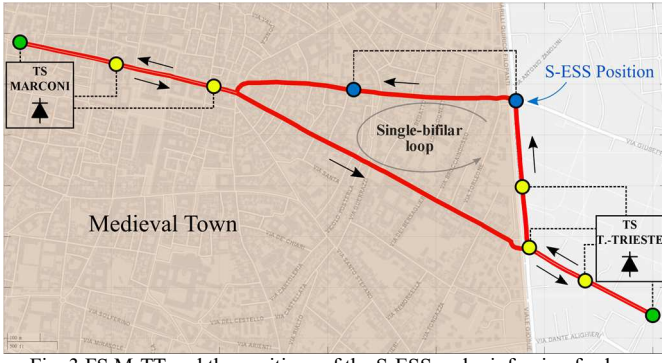


Fig. 3 FS M-TT and the positions of the S-ESS and reinforcing feeders.

A. The simulation steps

The simulation model can be divided into three main stages. Firstly, initial trolleybus positions within the FS of Fig. 3 and respective currents absorptions are defined. Secondly, power flow calculations considering the trolleybuses movement are performed using the Simulink model of [18]. Every simulation lasts 50 s, and data is stored at a 10 Hz sampling rate, resulting in 500 voltage and current data points every run. To provide the Monte Carlo analysis, 2000 simulations have been performed considering a scenario without S-ESS, which is named here as the base case (BC) scenario and further 2000 simulations for a scenario with S-ESS, named as S-ESS scenario. Finally, losses calculation in the DC network in both scenarios has been performed and compared.

B. The chosen network position for the S-ESS

The S-ESS is placed about 800 m from TS T-T (around 2800 m from TS M). To better support the network, a 600 m feeder (Fig. 3) also connects the S-ESS to another point of the line, 1400 m from TS T-T (3400 m from TS M). The S-ESS position has been chosen just outside medieval town in a position not subject to cultural and landscape constraints (Fig. 3). Because of FS morphological characteristics, the chosen points statistically present a substantial voltage drop, and the installation of an S-ESS might benefit the most.

C. The choice of the S-ESS and its current control

The S-ESS has been designed as a mid-line battery stationary storage with 700 Ah capacity and a nominal voltage of 400 V, considering that the control system starts to inject a constant current at a 2C rate (1400 A) only when an overload operation is identified through a low catenary voltage profile. The control system to identify this situation is outside the scope of this paper. The S-ESS can support the FS M-TT for approximately 24 minutes if operating uninterrupted, but in an actual application, the storage can be activated intermittently during periods of high load, for example, in the morning between 7 am and 9 am when the demand for public transport is very high.

The battery packs are connected to the catenary through a standard interleaved bidirectional DC/DC converter [20]. The current at the converter's output does not exceed 900 A, in accordance with the DC network compliances. No anti-islanding controller is implemented at this stage.

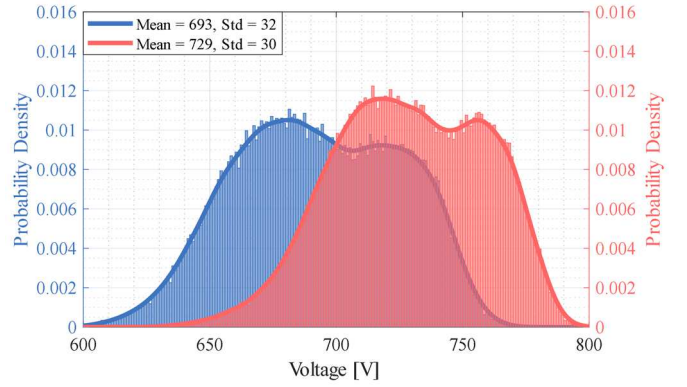


Fig. 4 Voltage PDFs in TS T-T for the BC (blue) and S-ESS (red) scenarios.

