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Energy Recovering in DC Railway Systems

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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 the energy regenerated with dynamic braking. The adoption of an energy storage system can greatly improve this situation by increasing energy saving. This paper explores this issue starting from experimental data recorded during the monitoring of a railway traction unit in commercial service on different tracks. The energy flows during braking in real conditions has been analyzed, quantifying the amount of energy that can be recovered by adopting an energy storage system placed on-board trains or in railway stations.

1. INTRODUCTION

European governments are pushing for a significant shift towards low-emission transportation, aiming for a 60% reduction in greenhouse gas emissions compared to '90s levels. This ambitious target outlined in the 2011 Transport White Paper can be achieved through optimizing and electrifying the transport sector [1, 2].

In particular, EU policy has rediscovered the railway system, which is more environmentally sustainable than other modes of transport and encourages its wider use. In fact, the modern railway system can remarkably reduce urban pollution and transport emissions, because it is characterized by a relatively low ratio between energy consumption and transport capacity. A further feature that makes railway systems even more interesting from the point of view of energy efficiency is the capability of exploiting the energy produced by the train during the braking phase (electrodynamic braking). In fact, when an electric vehicle brakes, the motor can be managed to act as a generator, converting the kinetic energy back into the electric form. In electric cars, this energy is all recovered and stored in batteries. In trains, that are not equipped with electrical energy storage systems, the only possibility to profitably use this energy on board is its usage to supply the auxiliary systems. However, despite the variability in the absorption of the auxiliary systems, the energy regenerated during braking time is normally much greater than the one required by auxiliary systems, so there is a large amount of energy that cannot be reused on board. Then, the traction control system tries to inject the excess energy into the feeder line to allow another train to use it. This injection is operated by increasing the voltage at the coupling point between the train and feeder line to invert the current flux [3].

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 [4]. This condition randomly applies with high dependence on the number of scheduled trains on the same line. For instance, it applies more frequently in the Metro system or when the train is braking approaching an important railway station. Very frequently, in normal railway sections, there is no train on the same line that can reuse the regenerated energy [3].

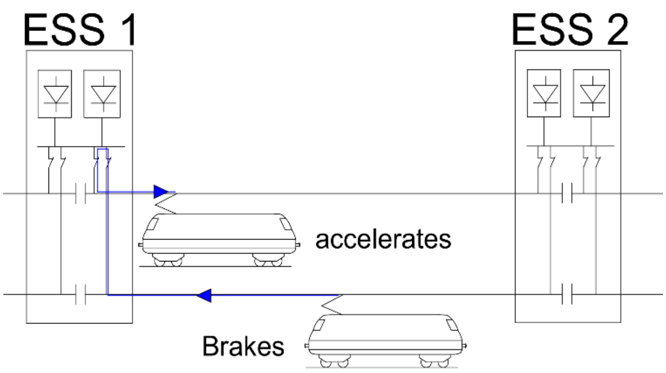

Figure 1. Reuse of the regenerated energy

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 [5]. 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 [6]. 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 [7]. 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 [8].

So, there is still room to improve energy savings by considerably taking advantage of the recent developments in Energy Storage System (ESS) technologies. In fact, it could be possible to accumulate the excess part of the braking energy and reuse it later. These storage systems can be collocated on-board or along the line [9, 10]. There are advantages and drawbacks to both solutions.

On-board ESSs can be very effective in energy savings since the energy recovered and stored during the braking process can be reused to power the vehicle itself during the next acceleration, minimizing the distance between energy generation and usage. Moreover, the control systems of the storage devices can operate a selective use of this energy to reduce the maximum power peak absorbed by the vehicle. This approach can also reduce the energy dissipated along the contact line between the rolling stock and the ESS as the voltage drop along the contact line. On the other hand, it is expensive as each vehicle must be equipped with its own ESS, it is not easily applicable to the vehicles already in service and leads to an increased consumption of traction energy due to the increase in vehicle mass.

