Energy Analysis of a Metro Train

Daniele Gallo[1], Antonio Delle Femine[1], Domenico Giordano[2], and Davide Signorino[2]

Abstract— **For over a decade, Europe has focused on greening public transport, with modern railways playing a key role to reduce pollution and transport emissions because it is characterized by a relatively low ratio between energy consumption and transport capacity. However, DC railways waste a significant amount of energy regenerated with dynamic braking. Despite the evident importance of the presented topic, there is a lack of experimental knowledge in technical and scientific literature about the amount of energy and the power levels that are involved in the described mechanism though this is fundamental information for the design of the storage system. This paper presents some experimental results of an energy analysis of a metro train**

Keywords— **Power and Energy Measurement, DC Railway System, Energy Saving, Metro Train.**

I. INTRODUCTION

EU policy has increasingly recognized the value of railway systems as a more environmentally sustainable mode of transport and is actively promoting their broader use. Modern railway systems can significantly reduce urban pollution and transport-related emissions due to their relatively low energy consumption compared to their transport capacity. Additionally, railways offer energy efficiency benefits, particularly through the ability to recover energy generated during braking (electrodynamic braking). When an electric train brakes, its motor can function as a generator, converting kinetic energy back into electricity. While electric cars recover and store this energy in batteries, trains typically lack onboard energy storage systems. As a result, the regenerated energy can only be used to power the train's auxiliary systems.

However, since the energy produced during braking usually exceeds what is needed for auxiliary functions, a substantial amount remains unused onboard. To address this, the traction control system attempts to feed the excess energy back into the power grid, allowing it to be used by other trains. This is achieved by raising the voltage at the connection point between the train and the feeder line, reversing the current flow to inject the energy back into the system [1].

This mechanism of reuse of energy can be successful if there is, at least, one other train that is on the same line and not too far from the braking train, which requires, at exactly the same time, energy for traction, see Figure 1. This condition randomly applies with high dependence on the number of scheduled trains on the same line. For instance, it applies more frequently with the Metro system or when the train is braking approaching an important railway station. Very frequently, in normal railway sections, there are no trains on the same line that can reuse the regenerated energy.

In AC railway supply (f.i., high-speed railway networks), even the absence of other trains in the traction phase may not be a problem, because, thanks to the intrinsic bidirectionality of the power transformers, excess energy could be injected into the upstream electrical grid to be reused elsewhere. However, there is a limit to this reuse because the further away the load that should reuse the energy is, the higher the voltage level that the pantograph of the braking train should reach. But the permissible voltage is limited by the railway safety standards which effectively prevent re-use beyond a certain distance.

In DC railway supply (f.i., most normal-speed trains) the situation is worse because the traditional power supply substations are unidirectional and do not allow the reversal of the energy flow [2]. Substations that allow a bidirectional flow were developed but, at the moment, are not very widespread due to the increase in cost required for installation. Then, the excess energy that cannot be reused must be dissipated on board to avoid dangerous working conditions: when the voltage level becomes excessive, specific resistors are activated and energy is wasted [3].

Despite the evident importance of the presented topic, there is a lack of experimental knowledge in the technical and scientific literature about the amount of energy and the power levels that are involved in the described mechanism. In the following, some results of a measurement campaign on-board a DC train in commuter service on the metropolitan of Madrid will be described that allow quantifying the actual energy that can be saved in a real application. To this aim, in the following, a detailed analysis of the energy flows has been performed. This analysis aims to provide valuable insights for infrastructure and train designers, helping in efforts to increase overall energy efficiency [4]-[5].

