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DOI
10.1109/ESARS-ITEC57127.2023.10114818

Publication date
2023

Document Version
Final published version

Published in
Proceedings of the 2023 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)

Citation (APA)
Diab, I., Chandra Mouli, G. R., & Bauer, P. (2023). Opportunity Charging of Electric Buses Directly from a DC Metro Catenary and Without Storage. In *Proceedings of the 2023 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)* (pp. 1-6). IEEE. https://doi.org/10.1109/ESARS-ITEC57127.2023.10114818

2023 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC) | 979-8-3503-4689-3/23/$31.00 ©2023 IEEE | DOI: 10.1109/ESARS-ITEC57127.2023.10114818

Opportunity Charging of Electric Buses Directly from a DC Metro Catenary and Without Storage

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***Abstract*—A typical approach to harvesting the excess braking energy of a railway car has been to use a storage system. However, research momentum has been growing in the direction of integrating smart loads like EV chargers into traction networks, and this can offer a more efficient and economical solution to the harvesting of braking energy. This paper examines the case study of a segment of the Amsterdam metro grid with two 350kW integrated DC opportunity chargers for charging electric buses from the traction grid. Of the charging episodes investigated, none of them broke the minimum line voltage requirements of the grid. They managed to greatly offset any additional line losses that they had caused by a successful recuperation of up to 1212kWh per day, depending on the charging duration. In all four schemes, about 22.8% of the picked-up charging energy of the buses per day came from harvesting otherwise-wasted metro braking energy.**

***Index Terms*—Electric Buses, Opportunity Charging, Smart Grids, Storage, Transport**

I. Introduction

A. Braking Energy Recuperation in Railway Grids

In railway systems, the braking energy that is generated by the train when it brakes is typically lost as heat, but it can also be captured by another vehicle or a storage device [1–12]. This process is known as regenerative braking harvesting, and it can help to reduce energy consumption and improve the overall efficiency of the system [2, 13–17].

In the absence of a vehicle nearby and the proper grid conditions (line resistance and substation voltage [18]), the excess braking energy of a vehicle is wasted on-board in braking resistors. One common workaround has been to place storage systems in the grid to harvest the braking energy and deliver it to an accelerating vehicle at a later moment. Still, this method is both expensive and subject to severe efficiency losses [7, 8, 11, 15–17, 19–23].

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B. Braking Energy Recuperation Without Storage Systems

On the other hand, there is a growing research momentum in re-thinking traction networks as active, multi-functional grids with integrated smart loads and renewables [1, 6–8, 11, 12, 18–22, 24–26]. In particular, the integration of smart loads such as electric vehicles (EV) chargers into transport networks can both increase the braking energy recuperation and provide a base load for the integrated renewable energy sources. Both are phenomena that can reduce the dependency on costly, inefficient, and complex storage systems [20, 21, 26, 27].

Indeed, an EV charger connected to the DC side (directly to the catenary/third rail) of a traction grid can recuperate some of the otherwise-wasted braking energy. However, this could increase the line voltage drops and thereby increase the total transmission losses. This would eventually increase the power demand on the substation in the non-linear fashion typical of transport grids. This motivates the need for a thorough study of the costs and benefits of adding an EV charger to a traction network.

C. Proposed Study

This paper looks at the case study of a segment of the metro line of the city of Amsterdam, the Netherlands, by integrating two electric bus chargers directly into the DC catenary.

For assessing the successful integration of these chargers, four parameters are taken into account:

- The maximum substation power demand per 15 minutes average: Traction grids are not typically billed on their per-second consumption but rather on a 15 minutes average. In this case study, a value of 1.1MW was suggested by the metro grid operator
- The minimum line voltage: The voltage should remain above 2/3 of the no-load voltage as per traction substation standards [1, 26, 28]. Here,

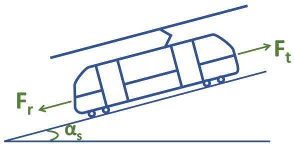

Fig. 1. Free body diagram of the vehicle

this is 540V, and special attention is already paid to values under the nearest rounded value of 600V

- The increase in transmission losses: It is expected that the addition of a load on the DC side would increase the line transmission losses
- The increase in the recuperation of braking energy: It is expected that this addition of a load on the DC side will increase the harvesting of braking energy by providing a base load to the metro grid

