REVERSIBLES SUBSTATIONS

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Index

Summary

In this article, the functioning of a traditional tramway network is analyzed, from the viewpoint of the energy braking regeneration . The tramway network has a 11 km length and 20 stops distributed approximately each 500 m with a 6 minutes circulation frequency.

It is represented through the corresponding graphics, that regeneration braking application produces a decrease in consumption around 40%, losing close to 6% that is burned in the train rheostats.

Increase efficiency in energy regeneration through the braking energy, would consist in using that 6% burned in the train rheostats, by installing another systems, such as reversible substations. However this exploitation cannot be complete, because transport losses of this energy would come out till the reversibility points, porque entrarían en juego las pérdidas por transporte de esta energía hasta los puntos de reversibilidad, just like losses in the actual reversible substation.

Keeping in mind that efficiency in braking recovering systems, depends on several parameters, such as track pack, trains characteristics, circulation characteristics (frequency, number and distance between stops, accelerations, deceleration, etc.), not every system behaves the same, so it is necessary to make a previous evaluation of each installation to define the need and location (in case) of reversible substations.

1. Introduction to the energy analysis in tramway networks.

It consists in rising the efficiency of railway electrification facilities together with their reliability, their maintenance and their improvement.

The evolution of mechanical and structural characteristics of the catenary allow the increase in trains speed or easier assembly for reduced speeds.

Otherwise, trains that are actually travelling have different operating features from those that travelled years ago, basically due to the incorporation of power electronics, this technology allows systems to recover the energy produced during trains stopping.

Keep it in mind that there are still routes where the trains that are in circulating do not allow energy recovery braking.

One of the most important expenses item that railway administration has is that one caused by the consumption of traction energy from their trains, so if will be quite important to reduce it.

In the last years, several systems appear to reduce electrical consumption from trains traction, which also means to rise traction efficiency, although in this study we focus exclusively in braking energy recovering and reversible substations.

In ***Electrificación y Estudios Ferroviarios S.L.***, from now on ***e2f***, through the *CECAT* simulation software, we have carried out energy efficiency studies in different type of networks (tramways, metropolitans, high speed lines, etc.),analyzing the difference between studies with considering braking recovery energy and studies without its consideration.
We have also analyzed networks considering the existence of reversible equipment in the traction substations, that could allow in certain conditions, taking energy from the catenary (both in continuous and alternative current) and send this energy to a external network, and we have concluded, that there is no an uniform behaviour, and that there are multitude parameters that could make results change from one installation to another.

In this way, energy efficiency obtained in a metropolitan tramway network, with a 2/3 minutes train frequency is not comparable to another with a 10 minutes tramway frequency or a conventional train network with trains every 30 minutes or a high-speed train network working with alternative current. For example, for the same type of train, to modify the power consumption curve by the ATO system, allows us to modify traction efforts and therefore it affects to the global operation of the line.

Every time, it would be necessary to make a detailed study for each case, taking in account the electrical features of the circuit, if the track is single or double, and in the second case if the tracks are connected or not, just like distribution and distance between substations, catenary features, train frequency, maximum values of acceleration and deceleration, distance between stops, etc. just like train features (power consumption, electrical braking power, etc).

Simulated calculations have been carried out by **CECAT** software developed by the enterprise **Electrificación y Estudios Ferroviarios S.L.**, **e2f**, that allows the energy sizing of overhead contact lines and substations in continuous and also in alternative current (1x25 and 2x25 kV).

Our software carries out every calculation keeping in mind recovery braking in trains, obtaining the values of the different energies: regenerated energy, burned energy in train rheostats, auxiliary services energy, returned energy in substations, braking energy that cannot be produced and also returned energy to the alternative current line in the reversible substations etc., and the variation of power consumption depending on the voltage.
For more information about our software, please visit our website:
http://www.e2f.es/pdf/ES_CeCat.pdf

In this study, consumptions produced in a new design tramway system in Albacete, will be analyzed. Its features and operating modes are indicated below.

2. Characteristics of the studied installation.

2.1. Track.

The track of the tramway line has a 10,8 km length with a 10,8 km with smooth slopes that are always under 2-3 per thousand, double track, 54 kg/m.l. rail being connected both tracks between them each 500 m.

Albacete tramway stops will be distributed along the track path, located each 500 m one to another according to the following table:

Name stops	PK
Santa Isabel	0+580
Cruce Avda. Primera	1+080
Cruce Avda. Segunda	1+500
Cruce Avda. Tercera	1+900
Cruce Avda. Cuarta	2+230
Imaginalia	2+940
Los Llanos del Águila	3+340
Parque Bomberos	3+690
La Soledad	4+060
Fiesta del Árbol	4+510
Feria	4+860
Carretera Jaén	5+253
Hospital Perpetuo Socorro	5+616
Carrefour	6+626
Pedro La Mata	7+062
Parque Sur	7+534
El Corte Inglés-Avda. España	8+334
Puerta de Murcia	9+128
Hospital Provincial	9+384
Puerta de Valencia	9+750

Table nº1: Stops indicating its kilometre point

2.2. Overhead Contact Line.

Overhead contact line is formed by one contact wire of Cu-Ag 0,1%, with a feeder along the track path consisting in two underground aluminium wires (1,8/3kV isolation), that are connected to the contact wire approximately each 300 m.

The overhead contact line in both tracks are supplied independently of the traction substation, and they are not connected between them along the track path.

2.3. Traction substations.

Traction substations location, just like its power and transformer-rectifier are indicated in the table below:

Traction Substation	**PK**	**POWER [KVA]**	**Transformer-rectifier impedance**
SER nº 1: Santa Isabel	0+450	2x1250	0,0227
SER nº 2: Llanos del Águila	3+360	2x1250	0,0229
SER nº 3: Carrefour	6+700	2x1250	0,0232
SER nº 4: Hospital Provincial	9+400	2x1250	0,0234

Table nº 2: Traction substations (SER) indicating its P.K.

2.4. Circulation features.

For studying the circulation frequency of the trains, it has been considered a 6 minutes per track frequency.

Trains will stops 20 seconds in each stop.

Maximal circulation speed is 70 km/h.

Maximal acceleration considered in the study is 1,0 m/s^2, and the value for deceleration (braking) is 0,5 m/s^2.