The installation along the line of ESS can recover the energy generated by several trains on the line, it does not require any modification to the circulating vehicles, and their periodic maintenance does not affect services. Nevertheless, the relative distance between the train and ESS limits the amount of potentially recoverable energy (this is due to resistive losses in the catenary and limitation in voltage increasing during energy injection) therefore the efficiency of the energy recovery is strongly conditioned by the location of the ESS along the line [10, 11].

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 though this is fundamental information for the design of the storage system. In this framework, two measurement campaigns, part of the European Projects 16ENG04 and 22NRM04 [12-15], have been carried out on-board a DC 3 kV locomotive operating in commercial service. This activity has been carried out in collaboration with Trenitalia, the most important Italian railway company. The tests have been performed on the E464, a 3.6 MW locomotive widely used for commuter transport. The following text will refer to the first campaign, conducted in the Piemonte region of Italy, as the *northern campaign*. Similarly, the second campaign, conducted in the Emilia-Romagna region of central Italy, will be called the *central campaign*. The field measurement last several months; monitoring hundreds of train journeys and collecting a massive 3 terabytes of data. This data focuses on how energy flows between the train and the power line, including recovered and wasted braking energy, as well as electrical disturbances. This information is vital for making informed decisions about infrastructure investments aimed at saving energy.

In the following, a description of the on-board measurement setup used to accurately record energy flows will be presented. A detailed explanation of regenerative braking is provided, followed by an analysis of a real braking event. This analysis will showcase experimental results related to the identification and measurement of key quantities like power and energy during typical braking scenarios. The focus shift to the analysis of a specific railway track braking energy. Finally, a statistical analysis of the experimental data is presented. This analysis aims to provide valuable insights for infrastructure and train designers, helping in efforts to increase overall energy efficiency.

2. FIELD MEASUREMT OF ENERGY

The data reported in this paper have been recorded during an extensive measurement campaign conducted on board the train E464 operating in normal service on the Italian rail network. Figure 2 provides a schematic of the E464 locomotive traction unit and the monitored quantities. Voltage (V_P) and Current (I_P) at the pantograph have been measured to quantify the energy absorbed by the train during traction ($I_P >$ 0) and the energy sent back to the catenary during braking (I_P < 0). Instead, the supply voltage and the currents in both rheostats have been measured to estimate the energy wasted on-board trains. Note that the voltage drop across the resistors has been indirectly determined by the voltage after the inductance (V_F) and the one between the two series-connected capacitances (VHF half filter). The capacitive divider made of two equal capacitances implies that the voltage which feeds each of the two braking resistors is half the value of the V_F. VHF is therefore measured only as a verification of the effectiveness of the partition.

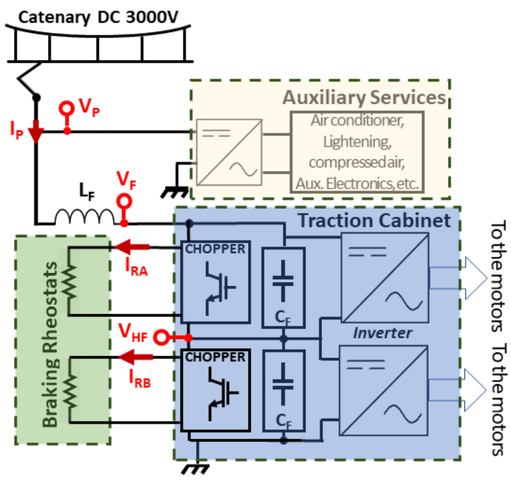

Figure 2. Scheme of the E464 traction architecture, identification and positioning of the monitored quantities

Figure 3 shows the actual field installation of the measurement system. The measurement system used in this experimental activity is based on the National Instruments Compact Rio 9034. Voltage and current transducers, suitable to adapt signals amplitude to the digital conversion stage, have been selected since the nominal voltage and current levels of the monitored quantities are considerably higher than the input range of the voltage modules. For currents, open loop Hall effect transducers were employed. In particular, LEM HOP

800-sb transducers, which feature a measuring range of ± 1600 A, are suitable to acquire the current in the rheostats and the current absorbed by the auxiliary systems. For the pantograph and the traction current instead, LEM HOP 2000 transducers, which features a measuring range of ± 3000 A, have been used. The transducers have an openable magnetic core, that allows the installation without modifying the already present electrical wiring.

