Kinetic energy recovery on railway systems with feedback to the grid

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1. Introduction

The increasing concern with energy saving and efficiency has a clear application in the regenerative braking capacity common to most rolling-stock. This possibility crashes with the non-reversible characteristics of the substations of direct-current catenary-based rail systems.

Different options for storage and subsequent reuse of energy have been studied for both on-board and substations. Storage options are more costly and bigger in size due to the power storage components used. Additionally, there are the limitations associated with the life time of the storage components. Direct return to the distribution grid has also been proposed as an alternative. This would be carried out by converters with capacity to transfer direct catenary power to the alternate three-phase grid.

Previous proposals, required to use an independent transformer associated to the recovery system in order to be able to work with catenary's voltages close to the voltage imposed by the grid and by the substation rectifier.

The solution presented in this paper deals with the design strategy and topology of a new converter developed for a 1500Vdc catenary subway traction system. The recovery system works connected to an already existing transformer in the substation, minimizing the investment needed.

2. RECOVERY SYSTEM DESIGN METHODOLOGY

The study, design and construction of the first prototype have been carried out for the Metro Bilbao subway traction system in Spain. The main features of this underground system are the following:

- Number of lines: 2.
- Total kilometres: 39 Km.
- Number of stations: 36.
- Number of substations: 10.
- Catenary rated voltage: 1650 Vdc.
- Mobile material: 24 S500 units + 13 S550 units (148 cars).
- Max. power of units: 4MW.
- Transit frequencies: 5 min, 6 min, 10 min, 20 min, 30 min. *NOTE: In the common segment of the two lines, the transit frequency is twice the specified frequencies.*

- Total kilometres per year: > 4.300.000 km.
- Total passengers per year: > 86.000.000 passenger.
- Annual consumption for traction: 52.5 Million kWh.

2.1 MEASUREMENT OF AVAILABLE ENERGY

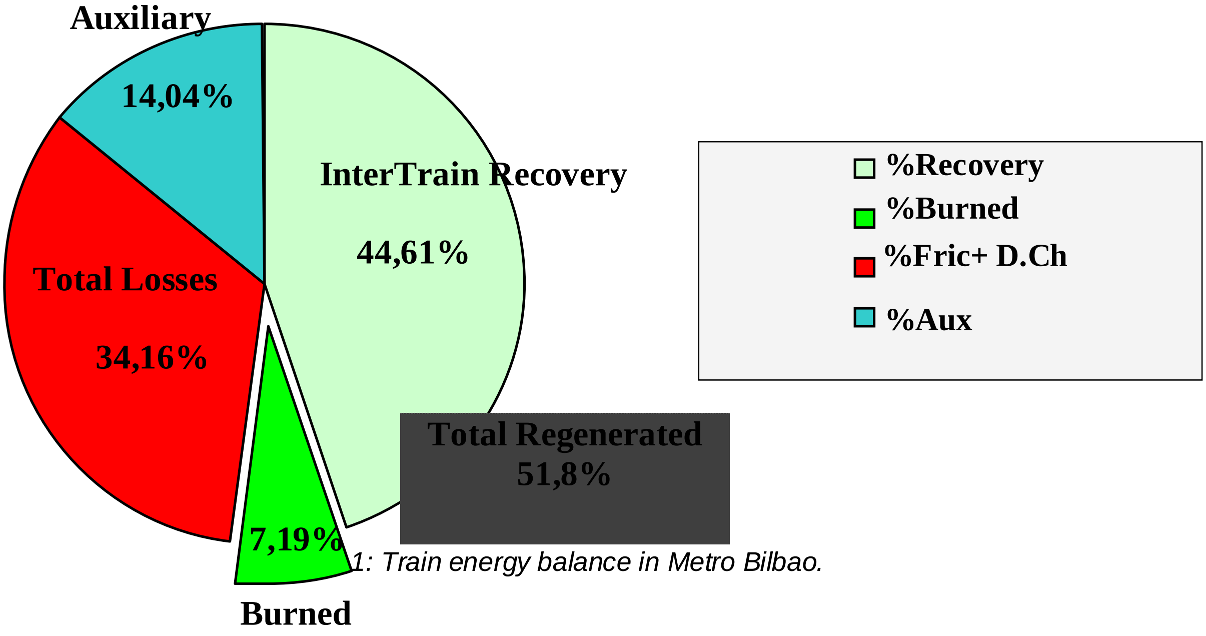
The first step is to check the amount of energy that at present is being burnt during train braking processes. The prior study involved acquiring on-board real traction and braking-power profiles, as well as the speed datum of a relevant number of Electrical Multiple Units covering the round-trip distance through all the existing lines and different operation frequencies.