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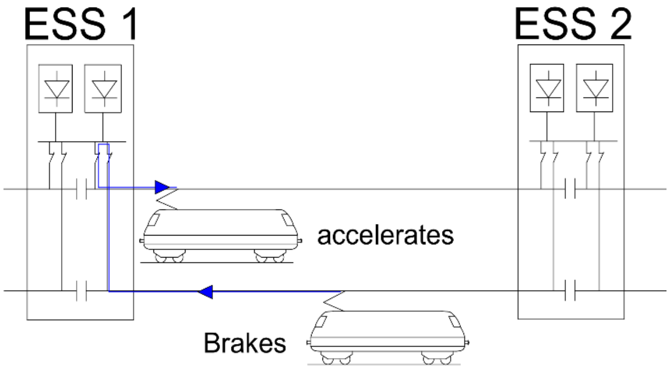

Fig. 1: Reuse of the regenerated energy

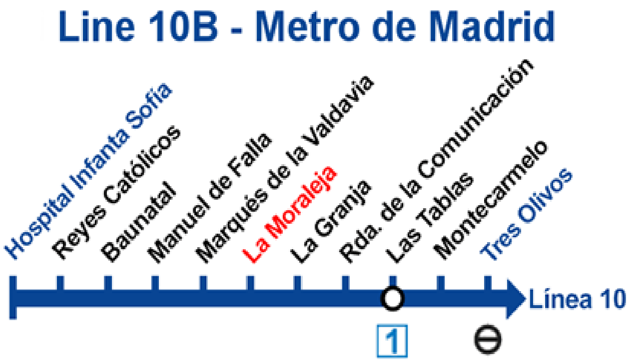

Fig. 2: The eleven stops of the line 10B

II. MEASUREMENT CAMPAIGN DESCRIPTION

The measurement campaign has been conducted on-board a train in commuter service on line 10B of Metro de Madrid. The line covers a distance of about 15 km and goes from Hospital Infanta Sofia to Tres Olivos, with 11 stations in total (see fig. 2). The overhead contact line is supplied by five substations that are positioned in Hospital Infanta Sofia, Baunatal, La Moraleja, Las Tablas and Tres Olivos. One of the substations was made reversible adding a DC/AC converter of 2 MVA in anti-parallel to the already installed rectifier of 3 MVA, in order to allow a bidirectional energy flow with minimal modifications of the existing electric system. A measurement system, implemented as previously described, has been installed on-board train to provide energy and power quality analyses in the different operating conditions of the train, [6]-[8].

The monitoring has been carried out on-board the train “S9000 3 CARS SS3” shown in fig. 3, which operates at a nominal voltage of 1500 V DC and features a maximum current absorption of 1650 A. The train features two traction systems that are fed by two independents pantographs. Since the two units are controlled by the same commands and work in similar conditions, it is reasonable to assume that the energy flows are nearly identical. Therefore, the measurement system has been installed on a single traction unit. To evaluate the energy flows of the whole train, the values must just be scaled by two. In Fig. 4 it is reported a simplified electric diagram of the traction carriage and the related monitored quantities and in fig .5 the actual installation.

The current absorbed through the pantograph (I_p) is divided and conveyed towards the traction unit (I_f), which is the main load, and the auxiliary services (I_a), that is the set of all the other loads on-board train (e.g. illumination, electric doors, air conditioning).

A second-order filter, composed of the inductance Lf and the capacitor bank C_f, is present between the pantograph and the motor to limit the voltage distortion coming from the line (V_p) towards the inverter (V_f) during traction and, at the same time, the current distortion produced by the inverter during the regenerative braking. As previously described, the energy generated by the engine during the braking cannot be completely injected into the catenary if the line voltage overcomes a safety threshold.

Fig. 3: S9000 monitored train

Therefore, the on-board resistor bank is necessary to dissipate the energy surplus. The amount of dissipated energy is managed by the chopper series-connected to the resistors, based on the required braking effort and the availability of the line to receive energy. For the monitored train, the PWM signal has a frequency of about 300 Hz and a rated peak amplitude of 600 A with a duty-cycle that can range from a minimum of 2 % to a maximum of 50 %.

To quantify the energy flows between the train and the catenary in all the operating conditions the following quantities have been monitored:

- voltage at the pantograph (V_p),
- the filtered voltage (V_f),
- the total current at pantograph (I_p),
- traction cabinet input current (I_f),
- current absorbed by the auxiliaries I_a,
- currents in the braking rheostats (I_{Ra} and I_{Rb}).

Since the inside of the traction cabinet is not accessible, the current at the input of the main inverter I_t has been determined from the difference between I_f and the total current dissipated in the rheostats I_R.

