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Diab, Ibrahim; Chandra Mouli, Gautham Ram; Bauer, Pavol

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Increasing the Braking Energy Recuperation in Electric Transportation Grids Without Storage

1st Ibrahim Diab
Electrical Sustainable Energy Department
Delft University of Technology
Delft, The Netherlands
i.diab@tudelft.nl

2nd Gautham Ram Chandra Mouli
Electrical Sustainable Energy Department
Delft University of Technology
Delft, The Netherlands
G.R.ChandraMouli@tudelft.nl

3rd Pavol Bauer
Electrical Sustainable Energy Department
Delft University of Technology
Delft, The Netherlands
P.Bauer@tudelft.nl

***Abstract*—When the braking energy in electric transportation grids is not met by another vehicle's demand, it is either harvested by storage systems or wasted in braking resistors. This paper looks at three methods for increasing the amount of harvested braking energy without the use of expensive storage systems: decreasing the substation voltage, decreasing the catenary/rail resistance, and adding smart grid loads such as EV chargers. Compared to the baseline scenario of a presented case study, the first method allowed the recuperation of all the braking energy yet increased the line transmission losses. The second method presented a better performance in both types of losses (23%), while the third method offered a 66% reduction in losses in addition to offering more utilities from the same infrastructure. The final paper will go into further detail with a full-day simulation.**

***Index Terms*—Metro, Regenerative Braking, Storage, Transportation**

I. INTRODUCTION

Braking energy recovery is a process in which the kinetic energy generated during the braking of a vehicle is captured [1]–[3]. This energy can be stored for later use or, in the case of catenary or rail networks, the excess power can be sent to neighboring vehicles. Typically, this power is not sent back to the grid because the traction substations use unidirectional rectifiers. If there is no recipient for the braking energy, onboard braking resistors turn it into heat and dissipate it.

The recuperated braking energy can be as much as 30% of the traction demand. This makes braking energy recovery a key technology for improving the efficiency and sustainability of transportation systems. By capturing and reusing energy that would otherwise be wasted, it can help reduce energy consumption, operational costs, emissions, and the overall environmental impact of transportation. This is especially important as traction grids begin to implement more sophisticated and power-demanding fleets [4]–[7].

A. Factors that limit the braking energy recuperation

When sharing the braking energy with another vehicle, the voltage of the braking vehicle needs to rise sufficiently to allow it to deliver power to the circuit. Depending on the braking vehicle's location with respect to the traction substation, this can put it in a narrow operating zone of needing to surpass the traction substation voltage and yet still remain within the maximum line voltage limitations of the grid. The efficiency and amount of shared braking energy are also limited by the line voltage drop between the braking vehicle and the receptive vehicle, which is dictated by the distance between the two nodes and the resistivity of the rail material.

In practice, this means unfortunately that a portion of the braking energy is sometimes wasted onboard despite the presence of receptive, power-consuming vehicles, and this portion of the energy demand needs to be supplied by the traction substation. Electrically, this problem needs to address two concerns:

1) Concern 1: Addressing the traction substation voltage
2) Concern 2: Addressing the impedance between a braking vehicle and a receptive load

B. Proposed Solution

For more recuperation of braking energy, the most common solution is to add a storage device, which comes at a considerable technical and financial cost and is subject to many round-trip efficiency losses [5], [8]–[11].

Another solution is to install a bidirectional converter at the traction substations to allow for the excess energy to be sent back. However, this solution is not technically or economically attractive, especially since the traction energy price usually comes at a highly subsidized rate.

This paper proposes three methods for increasing the braking energy recuperation in transportation grids, and quantifies the net output of their contradictory effects:

- Reducing the traction substation voltage: While this method facilitates the sharing of braking energy (Concern 1), it increases the transmission power losses
- Installing catenary/rail with lower material resistivity: While this method facilitates the sharing of braking energy (Concern 2) and reduces transmission losses, it could often keep the line voltage high enough to counter-effect the braking energy sharing, and might not compensate for the relative increase in rail material price
- Integrating smart grid loads like EV chargers into the transportation grid infrastructure: While this method facilitates the sharing of braking energy by placing more receptive loads along the line (Concern 2) and offers

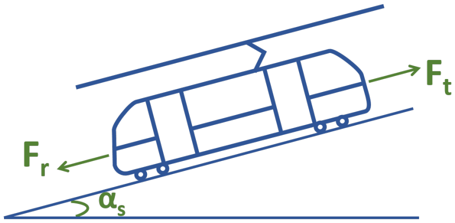

Fig. 1. Free body diagram of the metro vehicle

new functionalities from the transport infrastructure, it would increase the transmission losses and add more demand onto the traction substation when no regenerative vehicle is present. Furthermore, it could compete with other vehicles for the available braking energy

C. Paper Structure

This paper started with an introduction to the problem and the offered solutions to be investigated in this paper. Section II will explain the modeling methodology used. Section III will investigate a theoretical case study to test each of these scenarios as a proof of concept. Then, section IV will re-examine these scenarios in a full-day operation of the Dutch metro grid of the city of Amsterdam. Finally, section V offers conclusions.