The following conclusions could be made from the analysis of the gathered data:

The initial energy performance of the trains showed very high inter-train recovery data. This is due to the high transit frequency, particularly in the shared area of the two lines, and to the low impedance of the rigid catenary in line 2. Table 1 shows the percentages energy exchange between trains for the different segments of the route.

ENERGY RETURNED BY SEGMENT			
Common segment	**Line 1 middle segment**	**Line 1 final segment**	**Line 2**
47,04%	**39,72%**	**30,24%**	**46,31%**

Table 1: Recovery between trains, by segment.



1: Train energy balance in Metro Bilbao.

The mean energy balance at the substations can be calculated from the train´s behavior values above. Figure 2 shows the resulting percentages for the whole system consumption with an estimated catenary’s loss of 7% of the total traction consumption.

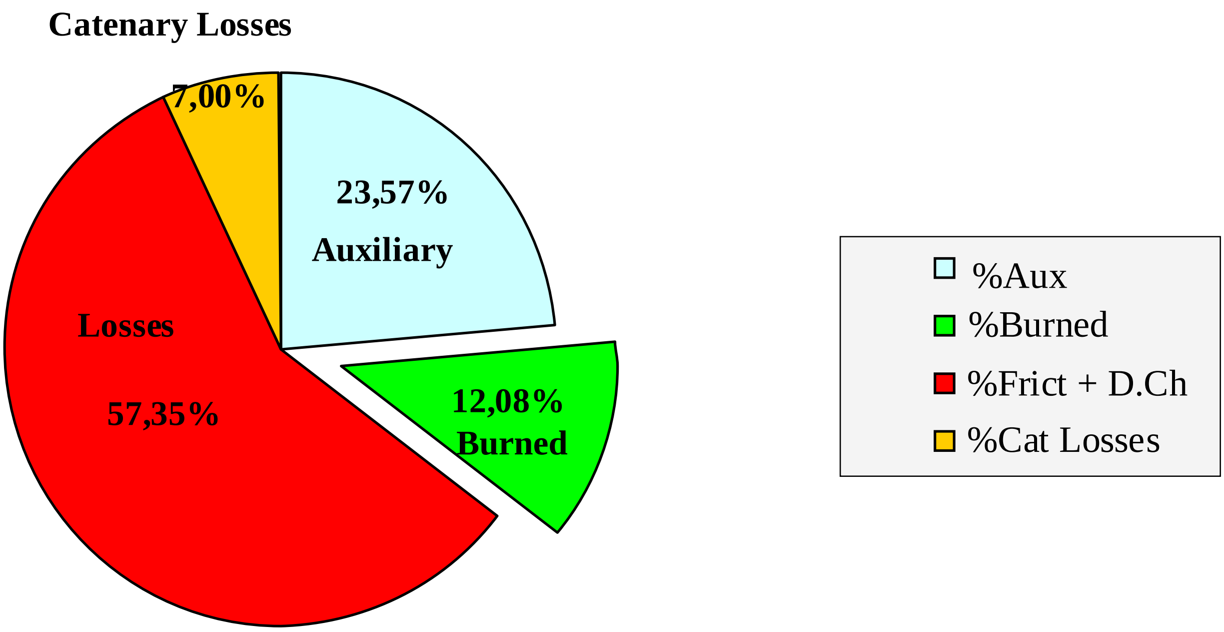


Figure 2: Energy balance of Metro Bilbao system.

The study shows that the burned energy represents **12.08% of the total energy consumed** for traction in the substations. This means:

Annual saving potential = 6.34 million kWh

2.2 RECOVERY SYSTEM SPECIFICATION

The next step was to determine the characteristics of the equipment to be installed at each of the substations, the required power capacity and the resulting work cycles for an optimum converter design.