Therefore, the measurement system has been configured to acquire two voltages and five currents. Two Ultravolt 40TF-CDCD dividers have been adopted to scale down V_p and V_f, that feature a nominal amplitude of 1500 V.

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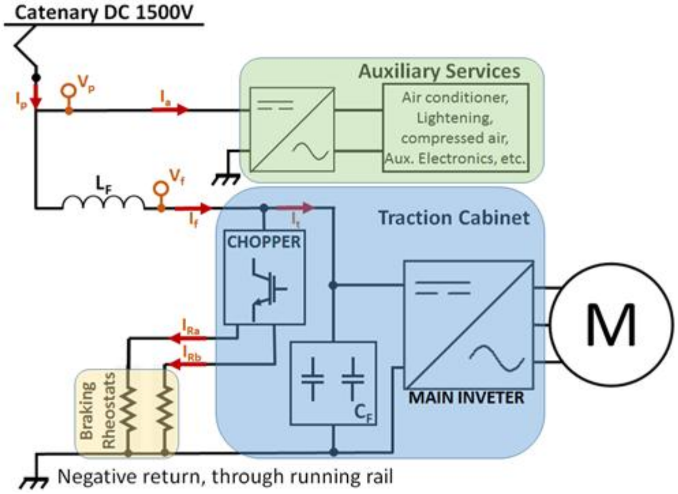

Fig. 4: Electric diagram of the traction carriage of S9000

Fig. 5: Installation of the measurement system

As regards currents, two LEM HOP 2000 have been utilized for I_p and I_f, whose amplitude can reach 1000 A, while I_{Ra} and I_{Rb} have been acquired through LEM HOP 800 transducers, since these currents reach significantly lower amplitudes (about 300 A), see fig 4, [9]-[12].

III. ENERGY FLOW ANALYSIS

To evaluate in a comprehensive way the energy flows from/towards the train starting from the quantities described in the previous section, during all operating conditions, the following balance of the DC energies can be determined:

$$E_p = E_a + E_L + E_t + E_D \tag{1}$$

where E_p is the energy absorbed at the pantograph, E_a is the energy absorbed by the auxiliary systems (e.g. lighting, air conditioning etc), E_L is the energy dissipated on the input filtering inductance, E_t is the energy absorbed by the by the traction system and E_D the energy wasted on the rheostats.

During acceleration, coasting and stop stages ($I_t \geq 0$) E_D is equal to zero since the current in the rheostats is zero, while all the other quantities in (1) are positive.

During the braking, I_t is lower than zero, so the energy flow is inverted (from the traction motor to the catenary) and E_t and Ep becomes negative. For sake of simplicity, the braking energy can be defined as $E_b = -E_t$, and the injected energy as $E_b = -E_t$. Therefore, (1) can be rewritten as:

$$E_{br} = E_a + E_L + E_{in} + E_D \tag{2}$$

E_{br} is typically recovered by the auxiliaries (E_a) on-board train and any additional energy is injected into the supply system (Ein), if some other load are available to absorb that energy. Otherwise, as previously stated, to avoid an excessive increase of the line voltage that can cause faults of the equipment, the control system that manages the braking chopper, starts dissipating energy on the braking rheostats (E_D) to reduce E_{in} and bring the voltage level in the normal operating range. In other words, E_{br} can be completely injected, except for the losses on the filtering inductance (E_L) and the consumptions of the auxiliaries (E_a), partially injected and partially dissipated or even completely dissipated (E_D), depending on the capability of the line to receive energy. It can be worth noting that both in traction and braking phase the consumptions of the auxiliary systems play a marginal role with an almost constant absorption that is in any case much lower that the peak value of E_t. Also E_L is a small percentage if compared to E_t [13]-[15].

IV. EXPERIMENTAL DATA ON THE BRAKING PROCESS

The measurement campaign lasted 18 days with a continuous monitoring of the train that operates on the same line to cover in a comprehensive and repetitive way the varied conditions of the line in terms of schedule and traffic density. About 350 roundtrip journeys were recorded with more than 500 GB recorded. This allows to cover all the working conditions in a similar way, obtaining statistical analyses that provide comparable results.