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

$$F_t - F_r - M_m g \sin \alpha_s = M_m a_m \tag{1}$$

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 [**?**] 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.

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

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

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

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 extends the traction grid model presented in [12] 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 (unless otherwise indicated)
- Substation impedance (feeder, converter): 40 mΩ
- Effective third rail resistance: $7.5 \cdot 10^{-6} \Omega/\mathrm{m}$
- Effective return rail resistance: $10.5 \cdot 10^{-6} \Omega/\mathrm{m}$
- Maximum allowed line voltage: 900V
- Distance between Substation 1 and 2: 1570m
- Distance between Substation 2 and 3: 1840m

III. THEORETICAL CASE STUDY RESULTS

This section looks at the braking and transmission power flows in a theoretical case study summarized in Table I. This theoretical case study is designed in a way to show an extreme scenario hostile to braking energy recovery: Two braking vehicles blocked in between two substations and a traction-demanding vehicle far away. The next section of this paper would look at a realistic full day of operation,

A. Baseline scenario

In the baseline scenario of Table II, despite the availability of 2500kW in braking power for the 3200kW load, only 9kW of braking energy is exchanged with the catenary. This is because the substation voltage and rail impedance are high enough that the braking vehicles need to rise to a voltage above the grid limit to send their power. This situation would be unacceptable, so the braking resistors are almost fully activated. Figure 2 shows the node voltages.

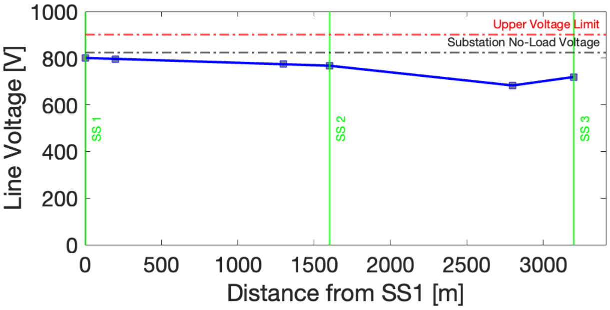

Fig. 2. Line Voltage of the Case Study: Baseline

B. Reducing the traction substation voltage

In the scenario of Table III with the substation voltages reduced to 750V, the braking energy is fully harvested. This is an important advantage to keep in mind when comparing the increased transmission losses to 878kW from the baseline of 665kW, as it means that the substation, in this scenario, was actually required to deliver less power. Most of the transmission losses come from the distance and high rail impedance between the braking vehicles and the accelerating

TABLE I
CASE STUDY BASELINE: ALL SUBSTATIONS ARE AT 825V AND THE THIRD RAIL IS OF STEEL MATERIAL OF $24m\Omega/km$ RESISTIVITY

Node Type	Substation	Braking Vehicle	Braking Vehicle	Substation	Accelerating Vehicle	Substation
Node Position (m)	0 (reference)	200	1300	1600	2800	3200
Node Original Power (kW)	N/A	-2000	-500	N/A	3200	N/A

TABLE II
THEORETICAL CASE STUDY BASELINE: ALL SUBSTATIONS ARE AT 825V AND THE THIRD RAIL IS OF STEEL MATERIAL OF $24m\Omega/km$ RESISTIVITY

Braking Power Lost		**Transmission Losses**	**Total Power Lost**
Vehicle 1	Vehicle 2		
1998 kW	493 kW		
2491 kW		665 kW	**3165 kW**

vehicles, which motivates again the study of a material with reduced rail resistance.

Still, it is important to note that transmission losses would also be high during operation without braking vehicles. The net advantage of this method would be clearer in the final version of this paper, which takes a whole day of operation into account. Figure 3 shows the node voltages.