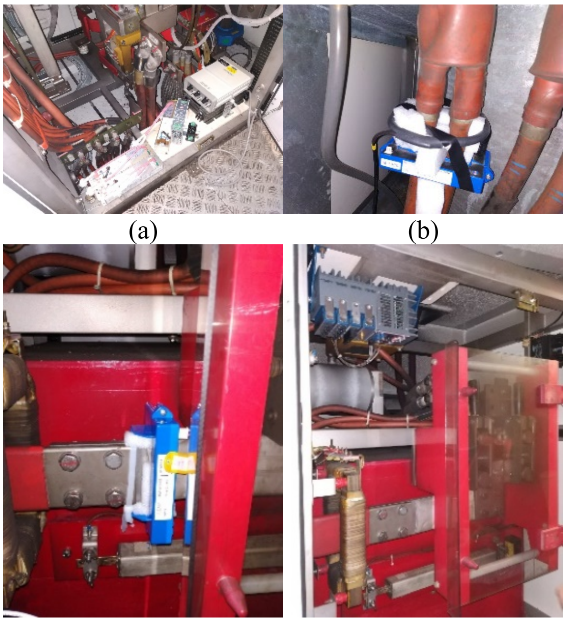

Figure 3. a) Voltage transducers and measurement supply system; b) Current transducers for rheostat monitoring; c) Transducer for current measurement at the pantograph; d) Compact Rio arrangement

Both transducer models feature a flat frequency response from DC to 10 kHz and an accuracy lower than 2%. Resistive-capacitive voltage dividers were used to acquire the voltages V_P, V_F and V_{HF}. In particular, three Ultravolt compensated dividers have been employed. These transducers feature a primary voltage of 40 kV, a nominal transducer ratio of 1000/1 and provide a bandwidth from DC to 10 MHz. The acquisition stage has been implemented with the cRIO 9034 that is equipped with an embedded controller with 1.91 GHz real-time processor, 2 GB RAM DDR3 and houses two 4-channel NI 9223 voltage modules. The voltage modules feature 4 differential input channels, 16-bit resolution and an operating range of ± 10 V.

The data acquisition has been performed at 50 kHz that allows a to an continuous monitoring of the signals without leading rapidly unmanageable amount of data and, at the same time, allows to analyse typical fast transient phenomena that can occur on-board train.

3. DETAILED ANALYSIS OF A DYNAMIC BRAKING

This section dives into real-world measurements to analyze how energy flows between the train and the power line during braking. It focuses on a single braking event on the Susa-Torino track, examining how key parameters change over time. Figure 4a reports the behaviour of the line voltage (V_P), the power absorption ($P_P=V_P \cdot I_P$), and the power of rheostats in typical braking ($P_R=V_F \cdot (I_{RA}+I_{RB})/2$), and the estimation of useful power regenerated by the train ($P_T = P_P - P_R$). The P_T and P_P values are negative because they are measured with the convention of the absorbed power. All the measured quantities are averaged over 100 ms. It is worth noting that, the actual regenerated power made available by the inverters is a little more than P_T because a certain amount of power is dissipated by the loss of the system (f.i., by the inductor, L_F). This amount can be roughly quantified in a few kW and therefore overlooked in the discussion.

The dashed blue line, V_{TH}, points out the voltage threshold that is used for starting on board dissipation: when V_P reaches this value the control system activates the chopper dissipating a certain amount of Energy with PWM techniques. As it is shown in Figure 4a, the braking starts as regenerative, it can be deduced by the negative value of the absorbed power P_P and the zero value of P_R, which means the power is totally transferred to the line, but the voltage V_F starts to increase.