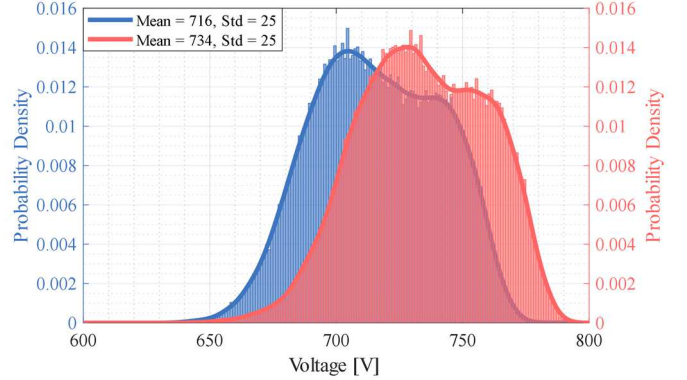


Fig. 5 Voltage PDFs in TS M for the BC (blue) and S-ESS (red) scenarios.

IV. VOLTAGE AND CURRENT IMPACT

This section presents the simulation results regarding voltages and currents along the circuit sufficient to understand the impacts of using the S-ESS on the catenary network.

A. The system voltage profile

Fig. 4 and Fig. 5 show the PDFs of the voltage profile of the TS T-T and TS M. Although the S-ESS is located 2800 m from TS M, it is possible to observe an increase in the voltage profile, moving the mean value of the PDF from approximately 716 V to 734 V (2.5% increase) while for TS T-T the mean value is shifted from 693 V to 729 V (5.2% increase).

The voltage distribution along the catenary is depicted in Fig. 6 for a circumstance where there is no S-ESS (in blue) and with a S-ESS (in red). The FS M-TT has a total length of 4400 m, and the two extremities refer to TS M. The TS T-T feeds the FS near the center of the line (about 2000 m). The points where the S-ESS is connected can be seen in Fig. 6 near the distances 2800 m and 3400 m.

In the simulation model, there is a voltage measurement every 20 m along the catenary (stored with 10 Hz frequency). As 2000 Monte Carlo simulations have been run, and each single simulation results in 500 measurements, for each set of measurements, there are 1.0×10^6 voltage values. For each measurement, set has been calculated with its values of the mean, maximum, minimum, and 95% inter-percentile range. From Fig. 6, it is possible to observe that the voltage mean value for the S-ESS scenario significantly increases in

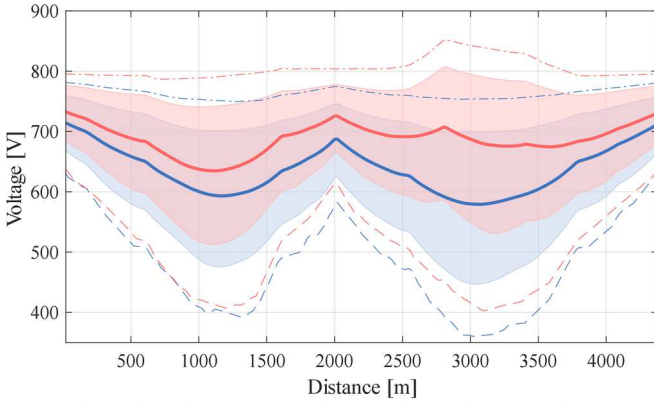


Fig. 6 Voltage along the catenary for the BC (blue) and S-ESS (red) scenarios. Voltage maximum (dot-dashed lines), minimum (dashed lines), mean (solid lines), and 95% central inter-percentile range (filled areas).

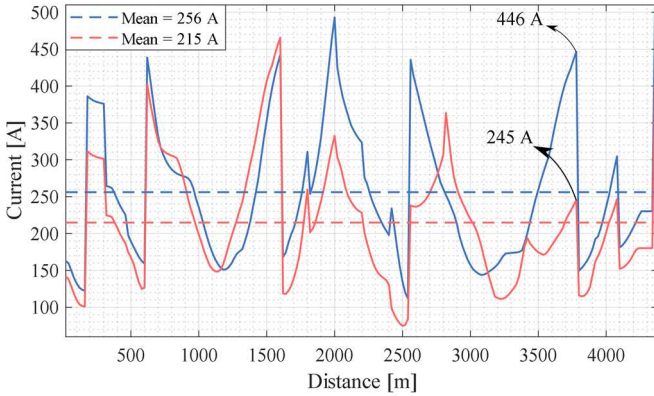


Fig. 7 RMS current computed for each measurement set for the BC (blue) and S-ESS (red) scenarios.

comparison to the BC scenario and can be quantified up to approximately +19% in the minimum voltage point (around 3000 m). In reference to the minimum voltage values (dashed lines) the voltage increase can be quantified as +15.5%. As visible from Fig. 6 inter-percentile range, the voltage distribution substantially increases when comparing the soft blue area (BC scenario) with the soft red one (S-ESS scenario).