Figures 6 reports the waveforms averaged over 0.1 s of voltage and current recorded during the initial trip on 14/10/2019. Observing the current, it is possible to distinguish the moments in which the train was accelerating, characterized by a high positive current absorbed (05:30:15 and 05:32:00). In correspondence of these high current absorption, the level of voltage remarkably decreases, because of the voltage drop along the supply line.

Also at a different time (05:31:10) a similar voltage reduction can be noticed. This is probably due to the acceleration of another train supplied by the same line. Observing instead the current, it is also possible to distinguish the braking phases, since a negative current was measured (05:30:30, 05:31:00, 05:31:30 and 05:32:20). It is interesting to observe also the current flowing into the braking rheostats during the same time interval.

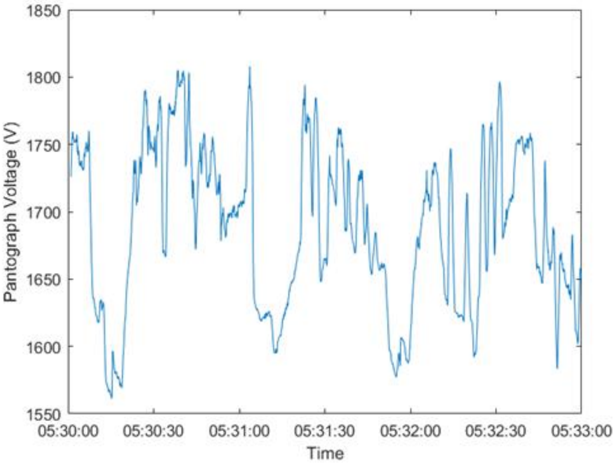

Fig. 6: Pantograph voltage recorded on 14/10/2019

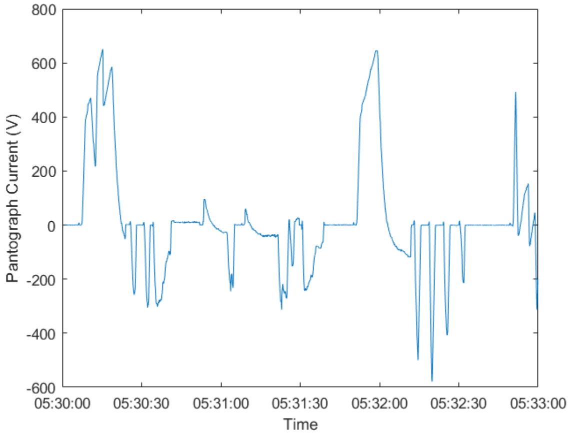

Fig. 7: Pantograph current recorded on 14/10/2019

In particular, in Figure 8 and 9 the values sampled at 50 kHz of the current in the first rheostat I_{Ra} have been reported, but I_{Rb} has a similar behaviour. It can be noted that in correspondence of every braking, the rheostats start dissipating when the voltage level exceeds 1700 V. The amount of energy dissipated is “modulated” through a PWM technique. Fig. 7 and 8 report two different braking events in which, despite the same peak of current, the duty cycles are substantially different. This entails a different amount of wasted power.

During all the braking events, the train tries to inject energy into the catenary, but as previously described, the amount of energy actually injected depends on the contemporary absorption of other trains that are supplied by the same line. If this condition does not take place, the energy regenerated should be carried to the RSS. When the supply line has not the capability to absorb all the generated energy, the excessive voltage increment triggers the on-board dissipation on the braking rheostats.