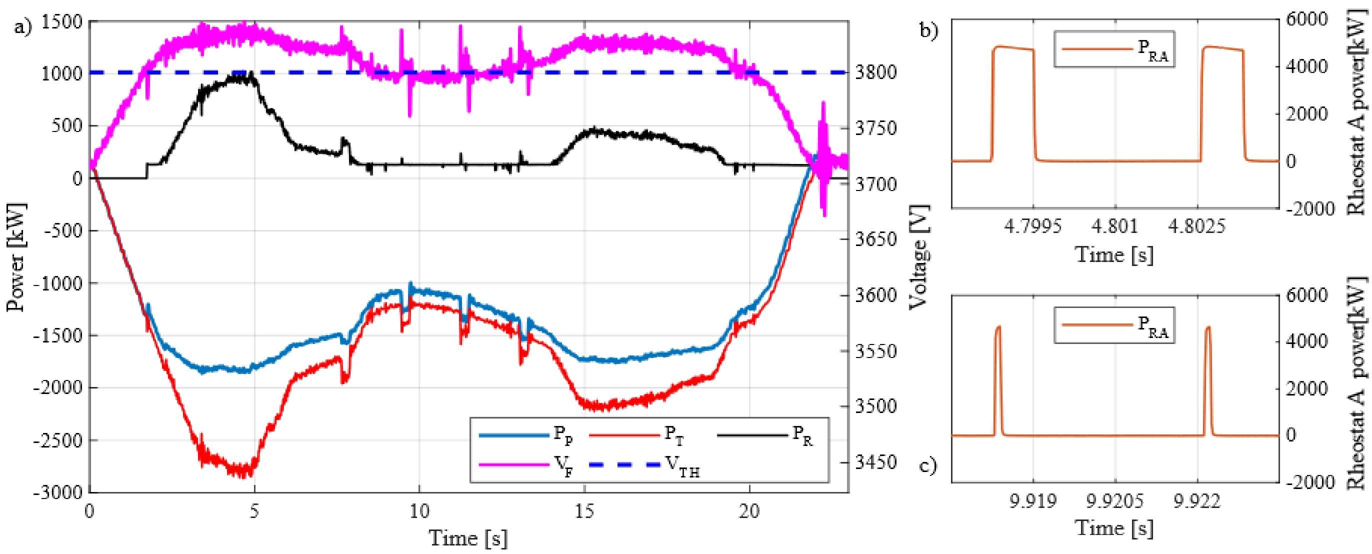

Figure 4. Example of a mixed braking during Susa - Torino: (a) the powers averaged over 100ms; (b, c) instantaneous rheostats power

Slightly after second 2, the threshold value of 3.8 kV, V_{TH}, is reached, the chopper starts working ($P_R > 0$), and the locomotive wastes part of the regenerated power made available by the inverters, P_T, on the braking rheostats, the dissipated share start rising, reaching a maximum of 1 MW around second 5 (this is appreciable observing the black line PR). At the same moment (second 5) the braking power is almost 3 MW, consequently the power injected on the line is almost 2 MW. The braking continues in a mixed scenario, between dissipation and generation; when voltage drops under the threshold, the power is totally injected; when the braking effort increases at the second 14 (causing an increment of the line voltage, of course) the dissipation increases in turn.

As previously mentioned, the chopper regulates the amount of dissipated power with a PWM technique varying the duty cycle and, thus, changing the relative duration of the time interval in which the resistors are connected and disconnected. This modulation is appreciable in the enlargement reported in Figure 4b and 4c. Note that, around the second 5, as the duty cycle is about 20% (Figure 4b), the dissipation is high.

In contrast, duty cycle is only 4% (Figure 4c) around the second 10, in which the pantograph voltage drops below the V_{TH} threshold, the power dissipated on the rheostats is minimal and, consequently, the power generated by the traction inverters it is almost totally injected on the line.

The amount of energy dissipated in the rheostats is energy that could be saved by adopting a proper energy storage.

4. ANALISYS OF A RAILWAY TRACK

The considered route (see Figure 5) is the Rimini-Bologna round trip. A track 115 km long and covered in about 1.5 hours. It is interesting evaluate a typical braking pattern while a train is approaching railway station. In Figure 6 a typical braking event is reported: it was the braking for stopping at Forlì station on the track Bologna-Rimini on 1 January 2022 at 4:50. As can be seen, the train driver uses braking of decreasing intensity: the first two brakings are of considerable intensity to obtain a drastic reduction in speed. The last braking is instead of a modest entity and is used for the final stop. Between the brakings the train moves forward in coasting (proceeds by inertia without traction effort).