2.5. Trains features.

Capacity	206
Sections	5
Motors per bogie	2
Bogies	4
Motors	8
Rated motor power (traction to 1800 rpm)	60 kW
Maximal total power	480 kW
Power supply voltage (Vcc)	750 V
Maximal Traction stress per bogie	35 KN
Total stress traction	140 KN
Maximal start acceleration	1,2 m/s^2
Deceleration (service braking)	1,2 m/s^2
Maximal speed	70 Km/h
Vehicle length	32,366 m
Minimal curve radius	20m
Capacity:	
Seats	52+4 pmr
Standing (3,5 p/m^2)	154
Total	206
Unladen weight	45,45 Tn
Load weight	62 Tn
Auxiliary services power	80 kW

Table nº 3: Tramways features

For calculations, we also consider the following features of the train:

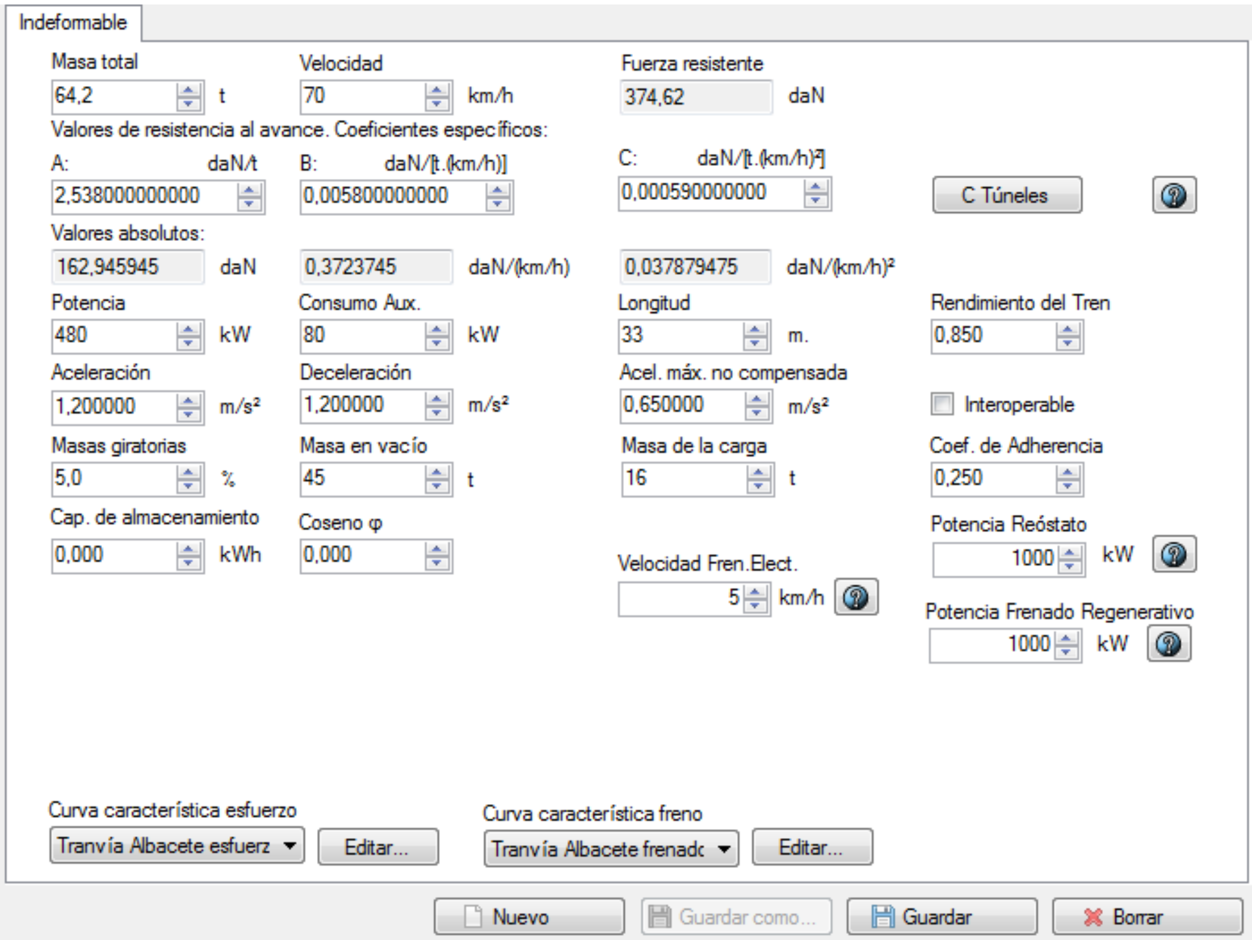

Table nº 4: Simulation tramways features

Showing values of the resistance to advance, the percentage of rotatory masses considering, uncompensated acceleration, traction engines performance, maximum power of regenerated power and electrical brake power, as well as minimum speed (5 km/h) applicating the electrical brake (it is not considered with a minor speed, etc.).

3. Energy analysis of the Albacete tramway

The simulation study has been carried out by following the phases below:

Phase 1: The energy evaluation of the installation is been carried out considering that the trains are circulating without recovery braking energy.

In these conditions, we obtain the following values:

- Energy consumed by the traction trains.
- Energy consumed by auxiliary services in trains.
- Substations traction losses.
- Catenary losses.

With these values, total consumption energy in traction substations could be represented, just like consumption energy in each of them. Pantograph voltage values are also represented for each train along the path.

Phase 2: We carry out the energy balance of the installation, considering that trains travel with braking recovery energy.

Under these conditions, the following values are obtained:

- Energy consumed by the traction trains.
- Energy consumed by auxiliary services in trains.
- Substations traction losses.
- Catenary losses.
- Maximal energy produced by trains.
- Used energy by trains.
- Unused energy by trains (burned in trains resistors).

The comparison between phase 1 and phase 2 , will permit us to determine which is the energy efficiency produced when trains use or not energy recovery braking, just like unused energy that we cannot use because there are no trains consuming or close enough to consume the energy that the one generating.

Phase 3: We carry out the energy balance of the installations, considering that trains travel with braking energy recovery and that also in all the substations there is an inverter to revert the excess of energy to another extern systems of alternative current.

Under these conditions, the following values are obtained:

- Energy consumed by the traction trains.
- Energy consumed by auxiliary services in trains.
- Substations traction losses.
- Catenary losses.
- Maximal energy produced by trains.

- Used energy by trains.
- Unused energy by trains (burned in trains resistors).
- Regenerated energy by the inverters in the traction substations and sent to an extern line.