II. Methodology

A. Metro Vehicle Model

The metro traction force, F_t, is obtained from a dynamics model (Figure 1) of the metro vehicle whereby

$$F_t - F_r - M_m g \sin \alpha_s = M_m a_m \qquad (1)$$

Where M_m is the vehicle mass, α_s is the slope angle, a_m is the vehicle acceleration, g is the gravitational constant, and F_r is the total frictional force (drag and rolling resistance). The experimentally-obtained Davis coefficients describe this latter force [29] as presented in Eq.3. For this study, these values were available both for open-air and tunnel environments, taking into account the relatively increased drag force on the vehicle inside a tunnel for the same vehicle velocity, v.

$$F_r = \begin{cases} a_1 + b_1 v + c_1 v^2 & , \text{ in open-air} \\ a_2 + b_2 v + c_2 v^2 & , \text{ inside a tunnel} \end{cases} \qquad (2)$$

Then, the vehicle power, P_t, is obtained from the traction force and the total system efficiency, η:

$$P_t = \begin{cases} F_t / \eta & , \text{ if traction} \\ F_t \cdot \eta & , \text{ if braking} \end{cases} \qquad (3)$$

The metro schedule is based on the Amsterdam Noord-Zuid line schedule, running from 05:20 am to 00:30 the following day.

B. Grid Power Flow Model

The metro grid power flow model is an extension of the traction grid model presented in [1] that looks at a trilateral case (triple substation flow). The model is based on the forward-backward sweep convergence method.

For this study, the following grid parameters are used:

- Substation voltage: 825 V
- Substation impedance (feeder, converter): 40 mΩ

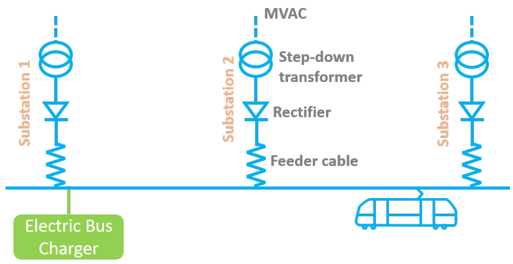

Fig. 2. Layout of the three substations (SS1 to SS3) and the electric bus charger location

- Effective third rail resistance: $7.5 \cdot 10^{-6} \Omega/\text{m}$
- Effective return rail resistance: $10.5 \cdot 10^{-6} \Omega/\text{m}$
- Maximum allowed line voltage: 900V
- Distance between Substation 1 and 2: 1570m
- Distance between Substation 2 and 3: 1840m
- Distance of charger from Substation 1: 50m (location of the bus parking plaza)

The layout of the studied zone is illustrated in Figure 2. The simulations are run for one full day, with a 1 second resolution.

C. Electric Bus Opportunity Charging Profile

The bus charging is selected as 2x350kW DC chargers (total 700kW) connected at the DC side.

Four charging profiles are selected for the opportunity charging:

- **EV-05/30** (short): Two electric vehicles (bus) are charged for 5 continuous minutes every 30 minutes, 350kW each
- **EV-15/30** (long): Two electric vehicles (bus) are charged for 15 continuous minutes every 30 minutes, 350kW each
- **EV-10/60** (short): Two electric vehicles (bus) are charged for 10 continuous minutes every 60 minutes, 350kW each
- **EV-30/60** (long): Two electric vehicles (bus) are charged for 30 continuous minutes every 60 minutes, 350kW each

The bus charging is done from 6:00 am until midnight, as an overlap with the metro schedule (5:28 until 00:30).

III. Results

A. Analysis: The maximum substation power demand per 15 minutes average

Figure 3 shows the 15 min average of the power demand on substation 1 for the short EV charging scenarios of 5 minutes per 30 and 10 minutes per 60. While this average exhibits an expected increase from the baseline, it remains well below the 1.1MW threshold.

The first trivial reason for this controlled increase is that both these charging profiles end their charging duration well within the 15 minutes period, allowing the average to drop again. Three other factors are 1)

better harvesting of the braking energy that supplies some of the charging load, 2) natural reshuffling of the supply load share from substations 2 and 3 caused by the presence of a demanding load very near substation 1, and 3) a lower line voltage due to this added load that again cause a re-iteration of the supply load share between substations.
Finally, the 05/30 and 10/60 profiles are not symmetrical regarding the financial impact on the grid operator. The 05/30 has a better performance as it both spreads the load over multiple billing periods and increases the chances of recuperation of braking energy by this spreading out the charging episodes. Especially if the billing is non-linear, this could have serious financial implications.