The peak of power generated during the event is of about 2.4 MW and the amount of energy related to each pulse has order of magnitude of about ten kilowatt per hour. So, for this type of energy and power flows, fast energy storage systems are needed to fully manage and exploit the braking energy.

As mentioned before, the braking reported in Figure 6 was recorded at specific location in a specific time and taking as reference a specific train (E464). Anyway, adopting proper statistical methods, it is possible to explore the possibility to extrapolate such results extending their validity. To this aim, it is possible to analyze the different braking that the same train at the same day (1 January 2022), performs on the whole considered track (Bologna-Rimini). Thus, in Figure 7, the values of the power dissipated by the train during braking in the considered track are reported.

The considered track covers a distance of 115 km with an overall duration of the journey of one hour and a half. An analysis on a round trip performed by the train has been conducted. In fact, the values related to the outward trip are represented by the blue line (from Riccione to Bologna), while the one related to the return are represented by the blue line (from Bologna to Riccione). During this round trip, the train absorbs 3.4 MWh, while only 19 kWh in all are sent back to the catenary during the braking phases, against 418 kWh of energy dissipated on board the rheostats. Therefore, the amount of energy recovered does not overcome 5 % (see Figure 8). This low percentage is due to limited number of trains, circulating on the same line at that time. At first glance, it can be noted that the maximum of braking power during the considered route is of about 2.8 MW and that the braking events are mainly localized near the stations.

It is apparent that similar braking applies at all railway station and similar results can be obtained also for other routes. Moreover, the braking effort is quite similar if you compare the journey in the two directions as the route is flat but obviously the events are in symmetrical positions with respect to the stations due to the opposite direction of the train.