Comparison between phases 2 and 3, will permit us to analyze the increase of efficiency that could exist if the inverters are, or not, installed in the traction substations; therefore we could establish its economic viability.

3.1. Phase 1 simulation. Without regeneration.

We carry out phase 1 simulation, where the braking energy produced by trains is being ignored.

The time interval chosen is between minutes 60 and 120, in which all trains are circulating and also voltages and consumption values are already stabilized.

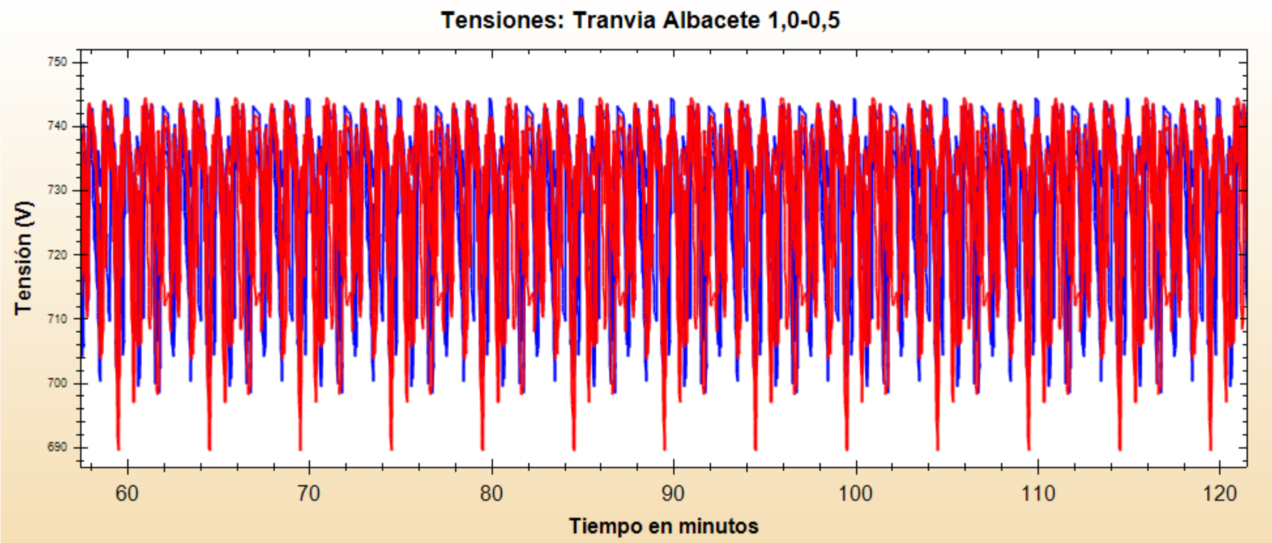

Figure nº 1.Pantograph voltage in trains. Circulation without braking energy recovery.

In figure 1, (rising tramways in red and descending tramways in blue) we can observe, for a 750 V voltage, that the maximal voltage value in the pantograph of tramways is in the order of 744 V, and the minimal one is close to 690 V.

Total power in the substations group is represented in the figure below:

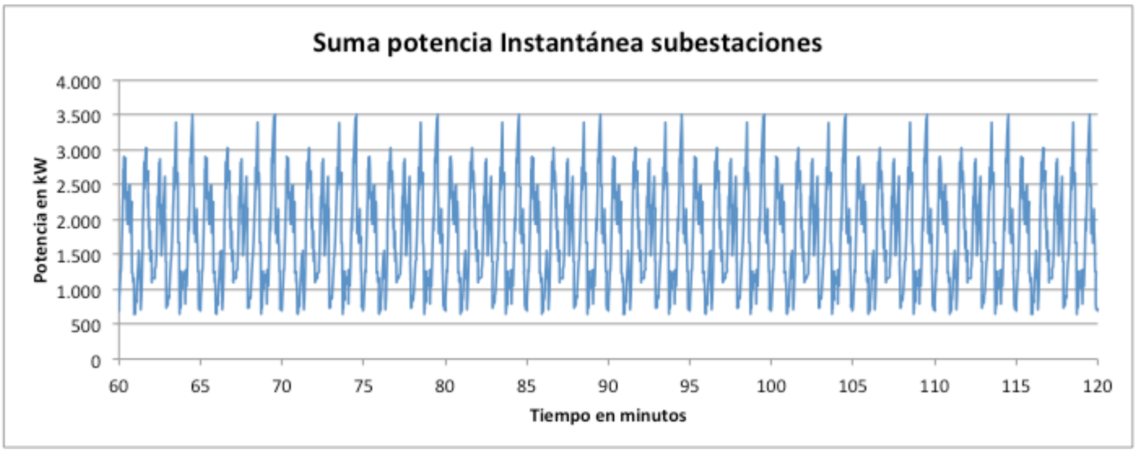

Figure nº 2. Total amount of instantaneous powers in substations.

The instantaneous power of the trains in every substation is represented in the figure below:

Figure nº 3. Instantaneous power in SER Santa Isabel

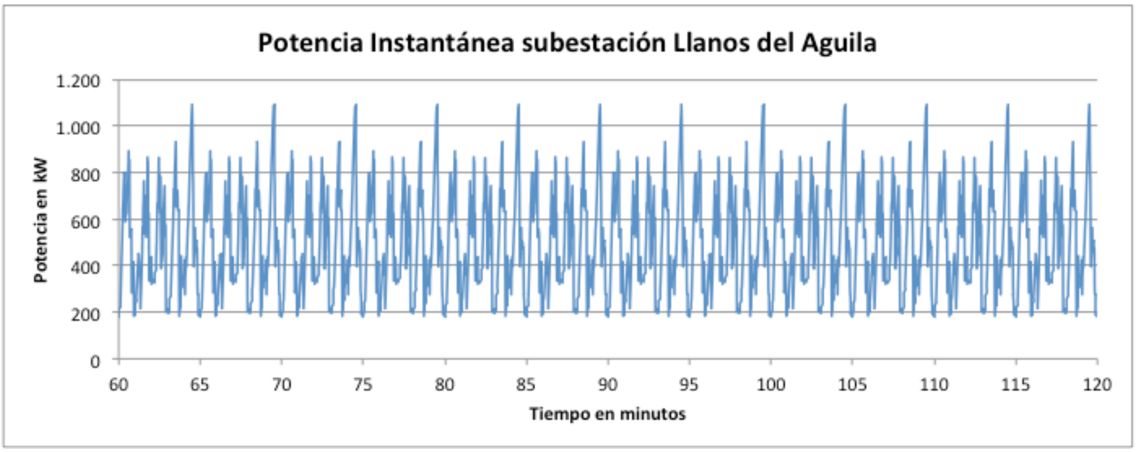

Figure nº 4. Instantaneous power in SER Llanos del Águila

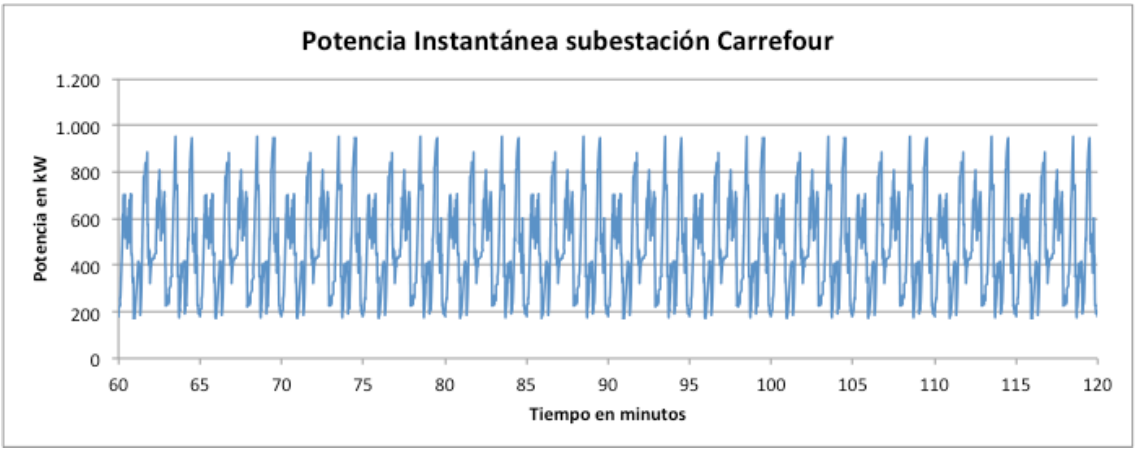

Figure nº 5. Instantaneous power in SER Carrefour

Figure nº 6. Instantaneous power in SER Hospital Provincial

	Total Consumed Energy [kWh]	SER Losses [kWh]	Catenary losses [kWh]
SER Santa Isabel	386,87	7,81	
SER Llanos del Águila	494,52	6,60	
SER Carrefour	478,42	7,41	
SER Hospital	395,31	4,66	
Suma	1755,12	26,48	20,54

Table nº 5. Consumed energy and losses in SER

If we represent the different values of consumed energy in the group of traction substations, we obtain the following figure:

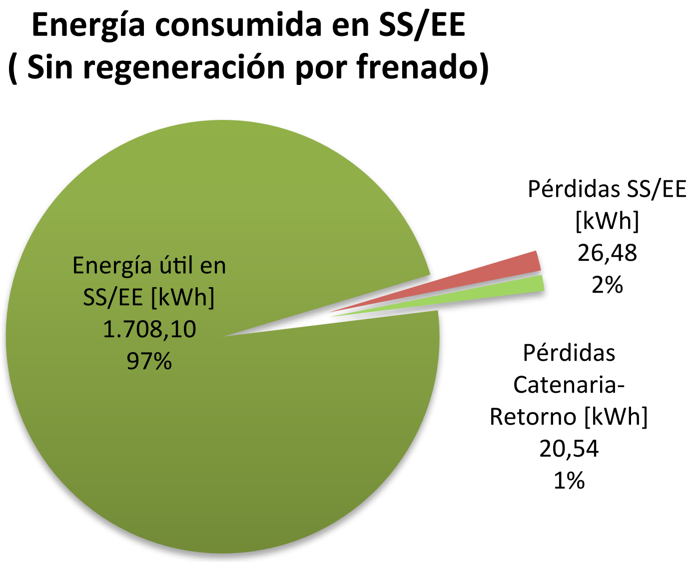

Figure nº 7. Consumed energy by substations, and its distribution, not considering recovery braking energy.

The amount of the energies, with the useful one and the losses we obtain 1755,12 kWh.

3.2. Phase Simulation 2. With regeneration:

In this phase we realised the simulation when the trains are circulating, considering the capacity of energy recovery in the braking process.

Voltage values obtained in the pantograph in phase 2 are represented in the figure below:

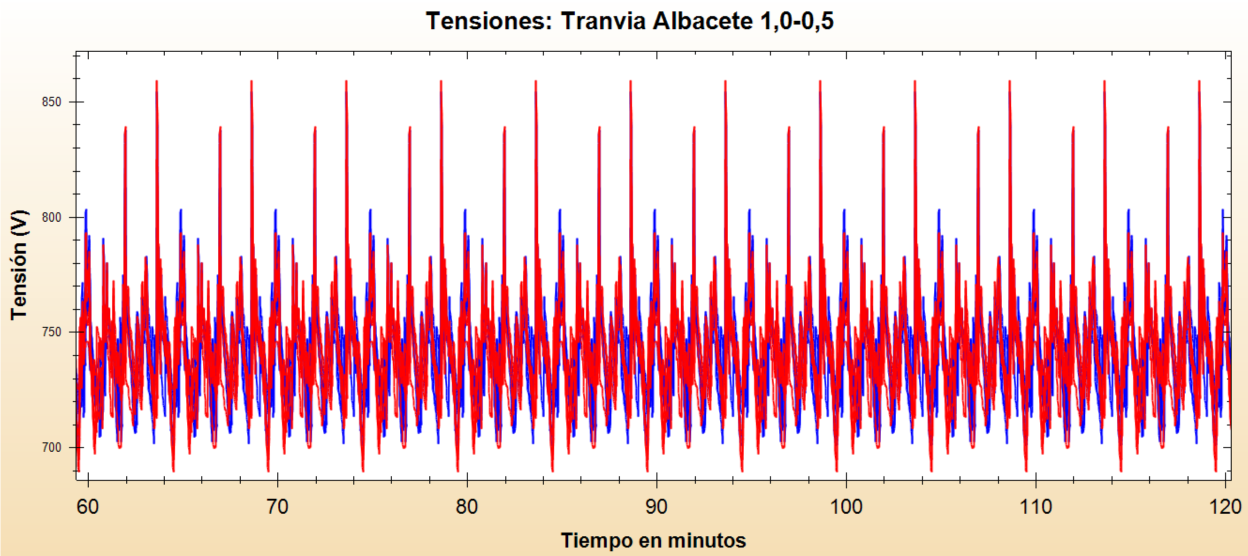

Figure nº 8 Pantograph voltage in trains circulating with braking recovery energy.