A. The system current profile

In a similar way to the analysis done for the voltage, every 20 m a measurement block stores the current in the bifilar line in a 10 Hz frequency (1.0×10^6 current values for each set). Because of the measuring instrument orientation and the vehicle's travel direction, the current measurements in the catenary provide positive and negative values. To better comprehend the catenary current profile (and associated losses), the RMS value has been calculated for each 20 m set of measurements. The red curve in Fig. 7 demonstrates a reduction in overall current lines for the S-ESS scenario compared to the BC scenario (blue line). Each 20 m set of measurements has a corresponding RMS value, and to understand the average current in the DC network for both scenarios, the average of the RMS values previously mentioned has been calculated. The dashed lines represent the average current value for the BC (blue line) and the S-ESS (red line) scenarios, and a reduction in the circuit current can be quantified as 16%. The place where the current reduction is

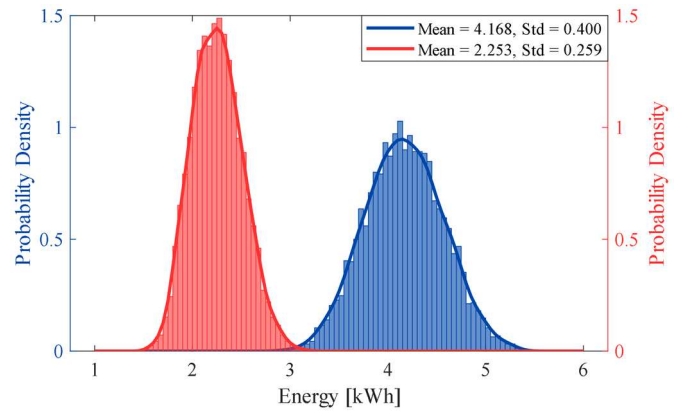


Fig. 8 PDFs of the catenary losses for the S-ESS (red) and the BC (blue) scenarios.

more expressive is at approximately 3700 m, with a reduction of about 45% in the current level.

At first, it seems counter-intuitive that the inclusion of a S-ESS causes a reduction in the current of the catenary system, but this happens because instead of having only the two TS as power sources, the S-ESS acts as a third source, so the total current demanded by the loads (trolleybuses vehicles) is now supplied by three different points in the circuit. The voltage level increase provided by the S-ESS also contributes to the reduction of current in the circuit since the current required by the loads to maintain the same demanded power is lower.

V. THE ENERGY ANALYSIS

At the end of every single simulation, it has been possible to estimate the total energy generated by the substations, the energy injected by the S-ESS, and the energy absorbed by the vehicles. Consequently, the losses in the bifilar lines, supply, and reinforcing feeders have been calculated through the energy balance of the system, in which the losses are equal to the energy generated minus the energy consumed by the loads. Fig. 8 shows the PDFs of the catenary losses for the BC and the S-ESS scenarios, built with 5000 simulations instead of 2000 to provide a better shape of the PDF.

As a result of the current reduction that circulates in the network when the S-ESS is in operation, Fig. 8 shows a reduction of the ohmic losses in the catenary system for the E-ESS scenario compared to the BC scenario. But a deeper analysis is required considering the calculation of ohmic losses in the network during battery charging and the efficiency of the block compounded by the battery and the converter.

B. Catenary losses during the S-ESS charging process

The theoretical time (in h) to charge and discharge a battery is related to its rated capacity C (in Ah) and the current by:

$$t = \frac{C}{I} u, \quad (6)$$

where u is the percentage corresponding to the useful capacity of the battery that, in this case, is 80% because the battery is considered to operate within the range between 10% and 90%. The battery charging is carried out at night, and there is no vehicle circulation during this period.

TABLE I
ENERGY CALCULATION FOR THE BATTERY CHARGING.