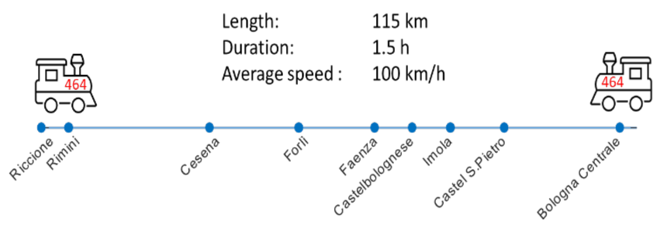

Figure 5. Considered route of the *central campaign*

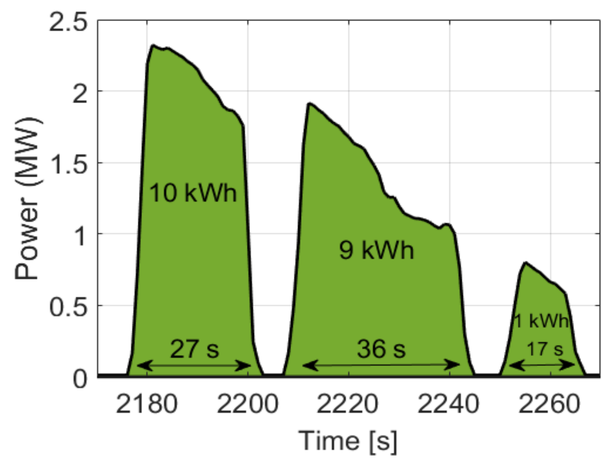

Figure 6. Power generated during a typical braking event, P_T

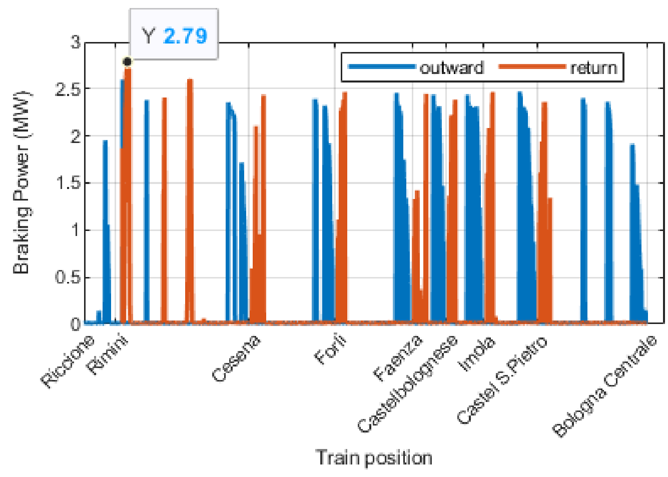

Figure 7. Behaviour of the braking power during the Bologna-Rimini

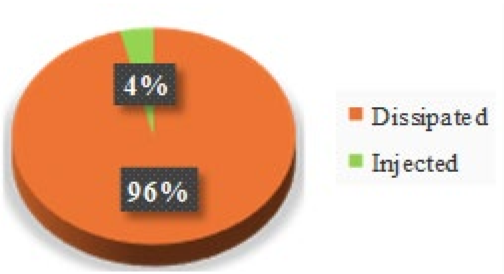

Figure 8. Recovery ratio in the considered route

5. MEASUREMENT CAMPAIGN RESULTS

Figure 9 shows the values of net absorbed electrical energy compared with the energy generated during the braking for various journeys of the *northern campaign*. The total braking energy is obtained summing the measured values of dissipated and recovered energy. The braking energy varies greatly depending on the route. During Bardonecchia Torino journey we have the maximum amount of braking energy due to steep downhill. It is apparent that for most of the journeys, a remarkable amount of the braking energy is not recovered and wasted. This value depends on the capability of the DC supply system to receive energy, that greatly changes with the presence of other trains, their distance and their operating conditions. Anyway, in the considered period, the total absorbed energy was about 60 MWh and the total amount of energy not recovered was about 4 MWh. Note that the dissipated share is about 41% of the total braking energy on average. With the adoption of on-board storage systems, properly designed, or with the adoption of reversible substations, this amount of energy could be saved.

A statistical analysis of dynamic braking during journeys between Torino PN and Susa (both directions) was conducted, based on data from 25 outward and 24 return trips. The track is about 51.5 km long with an uphill altitude difference of 264 meters from Torino to Susa. The braking time intervals have been identified, detecting negative value of the current at the pantograph and positive current in the braking rheostats). The probability density functions (PDFs) of recovered and dissipated energy are shown in Figures 10 and 11 for the outward journey and Figures 12 and 13 for the return one.