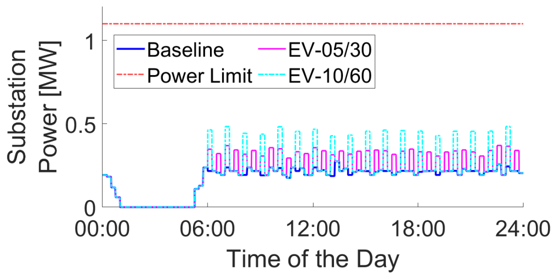

Fig. 3. Average power demand per 15 minutes on substation 1 for the short EV charging scenarios

Figure 4 shows the 15 min average of the power demand on substation 1 for the long EV charging scenarios of 15 minutes per 30 and 30 minutes per 60. Again, there is an expected increase in the average power demand. Here, it is more severe than the cases presented in Figure 3.
The first trivial cause of this increase is the fact that these long charging episodes span over a whole billing period. However, there is no net increase of 700kW (2x350) in the substation power. This is a stronger proof of the above-mentioned factors: 1) better harvesting of the braking energy, 2) natural reshuffling of the supply load share from substations 2 and 3, and 3) a re-iteration of the supply load share between substations caused by the lower line voltage.

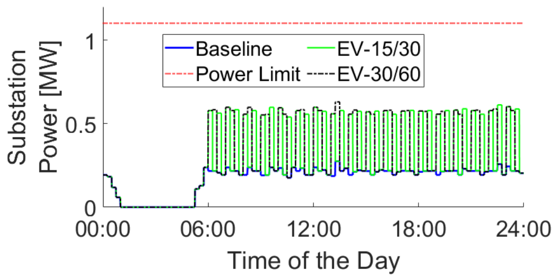

Fig. 4. Average power demand per 15 minutes on substation 1 for the long EV charging scenarios

B. Analysis: The minimum line voltage

The minimum line voltage analysis summarized in Table I reassures that the grid voltage is within the operational limits. More reassuringly, the recorded voltage drops under 600V are less than 45 seconds per day in all cases. This shows that there is still room for unexpected vehicle delays and accelerations.
It is worth noting that a (slight) asymmetry between both seemingly similar couples of 05/30 with 10/60 and of 15/30 with 30/60 is recorded due to the metro vehicle scheduling.
Finally, despite remaining in the allowed operational range, all four charging profiles caused a drop compared to the baseline voltage profile, which does not see a voltage under 605V. This would negatively affect the transmission losses as the power flows in a traction grid are not linear [22]. However, this can also increase the braking energy recovery, and usher in better power-sharing of the EV load between the three substations [18, 30].

TABLE I
SIMULATION RESULTS OF THE MINIMUM LINE VOLTAGE ON THE METRO GRID FOR A DAY

Scenario	Minimum Recorded Line Voltage	Number of Occurrences (seconds in a day) Min. Line Voltage <=600V	Min. Line Voltage <=540V
Baseline	605 V	0	0
EV - 05/30	558 V	28	0
EV - 15/30	558 V	42	0
EV - 10/60	558 V	16	0
EV - 30/60	558 V	43	0

C. Analysis: The increase in transmission losses

As expected in the earlier analysis, the transmission losses are significantly increased by adding an opportunity charger on the DC side. Although slightly asymmetrical, these increases are about 12% and 60% for the short and long charging sessions, respectively. While these values seem discouraging initially, they are offset by the additional harvesting of braking energy as reported in the following section.
It is also worth mentioning that the values of the transmission losses also include the losses in the transfer of the shared braking energy. This means that not all of the reported energy losses are an added load to the substations.