For dimensioning purposes, a simulation tool capable of calculating the interaction between the different substations and the different trains linked to the same catenary was developed. An electrical model of the static system was created, including substations, stations as well as catenary impedances. The main characteristic of the simulation tool is its capacity to use data obtained from the real measurements taken of each unit, calculating successively the evolution of the trains' position, the evolution of the impedances in the catenary’s sections between the different components, and the resulting power flows for each instantaneous configuration.

- Validation: The program and the model created were first validated by carrying out a simulation of the real installations and comparing the results obtained with real values.

- Simulations. Once the simulation tool was validated, the recovery systems were included in the mathematical model and new simulations were run in order to calculate the recoverable power profiles for each substation. The aim of these new simulations was to determine the optimal power capacity values for a given recovery system. The optimal values were calculated in terms of the following required characteristics:

- Total energy recovered
- Investment costs.
- Amortization ratios.
- Single converter design and modularity for an easy implementation on existing substations.
- Existing substation characteristics. Nominal Power of the substation transformer to be used (2,25MW).

The final conclusions after successive simulations were as follows:

- Number of substations to equip: 5.
  - Line 1-2 shared segment: Ariz, Ripa,
  - Line 1: Lutxana, Aiboa.
  - Line 2: Urbinaga.
- Max. power of the unit to be installed: 1500kW.
- **Total savings obtained: 8,26%.**
- **kWh recovered annually: 4.6 million kWh.**

The following table summarises the estimates of energy recovered annually in each of the selected substations.

	ARIZ	RIPA	LUTXANA	AIBOA	URBINAGA	TOTAL
$E_{Recovered}$	900 MWh	1030 MWh	650 MWh	1060 MWh	960 MWh	4600 MWh

Table 2: Annual recovery by equipped substation. Data in megawatts hour.

At first sight, the expected recovery percentage may seem to be low, this is due to the high level energy exchange between train that is already happening on the system.

The data that really needs attention is the recovered energy absolute value, its enviromental impact and the resulting amortization time. In the case of Metro Bilbao, the expected average amortization period is 7 years for equipment with a useful life of 30 years.

3. NEW CONVERTER TOPOLOGY

When recovering energy from the catenary, the converter has to inject into the distribution grid a high quality current with low harmonic components (THD<5%). In order to attain a good current regulation, and given that the power drops in outlet filters, the converter requires a minimum voltage level at the DC side. This means that the voltage at the DC side of the inverter always needs to be over the peak voltage at the AC side in order to achieve the required current quality. This fact can limit the capacity of the system to recover the power available to a great extent, especially when the voltage at the substation incoming feeder raises and gets close to the braking voltage of the trains.

The solution presented in this paper proposes a cascade connection between an elevator chopper and an inverter. The chopper increases the existing voltage in the catenary by generating sufficient voltage for the inverter to return power to the distribution grid. This way, the catenary voltage margin with which the power recovery system is able to run is the maximum for any grid voltage situation, optimizing power recovery under all circumstances.

Regarding the integration of the new recovery converter in the substation, the converter is directly connected in paralel to the existing rectifier. Due to the above described cascade topology with the DC voltage elevation stage, there is no need for an additional power transformer and the rectifier´s pre-existing transformer is used for the connection of the converter to the distribution grid.

Reliability of the whole system is an essential issue for any railway application. The converter is designed to enable its disconnection from both, the DC and AC sides. By this means, in case of any event happening, the converter is able to self-isolate from the substation without compromising its operation.

The following figure shows the power diagram of the converter and its integration into the substation.