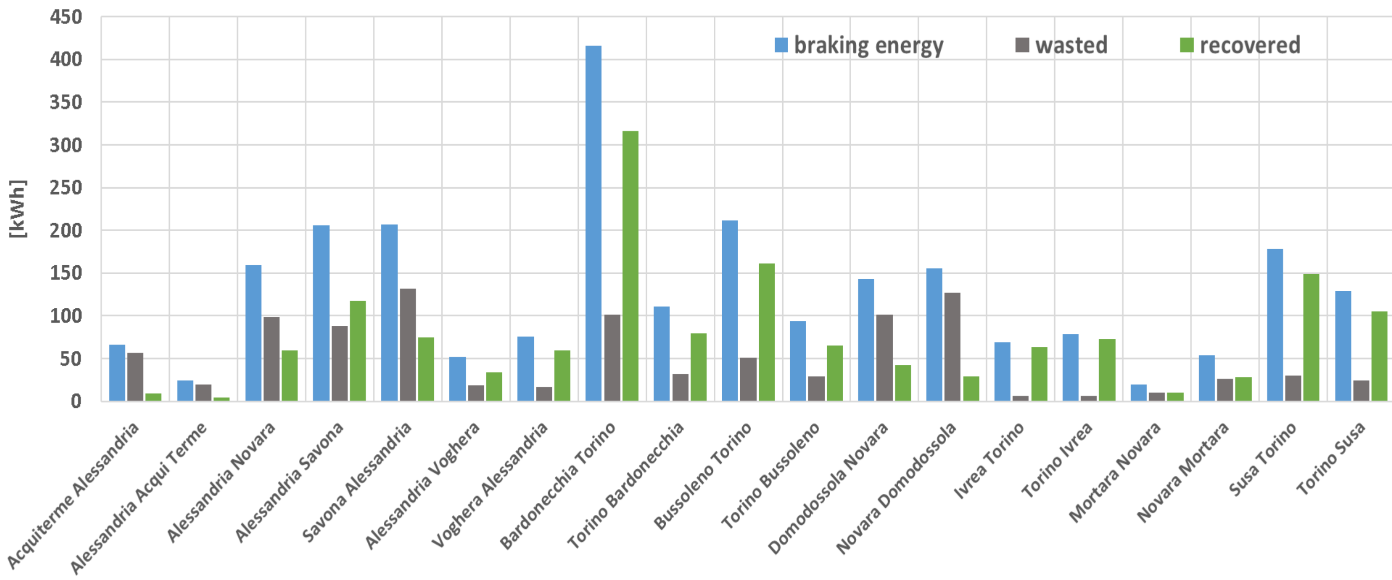

Figure 9. Braking energy analysis of all the monitored route of *northern campaign*