In the case of tramways with energy recovery braking,(rising tramways in red and descending tramways in blue) we can observe, for a 750 V voltage, that the maximal voltage value in the pantograph of tramways is in the order of 860 V, and the minimal one is close to 690 V.

	With energy recovery	Without energy recovery
V máxima	860 V	744 V
V mínima	690 V	690 V

Table nº 6. Maximal and minimal tension values in pantographs (With and without energy recovery)

The difference of the maximal voltage between both cases (with and without braking energy regeneration) happens because trains that are braking works as current generators, and that current need to have a significant difference in electrical potential, in relation to rated voltage in traction substations for being consumed by another tramways.

The maximal value of tension in the "generator" train is regulated by the train operator, and it cannot be bigger than the value indicated in EN 50163 standard, as V_{max1}, which in this case is 900 V.

As a criterion, it is established that, when a train is regenerating, the first consumer is the train itself, through their own auxiliary services, if the generated energy surpasses the consumed energy by the auxiliary services, then it would be sent to another consumer trains, while the pantograph voltage in the "generator" train might not exceed V_{max1} value indicated in EN 50163 standard, or a more restrictive value imposed by the train operator.

If the "generator" train has indeed generated energy, and V_{max1},has been reached, then that energy will be burned in the own train resistors, until reaching the maximal value of burned power. Even so there is still braking energy available to use, it could not be used and it would be unusable for the electrical brake.

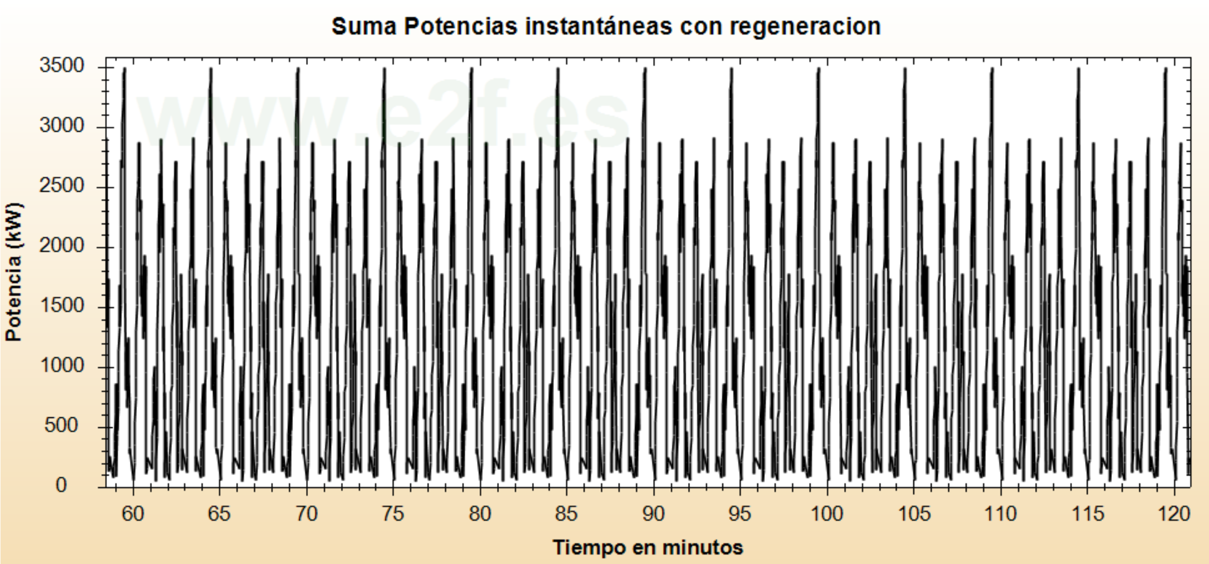

Figure nº 9. Total amount of instantaneous powers in substations.
Case of energy regeneration braking

If we compare instantaneous powers of figures 3 and 8, we could observe that maximal powers are approximately the same, around 3.500 kW, meanwhile minimal values in figure 3 (without regeneration) are around 600 kW, and in figure nº 8, they almost reach zero (There are vacuum losses in transformers that make impossible to reach zero).

	Without regeneration		With regeneration	
	Consumed energy [kWh]	Substations losses [kWh]	Consumed energy [kWh]	Substations losses [kWh]
SER Santa Isabel	386,87	7,81	240,38	4,40
SER Llanos del Águila	494,52	6,60	273,08	5,80
SER Carrefour	478,42	7,41	268,31	5,67
SER Hospital	395,31	4,66	255,45	5,38
Total energy supplied by substations	1755,12	26,48	1037,22	21,25

Table nº 7. Energy values in substations
(with and without braking energy recovery)

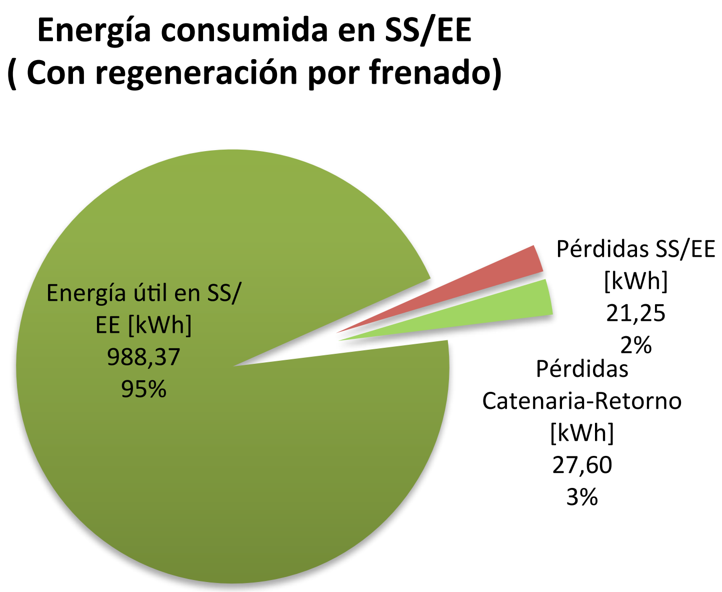

Figure nº 10. Consumed energy by traction substations, and its distribution, in normal operating conditions, considering that tramways generate energy in their braking process.