TABLE III
CASE STUDY REDUCED SUBSTATION VOLTAGE: SUBSTATIONS ARE AT 750V AND THE THIRD RAIL IS OF STEEL MATERIAL OF $24m\Omega/km$

Braking Power Lost		**Transmission Losses**	**Total Power Lost**
Vehicle 1	Vehicle 2		
0 kW	0 kW		
0 kW		878 kW	**878 kW**

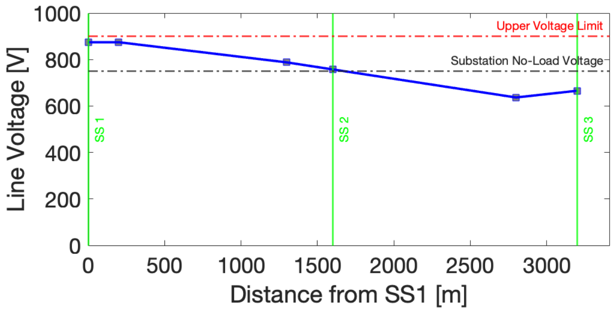

Fig. 3. Line Voltage of the Case Study: Reduced Substation Voltage

C. Installing catenary/rail with lower material resistivity

In the scenario of Table IV, the resistance in the rail is reduced by replacing the steel material of $24m\Omega/km$ with Aluminum material of $6.6m\Omega/km$.

This lowered resistance allows the braking vehicles to send more current to the accelerating one while still being restrained to an acceptable line voltage. This method brings advantages in both braking energy harvesting and transmission losses. Depending on the transportation grid, these savings could economically offset the costs of the rail material. Figure 4 shows the node voltages.

TABLE IV
CASE STUDY REDUCED SUPPLY RAIL RESISTANCE: SUBSTATIONS ARE AT 825V AND THE THIRD RAIL IS OF ALUMINUM OF $6.6m\Omega/km$

Braking Power Lost		**Transmission Losses**	**Total Power Lost**
Vehicle 1	Vehicle 2		
1812 kW	226 kW		
2038 kW		397 kW	**2435 kW**

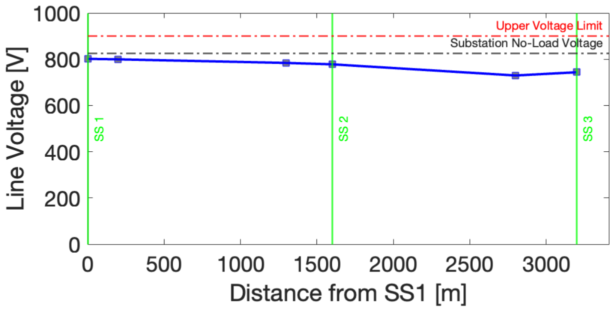

Fig. 4. Line Voltage of the Case Study: Reduced Supply Rail Resistance

D. Integrating smart grid loads such as EV chargers

In the scenario of Table V, a 350kW EV charger is placed at the middle substation, namely SS2.

The presence of this load near the substation creates a local voltage drop (transformer, rectifier, and feeder cable) sufficient to allow for more regenerative braking power to flow through the grid. There is also an effective percentage reduction in transmission losses compared to the baseline, considering that this scenario includes a higher total load of 3200+350=3550kW.

This method then benefits both the braking energy harvesting as well as the transmission losses and offers more useful functionalities to the transport grid. It is worth mentioning that such functionalities are also important for the techno-economic feasibility of renewables integration in transport grids as has been argued in literature [13]–[16]. Figure 5 shows the node voltages.

TABLE V
CASE STUDY ADDED SMART GRID LOAD: ALL SUBSTATIONS ARE AT 825V AND THE THIRD RAIL IS OF STEEL MATERIAL OF $24m\Omega/km$ RESISTIVITY. A 350KW EV CHARGER IS ADDED AT SS2

Braking Power Lost		**Transmission Losses**	**Total Power Lost**
Vehicle 1	Vehicle 2		
399 kW	0 kW		
399 kW		664 kW	**1063 kW**

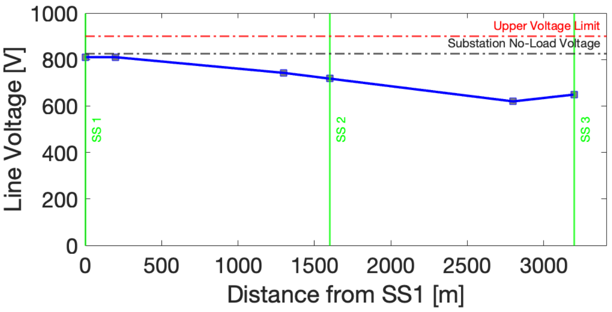

Fig. 5. Line Voltage of the Case Study: Added Smart Grid Load

IV. FULL DAY METRO OPERATION CASE STUDY RESULTS

The previous section looked at a specific instantaneous case of a metro network that highlights the possibility of large waste of braking energy. For a more comprehensive study, the metro line Noord-Zuid of the city of Amsterdam, The Netherlands, is investigated in this section.