Time	I_B	W_{TS}	W_{ESS-CH}	L_{CAT}
1 h	560 A	259 kWh	245 kWh	14.0 kWh
2 h	280 A	249 kWh	243 kWh	6.00 kWh
3 h	187 A	246 kWh	242 kWh	4.00 kWh
4 h	140 A	245 kWh	241 kWh	4.00 kWh
5 h	112 A	244 kWh	241 kWh	3.00 kWh

Table I shows the time and the current I_B to charge the battery from the SOC of 10% up to 90% in function of the catenary losses during the charging L_{CAT} , the energy generated by the substations for the battery charging W_{TS} , and the energy absorbed by the S-ESS during the charging W_{ESS-CH} . It is observable that the higher the charging current, the higher the ohmic losses in the catenary grid.

C. Estimation of the catenary losses during the S-ESS discharging

The PDFs in Fig. 8 have been built based on simulations that consider a 50 s operation of the trolleybus system. But the catenary losses should be estimated considering the trolleybuses operation for a time enough to discharge the battery from 90% to 10%. To calculate these losses, the following procedure has been adopted.

The time to discharge the battery considering a constant current injection of 1400 A (2C) is:

$$t(h) = \frac{700 \text{ Ah}}{1400 \text{ A}} \cdot 0.8 = 0.4 \text{ h} = 24 \text{ min} = 1440 \text{ s}. \quad (7)$$

Considering the same conditions of the simulations described in the previous sections, if the system operates for 1440 s (the time to discharge the battery fully), it is possible to statistically estimate the energy losses in the network according to the procedure below.

Considering the energy as a random variable, the expected value of a continuous random variable is defined as:

$$E[x] = \int_{-\infty}^{\infty} xf(x)dx, \quad (8)$$

where x is a random variable and $f(x)$ its probability density.

According to the linearity of expectations property, the expected values of a 1440 s simulation can be calculated based on the values of a 50 s simulation:

$$E[x_{1440}] = \frac{1440}{50} E[x_{50}], \quad (9)$$

where x_{50} is a random variable of the 50 s simulation and x_{1440} is the one considering a 1440 s scenario. Considering the PDFs of the energies in the system as normal distributions (Fig. 8), its expected values are equal to their mean values ($\mu = E[x]$).

The greater the number of Monte Carlo simulations, the better the analysis results, but due to computational limitations, the energy analysis works with 5000 simulations of 50 s for each scenario (BC and S-ESS ones). The estimation tool based on mean values is helpful to save time and computational effort since, based on 50 s second simulations, it is possible to make a statistical estimation for simulations with longer durations without having to run numerous simulation scenarios for it.

The variables considered for this analysis are the energy produced by the substation during the battery discharging

TABLE II
MEAN VALUES OF THE ENERGIES FOR THE 50 s AND 1440 s SIMULATIONS.

Time	Scenario	W_{TS}	$W_{ESS-DISCH}$	W_{BUS}	L_{CAT}
50 s	BC	27.2 kWh	-	23.1 kWh	4.10 kWh
	S-ESS	20.0 kWh	8.14 kWh	25.9 kWh	2.24 kWh
1440 s	BC	785 kWh	-	665 kWh	120 kWh
	S-ESS	578 kWh	234 kWh	747 kWh	65.0 kWh

W_{TS} , the energy injected by the S-ESS during discharging $W_{ESS-DISCH}$, the energy delivered to trolleybuses W_{BUS} and the catenary losses L_{CAT} in the BC and S-ESS scenario. Their respective mean values provided by the 50 s simulation and the estimated ones for a 1440 s scenario are shown in Table II.

As visible, the energy delivered to the trolleybus W_{BUS} is higher in the case of S-ESS. This difference is attributable to the model in [18], which considers trolleybus as constant-current loads rather than constant power. In an actual system, voltage improvements due to S-ESS cause absorbed current reductions leading to even more minor losses and, therefore higher efficiencies.

D. Losses reduction and overall efficiency improvement

Equation (10) shows BC scenario system efficiency:

$$\eta_{BC} = \frac{W_{BUS}}{W_{TS}} = \frac{W_{BUS}}{W_{BUS} + L_{CAT}}. \quad (10)$$

Equation (11) shows S-ESS scenario system efficiency:

$$\eta_{S-ESS} = \frac{W_{BUS}}{W_{TS}} = \frac{W_{BUS}}{W_{BUS} + L_{CAT} + L_{ESS}}, \quad (11)$$

where W_{TS} and L_{CAT} , differently from (10), collect contributions during both charging and discharging phases. The term L_{ESS} represent ESS losses expressed as:

$$L_{ESS} = W_{ESS-CH} - W_{ESS-DISCH} = W_{ESS-CH}(1 - \eta_{RT}), \quad (12)$$

having η_{RT} the converter and battery round-trip efficiency.