TABLE II
SIMULATION RESULTS OF THE TOTAL LINE LOSSES ON THE METRO GRID FOR A DAY

Scenario	Total Line Transmission Losses	Benefit Compared to Baseline
Baseline	1122 kWh	Benchmark
EV - 05/30	1260 kWh	-138 kWh
EV - 15/30	1775 kWh	-653 kWh
EV - 10/60	1247 kWh	-125 kWh
EV - 30/60	1795 kWh	-673 kWh

TABLE III

SIMULATION RESULTS OF THE HARVESTED BRAKING ENERGY ON THE METRO GRID FOR A DAY

Scenario	Available Braking Energy	Wasted Braking Energy	Used Braking Energy	Gain in Harvested Braking Energy	
				Energy per Day	Bus Kilometers Equivalent*
Baseline	12944 kWh	11308 kWh	1636 kWh	Benchmark	Benchmark
EV - 05/30	12944 kWh	10830 kWh	2114 kWh	478 kWh	172 km
EV - 15/30	12944 kWh	10096 kWh	2848 kWh	1212 kWh	436 km
EV - 10/60	12944 kWh	10867 kWh	2077 kWh	441 kWh	159 km
EV - 30/60	12944 kWh	10102 kWh	2842 kWh	1206 kWh	434 km

*Based on 90% efficiency and 2.5kWh/km

D. Analysis: The increase in the recuperation of braking energy

Table III shows how the additional harvesting of braking energy by the added charger offsets by far the amount of additional energy losses that this charger brings to the grid. This comparison is by more than a factor of 2, and resonates with earlier calls in the literature to the addition of smart base loads for the sustainability and efficiency of transport grids [3, 6, 20, 21, 24, 26, 27, 31–33].

Table III also offers an estimated equivalency in bus kilometers of this harvested energy. The calculation is based on a 90% total efficiency and a typical specific energy of 2.5kWh/km for a bus in extreme weather conditions (heating/cooling demand) [1, 34]. In the short charging scenarios, up to 172km of bus driving can be performed based solely on the harvested recuperative braking energy from the DC side of the metro grid. In the case of the long charging scenarios, this number stands at 436 km. In all cases, this is about 19.1-22.8% of the charging energy picked up during the entire charging session.

IV. COMPARISON OF THE CHARGING SCHEMES

The four charging schemes presented in this paper can be grouped into two types: short (05/30 and 10/60) and long (15/30 and 30/60).

First, in terms of the voltage drops, the short sessions performed better than the long sessions in absolute terms. However, all 4 schemes had satisfactory performance and no significant argument can be made for or against a specific scheme.

Second, in terms of the line losses, again the short sessions performed better.

Third, in terms of the harvested braking energy, all four schemes outperformed their additional transmission losses and managed to harvest up to 21.0-22.8% of their required energy pick-up from the otherwise-wasted metro braking energy in the case of the short sessions. In the case of the long sessions, this number is at 19.1-19.2%.

Finally, a difference can be spotted between the four schemes in terms of the average substation power demand. Here, according to the comparison of Figure 3 and Figure 4, the EV 10/60 scheme is the least preferred. This ”short” scheme gives billable power peaks similar to those of the ”long” schemes, with only a third of the picked-up battery energy during its sessions. This is a purely financial consequence of the energy billing process, where the power peaks of the 10/60 schemes are being penalized, while those of the 05/30 scheme are better spread across the day.

V. CONCLUSIONS AND FUTURE WORKS

This paper looked at the integration of a DC opportunity charger directly into the catenary of a metro system. Four bus charging schemes of two 350kW chargers (700kW total) were studied, namely the 05/30, 10/60, 15/30, and 30/60 schemes. The four schemes did not show any violations of the minimum line voltage of the maximum substation billable limit. Unfortunately, all four schemes showed a significant increase in line transmission losses. However, this was greatly offset by the extra braking energy recuperation, making the system more efficient overall. In fact, about 22.8% of the energy of each charging session was harvested from the braking energy of metro vehicles. Overall, the 05/30 charging scheme (using the charger for 5 min every 30 min) was preferred as it brought the best compromise between losses, braking energy harvesting, and operational flexibility.

Future works would look into a full assessment of the impact of the charger on all three substations, as well as investigating other positions of the charger. Furthermore, revisiting these results with randomized metro traffic and a more detailed bus charging demand profile is interesting.

ACKNOWLEDGEMENTS

The authors would like to thank Paul Voskuilen from the AMS Institute, and Will de Jager and Jos Meester from the Gemeente Vervoerbedrijf Amsterdam for their important contributions to this work.

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