In table nº7, it is observed that consumed energy has decreased from 1755,12 kWh to 1037,22 kWh, with a reduction of 717,90 kWh, equal to 40,90 % of savings.

In this regeneration process, not every generated energy of the tramway braking is used, but there is a loss part and it is sent to the rheostats to be transformed in heat.

The value of the energy sent to the tramway rheostats is 100,59 kWh, and it is produced in those situations where generated energy is bigger than the consumed energy by the tramways.

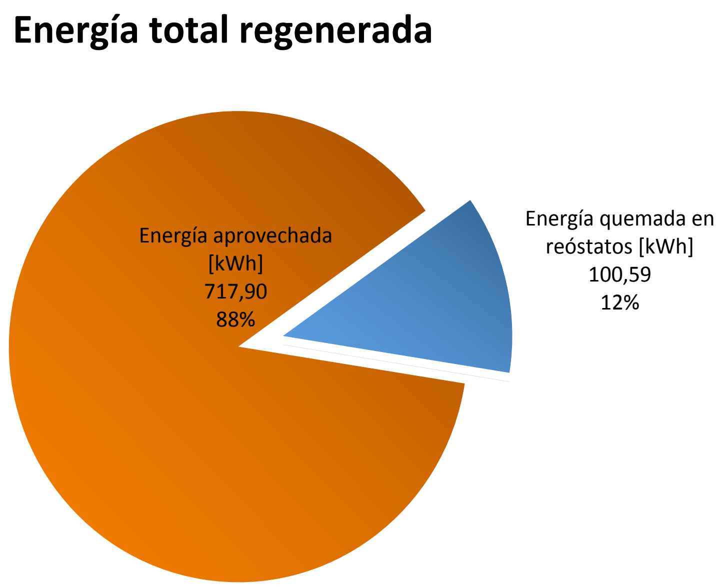

Figura nº 12. Creakdown of the regenerated energy by tramways.

This way the energy generated by trains during the braking process is equal to the addition of the difference between the values supplied by substations in phases 1 and 2, increased with the value of the energy that has been sent to the train rheostats.

The possible improvements that could introduced in the installation, will consist on getting rid of rheostats losses that suppose a 5,73% of the consumption (that is 12% of regenerated energy in the braking process) although not all of this energy could be used, because sending them to another systems such as consumptions points (continuous to alternative current, located in the track path) or inverters installed in substations, we will have losses in the inverters and added losses due to passing electrical energy from "generator" trains to substations where the inverter is installed.

For the consider interval between minutes 60 and 120, the energy sent to the braking resistors is indicated in the figure nº13.

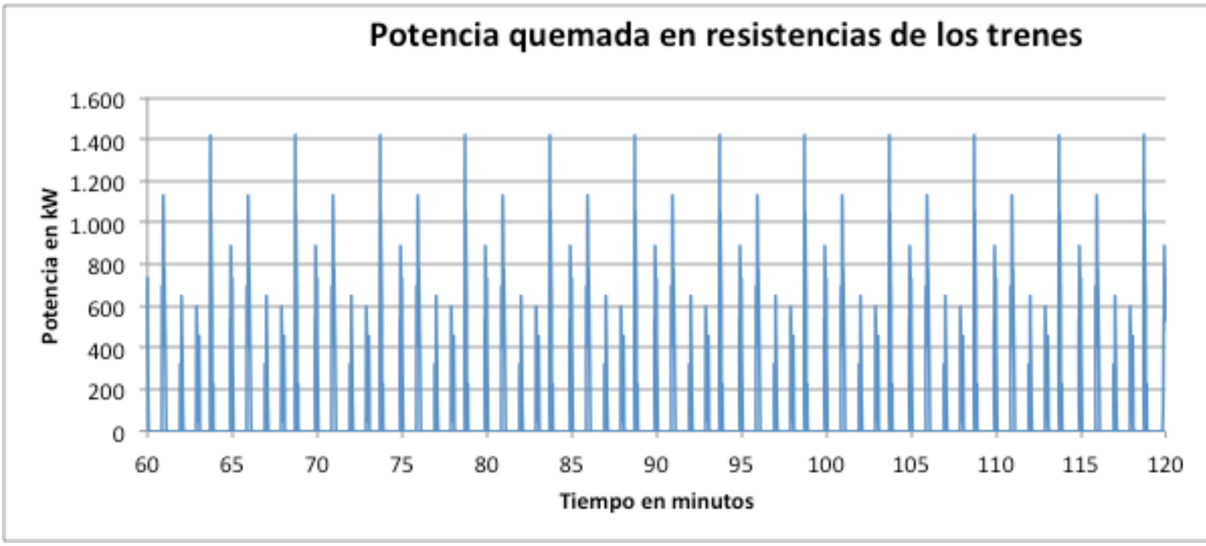

Figure nº 13. Instantaneous power burned in the train resistors.

Figure nº 14. Power sent to the rheostats between minutes 70 and 80.

3.3. Phase 3Simulation. With regeneration and reversible substations.

In this phase we analyzed the installation considering that trains are circulating with recovery braking energy and that there is also a inverter in every substations to revert the excess of energy to another systems of alternative current.

Through the suitable electronic systems, we can establish that the inverter will work only when voltage between their terminals is greater than the reference value.

without this reference value , the inverter will be able to modify its impedance and therefore the value of current that will circulate through it. This process of work is not the appropriate one, because it could receive current from the collateral substations and form the trains in the first moment the braking process began.

the principal criteria that should lead these actions is that energy efficiency consists in decrease consumption, but not in increasing it although a part of the energy was returned, because there is a difference of costs between the consumed and returned energy, being bigger the cost of the consumed energy that the deposit for the same energy back, without keeping in mind the performance of their transformation.

In this study, and considering maximal voltage those produced in trains during the braking process with energy recovery, it has been considered 800 V as reference voltage value for the inverter.

That is, when the inverter voltage value between terminals overtakes 800 V, then the inverter will work as an inverter, keeping himself blocked while voltage do not overtakes this value.