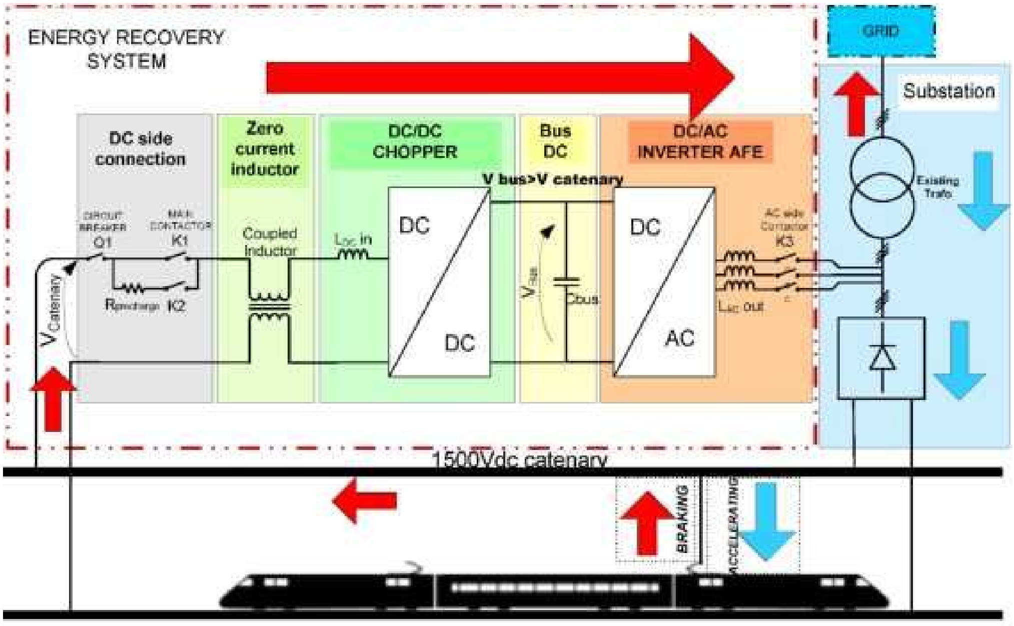


Figure 3: Power diagram.

As mentioned above, the maximum power of the converter was determined to be 1500kW. The converter was designed to be able to stand this peak power but it was thermally designed according to the work cycle defined by the simulations. This design strategy gives as a result an optimum sizing of the converter since its working cycle will always be pulsative.

4. REAL APPLICATION RESULTS

In order to validate the previous analysis, a prototype was designed and installed in one of the substations of the subway traction system. This particular substation was chosen because of its location in the catenary lane, since it is located in the middle of the section with highest train circulation - therefore the hardware and control requirements are expected to be more critical at this point. The simulations run for a single recovery substation deliver an expected recovery percentage range of 8% to 25%, based on system timetable and standard grid voltage variations (percentage values relate to the same substation consumption).

The data outlined below shows the main characteristics of the substation and recovery equipment installed:

No. of transformers	3
Nom. Power of transformer	2.25 MVA
Nom. Power of substation	6,75 MW
DC side Nom. Voltage	1600 V_{DC}
AC side Nom. Voltage (Tap -5%)	1177 V_{RMS}

Table 3: Main characteristics of the substation.

Max. Instant Power	1500 kW
DC Side Nominal Voltage	1500Vdc
Max. DC side Voltage	1950Vdc
Max. DC side Current	1000A
AC side nominal Voltage [±7%]	1150Vrms
AC side Max. Current	850Arms
Grid current THD	<3%
Output Frequency	50 Hz
System Cooling	Forced Air
Installation Area	7.5 m2

Table 4: Main characteristics of the recovery system converter..

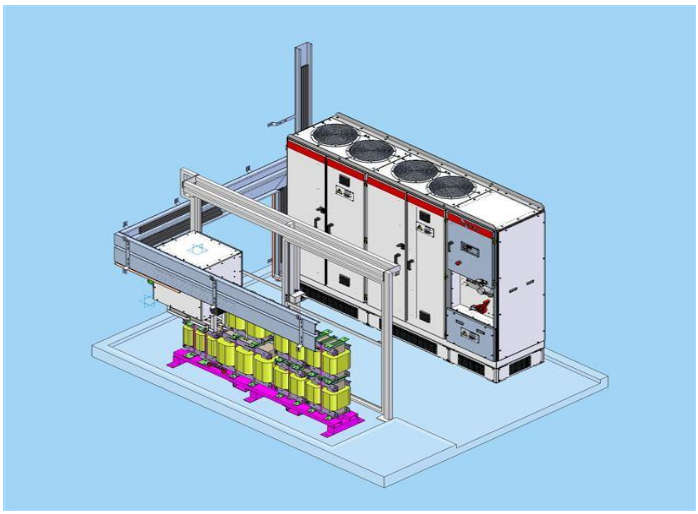


Figure 4: Recovery system 3D drawing.