The studied grid layout is, in fact, the one already presented in the theoretical study with the three substations. The electric bus opportunity charger is assumed to operate for 5 minutes every 30 minutes from 6:00 am to midnight.

Table VI shows the results of the full-day case study. The study uses the same scenarios suggested in the theoretical study, namely decreasing the substation voltage, reducing the third rail resistance by replacing the material, and adding an electric bus opportunity charger at the DC side of the substation.

Compared to the baseline line scenario, decreasing the substation voltage brought by the expected increase in braking energy recuperation. In total, 456 additional kWh of energy were recuperated as the energy sharing among vehicles is made more accessible throughout the day by this lowered voltage hurdle. However, the added transmission losses throughout the traction episodes amounted to 1673 kWh more than the baseline. This brings the net benefit of this method to an unnecessary 1217kWh per day of losses for the three substations combined. This method is not a favorable solution, although some work is still encouraged in investigating it in combination with other methods.

The reduced rail resistance method brought less benefits in braking energy recuperation than the lower substation voltage method. However, this still stood at an impressive 369kWh per day. More importantly, this method is the only one that reduces transmission losses as well. This benefit of 492kWh per day is more than what is recuperated in braking energy in the first scenario. In total, the net benefit here is of 861kWh. While this is a net positive value, there is still reason to worry that this method will not compensate for the added cost of the rail material and its replacement. A thorough economic analysis is encouraged on the net financial benefit of this method.

Finally, adding a 350kW charger at the DC side of the substation showed an increase in the braking energy recuperation, more pronounced when the charger is added at the middle station of the layout, SS2. This is a spatial consequence of the higher voltage drop that the charger would bring in this position, being fed from all three substations. With its overall line voltage reduction, this SS2 scenario brings about benefits in braking energy recuperation, similar to a reduction of the substation voltage. Unfortunately, this also brings the disadvantages of the reduced substation voltage as it is noticed that this scenario also has the highest losses among the charger placement options, going 102kWh above the baseline scenario. In the net calculation, however, this middle-substation placement still promises a higher benefit in the total energy gain. This scenario benefits the grid rather than the passive manipulation of the grid parameters of the other scenarios by allowing a total of 1050kWh of charging energy to the buses while using the same metro infrastructure. Furthermore, this is a synergetic reduction of the substation energy demand by the coupling of these two systems, as high as 136kWh per day for the middle-substation placement. Further work is still encouraged in looking at the power peaks and voltage drops caused by this DC side placement, and at the cost analysis of this system.

V. CONCLUSIONS

This paper looked at methods of increasing the braking energy recuperation in a metro grid without the use of storage systems.

Three methods were proposed: Reducing the substation nominal voltage, reducing the third rail impedance, and adding an electric bus opportunity charger directly to the DC side of the metro traction substation.

In the first theoretical study of one instantaneous grid scenario, the reduction of the substation voltage seemed to be the most promising solution. Adding the bus charger was the next preferred solution, while replacing the rail material seems to offer the least benefit compared to the baseline scenario.

However, in the full-day study of the metro of Amsterdam, the infrequency of cases, such as the theoretical-case-study proposal, made the third-rail impedance reduction scenario the most promising. Furthermore, the reduction of the substation voltage seemed to bring a net negative benefit to the metro grid, as the added transmission losses in the frequent traction moments outweighed the braking energy recuperation benefits. Finally, the addition of a bus opportunity charger remains the preferred suggestion. This is because it brings a net benefit to the metro grid while offering other load functionalities that can better utilize the grid reserve and relieve the main AC grid.

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TABLE VI
RESULTS OF THE FULL-DAY CASE STUDY OF THE AMSTERDAM METRO (3 SUBSTATIONS)

	Wasted Braking Energy (kWh)	**Gain in Braking Energy (kWh)**	**Line Losses (kWh)**	**Gain in Line Losses (kWh)**	**Total Energy Gain (kWh)**
Baseline	10243	Benchmark	1651	Benchmark	**Benchmark**
750V Substation	9787	456	3324	-1673	**-1217**
Reduced Third Rail Resistance	9874	369	1159	492	**861**
350 kW Charger at SS1	10069	174	1740	-89	**85**
350 kW Charger at SS2	10005	238	1753	-102	**136**
350 kW Charger at SS3	10075	168	1723	-72	**96**

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