The values of pantograph voltage in trains under this conditions are represented in figure nº19:

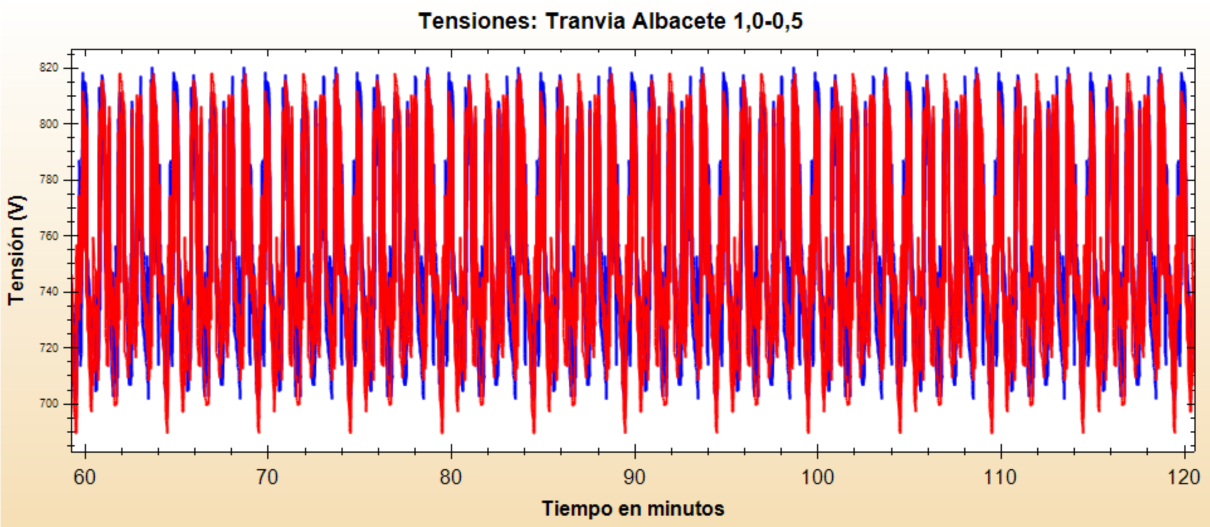

Figure nº 19.Voltage values in train pantographs, with recovery braking and reversible substations.

Maximal voltage values are close to 820 V, an the minimal ones are around 690 V.

If we compare this values with the values obtained before, we will obtain:

	Energy recovery + inverters	Energy recovery	No energy recovery
Maximal V	820 V	860 V	744 V
Minimal V	690 V	690 V	690 V

Table nº 8. Catenary voltage values in several situations

Maximal voltage value is 820 V, it is obtained as a consequence of having a 800 V reference value for the inverter, and therefore there are 20 V of difference corresponding to the increases due to voltage drops in the catenary where the train is regenerating until the inverter location of the substation.

Thanks to the simulation software , we could check that in that situation, there is no flow of energy to the train resistors.

Theoretically, the energy value that it should be sent by the inverters to an external alternative current network would be that corresponding in phase 2 to the burned energy in the train resistors, meaning, 100,52 kWh. Although as it can be observed in table nº9, it is not like that, because the consumption in the installation with regeneration but without reversible substations is minor than the consumption with reversible substations, existing an increase of 112,11 kWh.

This information is considered very important, because an increase in the consumption of the installation, could be against the system. .

	Regeneration+ No reversibles		Regeneration+ Reversibles	
	Consumed energy [kWh]	Substations losses [kWh]	Consumed energy [kWh]	Substations losses [kWh]
SER Santa Isabel	240,38	4,40	249,68	4,21
SER Llanos del Águila	273,08	5,80	320,18	6,99
SER Carrefour	268,31	5,67	302,23	6,31
SER Hospital	255,45	5,38	277,24	5,66
Substations energy	1037,22	21,25	1149,33	23,17

Table nº 9. Consumed energy and substations losses
(with and without braking recovery energy)

This increase in the consumption of the installation is produced due to the existence of situations, in the braking process, where part of the energy that could feed another tramways , and it is a value bigger than the 800V reference value, is diverted to the substation and it send it through the external. As a consequence the tramway, that would have to receive that energy has to take energy from another substation in its proximity.

That is, sometimes, we have changed the destination of the energy produced in the regeneration process , instead of sending it to the tramways, we send it to the external, and therefore that same energy, affected by losses and performances, has to be obtained in the nearest substation, not being a real energy advantage, especially when the price of selling this energy is minor to the price of buying this energy.

	Regeneration + Reversibles			
	Consumed energy [kWh]	Substations losses [kWh]	Consumed energy [kWh]	Substations losses [kWh]
SER Santa Isabel	249,68	4,21	31,15	0,23
SER Llanos del Aguila	320,18	6,99	35,55	0,27
SER Carrefour	302,23	6,31	26,55	0,18
SER Hospital	277,24	5,66	35,64	0,32
Substations energy	1149,33	23,17	128,89	0,98

Table nº 10. Consumed energy and substations losses
(with and without braking recovery energy)

If we compare the consumption in substations, that is the real energy paid, we obtain:

Saving percentage with tramways regenerating but without reversible substations: (1755,12-1037,22)/1755,12 = 0,4090 ⇒ 40,90%

Saving percentage with tramways regenerating and with reversible substations: 1755,12-1149,33)/1755,12=0,3452 ⇒34,52%

So we have passed from consuming 1037,22 kWh when tramways are regenerating , to consume 1149,33 kWh, when the tramways are regenerating and also we have reversible substations, which means an increase in the substation consumption of 1149,33-1037,22 = 112,11 kWh.

Furthermore the energy sent to the external, through reversible substations, is 128,89 kWh. We have a net decrease of consumed energy of 128,89-112,11 = 16,77 kWh. Nevertheless this decrease of energy, has to be affected of the difference of prices between Costs/sales energy, so in economical terms could mean losses, without keeping in mind the financing and maintenance costs of the reversible substations.