The prototype has been successfully working since august 2009. The performance obtained after this time is shown below.

Period	Train Circulation	Mean Recovery (kWh)	Mean % Recovery (% of Subs. Consumption)
Working Day (18 Hours)	Mainly 6 min.	2640 kWh	8,22%
Friday Night (2 Hours)	30 min	800 kWh	58%
Saturday (18 Hours)	6min, 10 min	3130 kWh	14,2%
Saturday Night (6 Hours)	30 min	1880 kWh	61,2%
Sunday (18 Hours)	Mainly 10 min	4050 kWh	24,6%
Week		**23080 kWh**	**11,32%**
- **Mean monthly recovery: 100,000 kWh.**			
- **Annual recovery: 1,200,000 kWh.** (>11% of substation consumption).			

Table 5: Performance summary.

It is easy to see that the performance is quite better over the weekends due to the fewer train circulation. The energy exchange between trains is drastically reduced when there are fewer trains running and as a result, a bigger amount of recovery energy is available even though the total energy flowing through the system is much smaller.

The registered annual recovery is higher than the values calculated on the previous analisys for the whole system solution with five substation equiped. This is due to the fact that nowadays the prototype in Ripa is recovering part of the energy that in the future will be recovered by the nearby equiped substations.

The variability on the performance as the influence of the existing voltage level on the grid has also been confirmed. The total energy recovery during a working day fluctuates between 1800 kWh and 4000 kWh, and raises up to 3000 kWh to 5000 kWh during weekends.

Vis	Tipo	Color	Nombre	Un. Ing.	Valor Cur 1	Valor Cur 2	Min Valor	Max Valor
☑		🟥	Energia regenerada:	mwh	10.756	12.730	10.000	14.000
☑		🟩	Energia consumida:	mwh	164.339	199.984	160.000	210.000
☑		🟦	Vred:		1255.124	1239.768	1200.000	1300.000

Figure 5: Evolution of energy consumed, energy recovered and grid voltage.

Y axe, percentage value according to the following minimum -maximum values:

Grid Voltage: [1200VRMS - 1300VRMS

Recovery Energy: [10000kWh - 14000kWh]

Consumption Energy: [160000kWh- 210000kWh]

Fig 5 shows the evolution of the grid voltage (blue), the total recovered energy (red), and the total energy consumption on the substation (green) during 24 hrs on a working day. Fig 5 illustrates the influence of the grid voltage on the ability for the energy recovery, as the local values of the dE/dt fluctuate, depending on the grid voltage level. In the same way, it can be observed that high dE/dt values are obtained at the beginning and at the end of the day. As explained before, this is because there is more available energy as a consequence of the fewer train circulation.

It is also interesting to point that not all the energy that the recovery system is injecting into the AC side is going back to the distribution grid. As it is common on railway systems, part of the total energy consumption is due to the infrastructure´s auxiliary charges, mainly on stations and depots. In many cases, the transformers feeding these auxiliary charges are connected in parallel to the transformers feeding the catenary. We have measured that almost 60% of the total recovered energy is internally consumed on the infrastructure auxiliary charges due to this configuration and only 40% is sent back to the grid. In practice, this internal consumption becomes in a lower total consumption of energy from the grid. These percentage values belong to the particular configuration in Metro Bilbao . It could happen not to have any internal consumption of the recovered energy (if the transformers are not in connected in parallel) or just the opposite case, all recovered energy being consumed on internal infrastructure charges.

5. CONCLUSIONS.

In this document we present a new technical solution for regenerative braking energy recovering in DC railway systems. The performance conclusions of the reversible substation prototype that has been successfully working for the last 18 months in Metro Bilbao are disclosed. We also have introduced the dimensioning methodology that Ingeteam Traction followed in order to find the optimal technical solution. All energy recovering potential predictions have been confirmed on the real application. The following step will be the installation of four new converters according to the optimal solution designed for the whole Metro Bilbao railway system.

Figure5. Photo of the system installed on the substation.