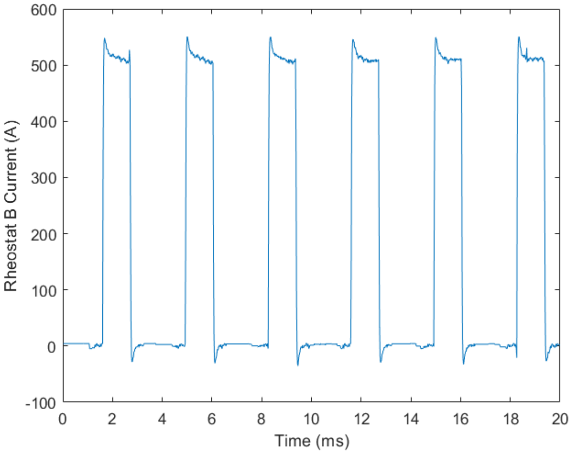

Fig. 8: Braking rheostat current recorded around 5:30:40

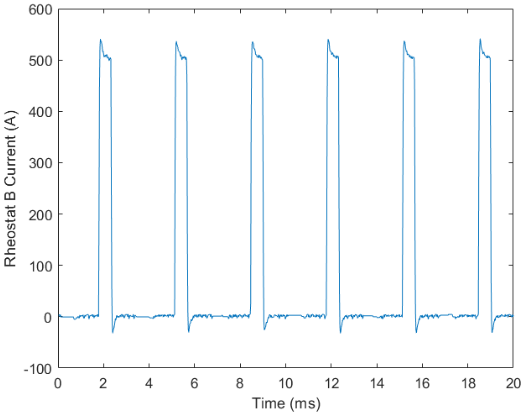

Fig. 9: Braking rheostat current recorded around 5:32:25

So, this capability depends on the dynamic state of the supply line (e.g. the relative distance between trains or the distance between braking train and RSS), but also on the operating condition of the other trains.

In figure 10 it is reported the traction current during a typical journey on the monitored line. The time intervals between two consecutive dashed lines correspond to the 10 movements from one station to the next. Moreover, in the last section, there is a speed limitation that, as a consequence, limits current absorption and injection.

V. CONCLUSIONS

In this paper, some results of a measurement campaign on-board a DC train in commuter service on the metropolitan of Madrid were described so allowing to quantify the actual energy that can be saved in a real application. A detailed analysis of the energy flows has been performed to provide valuable insights for infrastructure and train designers, helping in efforts to increase overall energy efficiency.

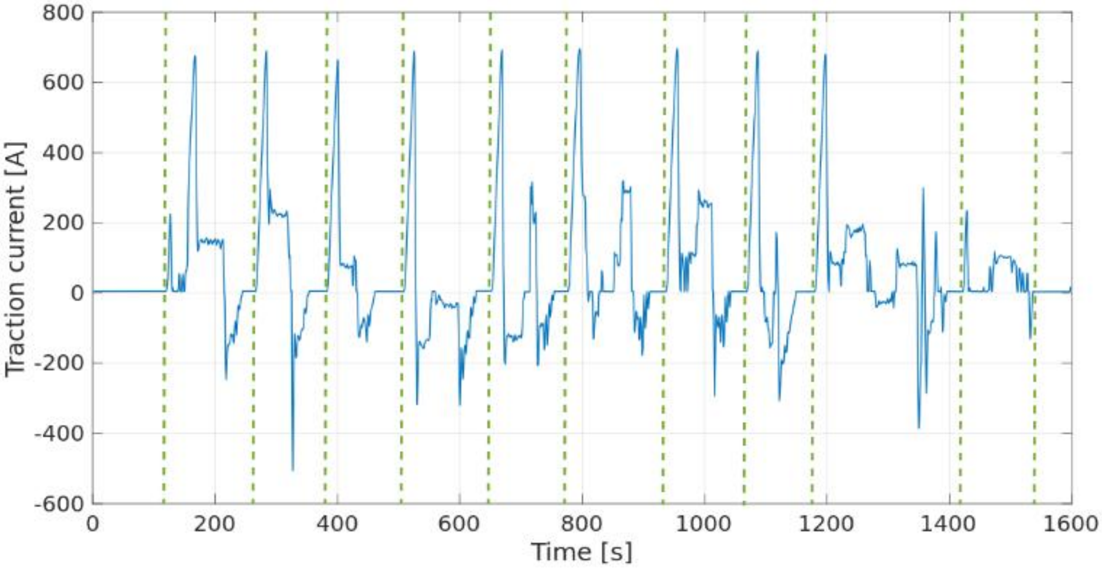

Fig. 10: Traction current during a trip.

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