Equalizing W_{BUS} , normalized losses reduction (ΔL) in the DC network due to the presence of the S-ESS can be computed as:

$$\Delta L = \frac{\eta_{S-ESS} - \eta_{BC}}{\eta_{S-ESS}(1 - \eta_{BC})}. \quad (13)$$

E. Results analysis and applicability of this work

Considering that the battery charges during the night for a period of 5 h (from 00:00 am up to 05:00 am), it is possible to calculate the overall efficiency of the system for the BC scenario (η_{BC}) and for the S-ESS one (η_{S-ESS}), with reference to the values shown in Table I and Table II. In the BC scenario, the trolleybus grid presents an efficiency of roughly 84.7%, while about 90.8% in the S-ESS one. Latter result is negatively biased by the delivered energy W_{BUS} mismatch discussed above. On the other hand, having considered the sole battery's internal resistance, overestimate the round-trip efficiency ($\eta_{RT} \approx 97.1\%$) producing a positive bias on η_{S-ESS} .

Nonetheless, it is still possible to provide a rough estimation of the η_{RT} break-even point and ΔL on the base of the current scenario. Indeed, from (10)–(11) and with reference to Table I and Table II, it is apparent that as soon as η_{RT} is higher than 72.2%, an overall efficiency increment considering the use of the S-ESS is guaranteed. According to [21], Li-ion batteries for stationary applications have an efficiency of approximately

TABLE III
EFFICIENCY AND LOSSES IMPROVEMENT FOR MULTIPLE VALUES OF $\eta_{B\&C}$.

η_{RT}	η_{S-ESS}	$\eta_{S-ESS} - \eta_{BC}$	ΔL
72.2%	84.7%	0.00%	0.00%
74.0%	85.1%	0.40%	3.07%
76.0%	85.6%	0.90%	6.87%
78.0%	86.1%	1.40%	10.6%
80.0%	86.5%	1.80%	13.6%
82.0%	87.0%	2.30%	17.3%
84.0%	87.5%	2.80%	20.9%
86.0%	88.0%	3.30%	24.4%

90%–92% considering a daily charge/discharge cycle. It is also known that the efficiency of DC-DC converters can be considered above 95%–97% [22], resulting in a round-trip efficiency of the block compounded by the battery pack and the converter above 85%. For the sake of completeness, Table III collects overall efficiency, efficiency improvement, and normalized losses reduction for multiple η_{RT} cases. Although efficiency improvement is clearly feasible, the usage of the S-ESS should have the main objective of improving the voltage and current profile of the catenary to support the trolleybus operation.

Although this manuscript focuses on the Bologna trolleybus system, this work can be easily replicated in trolleybus networks in other cities. Based on work [18], other catenary topologies can be built in Simulink, and then the Monte Carlo simulations can be easily reproduced based on the vehicle's probability density along the line and the current absorption profile. The IMC trolleybus current can also be an example for future works considering IMC vehicles.

VI. CONCLUSION

In the studied case, the FS M-TT of the trolleybus system of Bologna is analyzed considering a high energy demand situation in the context of two cases: the scenario in which a battery-based S-ESS is connected at two points of the line and a BC scenario without the presence of an S-ESS. A Monte Carlo approach has been used to deal with the randomness of the vehicle's initial positions and their respective currents.

According to the results shown in this document, it is possible to observe an increase of 2.5% and 5.2% in the average voltage value in the output of the TS M and TS T-T, respectively. The voltage distribution along the catenary has been exhibited, and an increase of about 19% has been observed in the minimum voltage point (3000 m) in reference to the average value. Similarly, for the network current, the most expressive reduction is constituted in a value of 45% at approximately 3700 m. Using an S-ESS can even increase the overall efficiency of the trolleybus system operation if the battery-converter round-trip efficiency is above 72.2%.

As this work analyzes the DC catenary operating at a high load situation, the results obtained can be taken as a reference for network improvements with the inclusion of the S-ESS. The application of the methods developed in this work to a daily operation of the trolleybus system as well as optimized control management for the S-ESS objecting a daily operation open space for future research.

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