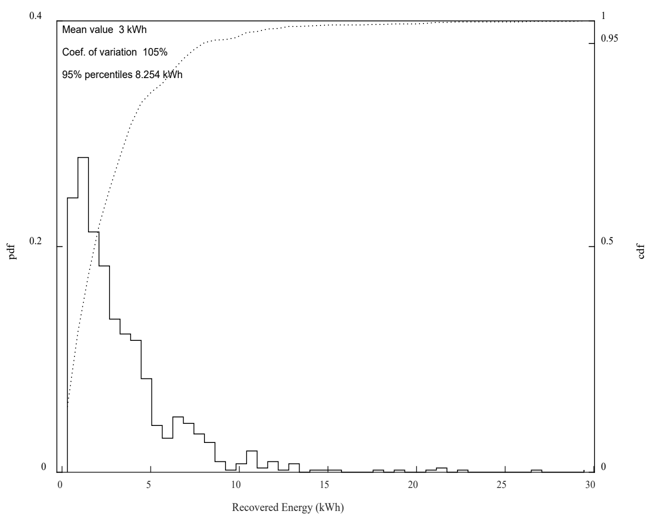

Figure 10. Recovered energy for the route Torino PN-Susa

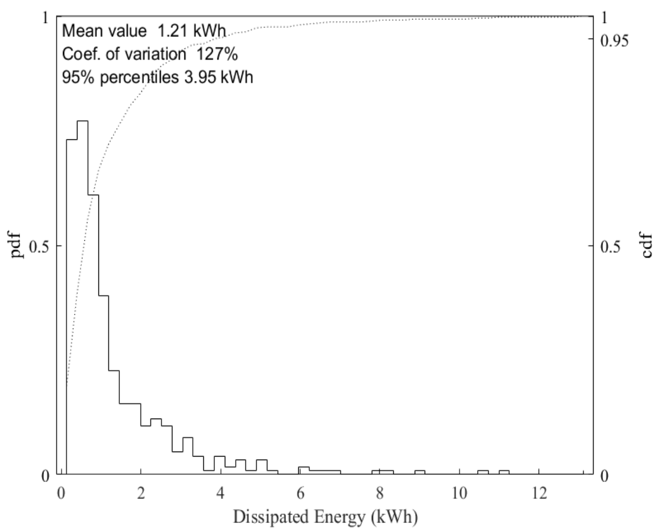

Figure 11. Dissipated energy for the route Torino PN-Susa

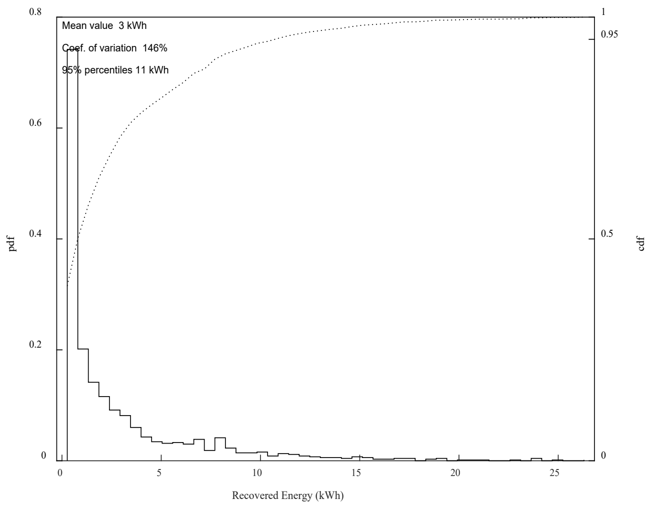

Figure 12. Recovered energy for the route Susa Torino PN

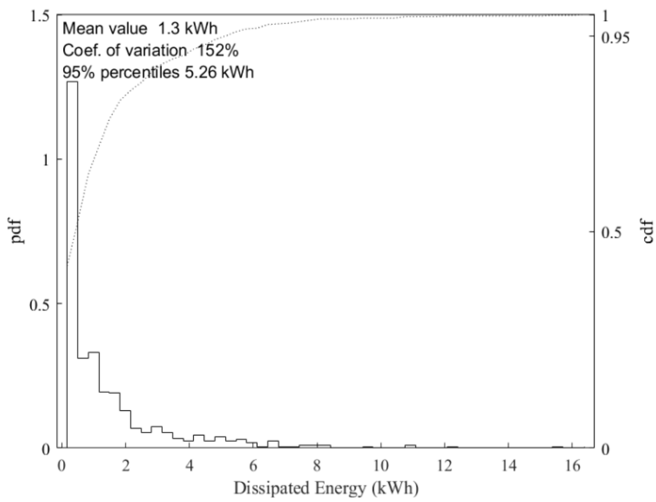

Figure 13. Dissipated energy for the route Susa Torino PN

Outward and backward journeys can be easily compared. During both journeys, the recovered energy prevails on the dissipated one. Meanwhile the dissipated energy related to the backward, on average, are greater than the one related to the outward. In fact, Figure 13 reports a mean value of 1.3 kWh, and a 95°% percentile of 5.26 kWh. Instead, as it can be seen in Figure 11, the statistical analysis shows a mean value of 1.21 kWh and a 95°% percentile of 3.95 kWh. As regards the regenerated energy, at a first glance one could expect that during the downhill path it should be greater than that of uphill. Instead, the average regenerated energy reveals to be almost the same. Nevertheless, the 95°% percentile of the backward journey Figure 12, is of about 11 kWh and, thus, greater than the 95°% percentile of the outward that does not exceed 8.25 kWh. There are two aspects that influence these results, both due to the slope of the path. Obviously during downward, the total braking energy is greater, but the line receptivity, due to the presence of other trains, is about the same. The higher generated energy must be consequently dissipated on the rheostats, causing numerous events with high regenerated energy.

Building on the previous findings, infrastructure changes could be suggested to decrease wasted energy. the rheostatic dissipation is controlled by voltage level, lowering the operating voltage would increase recovered energy. However, this might also cause higher transmission losses, requiring a careful analysis of the trade-off.

Another approach to increase the recovery could be the adoption of opportune storage system [16-20]. The presented results could be adopted for its dimensioning, in fact with a storage system of about 5 kWh on board train (see Figure 13) it is possible to recover the energy of 95 % of dissipative braking. Alternatively, the storage could be placed in substations in order to enhance the line receptivity. The dimensioning could be obtained multiplying the obtained value for the average number of trains on that route. To this aim, the suggested storage technology should be based on supercapacitor, because of the short response time required.

6. CONCLUSIONS

This paper investigates the potential for energy savings through the reuse of energy recovered during dynamic braking. Real-world data was collected by monitoring a commercial railway traction unit on various tracks. The analysis focuses on data that helps us understand how energy flows between the train's pantograph and the power line during braking. The statistical analysis conducted on the braking energy allows to quantify the potential energy recovery using on-board or station-based energy storage systems.

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