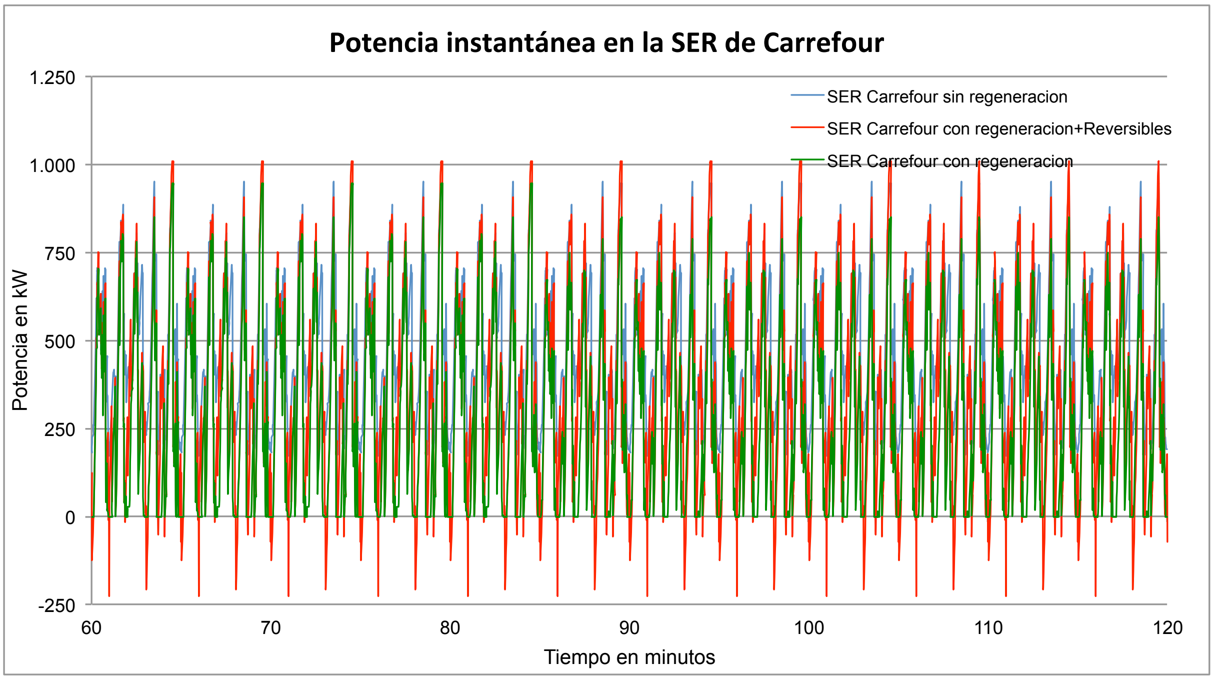

Figure nº 20. Comparison of instantaneous powers in Carrefour substation.

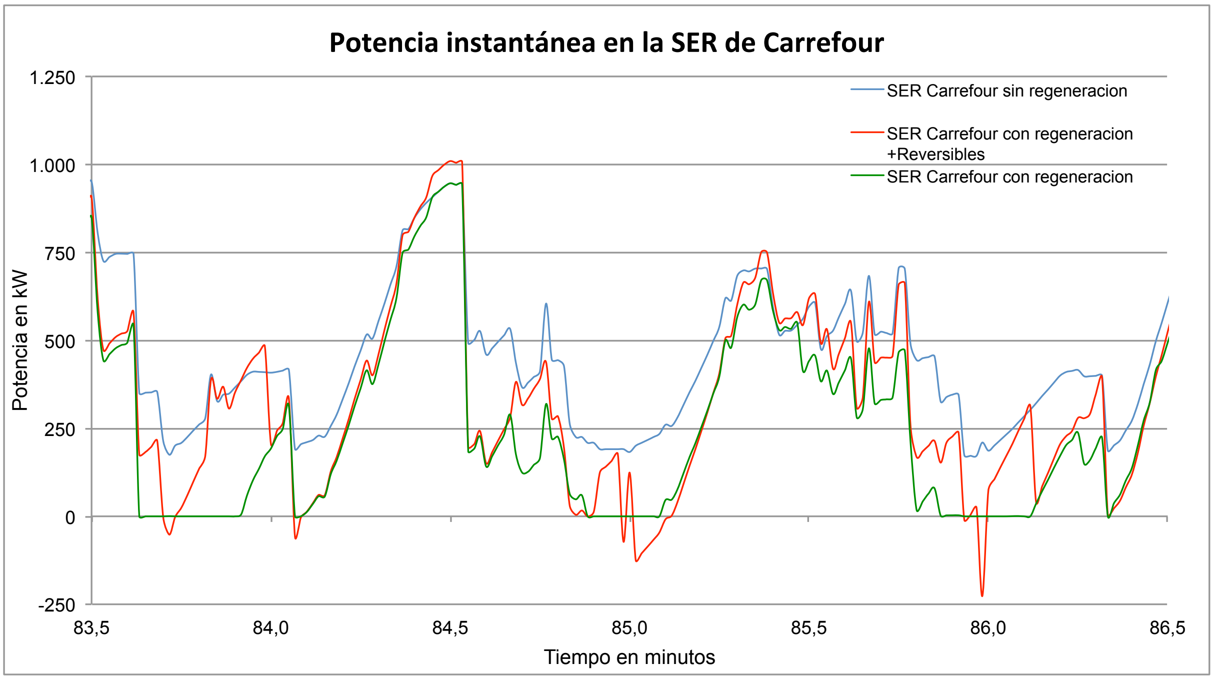

Figure nº 21. Detail of instantaneous powers in Carrefour substation.

4. Final summary.

We have considered a tram line, with 11 kilometers length, with a 6 minutes tram frequency of circulation in each direction, with a distance between stop around each 500 m.

The obtained results indicate that the tram braking with energy regeneration is highly beneficial and it produces a reduction of around 40% in the consumption.

In other analysis, we have found that reductions in consumption increases as the distances between stops are reduced, being of the order of 45% reduction for medium distances of 350-400 m.

In the same way, as the distance between stops is increased, the decrease in the percentage of reduction in consumption implies an increase of that energy lost in the train resistors, and it occurs ,in the case of existing reversible substations, a increase of the reversed energy to the AC line.

So in extreme situations, it can be said that in the situation of single track, a large tonnage of freight trains, which are forced to stop very often not to exceed the preset speed, will produce much braking energy , but it couldn´t be used, because there are no other trains (single track) or in case they were, the next train is placed in a large distance, so in that situation it may be better to install a reversible substation in the braking zone.

5. Conclusion.

From the study we reach the following conclusions:

1º The key criteria that we have to consider is to design the installations to consume the minimum for the trains operation. It is not only necessary to comply with regulations regarding brownouts, heating drivers, etc., it is necessary to consider other issues such as the losses that occur in both, catenary and substations, that are a source of unproductive expenditure.

2º It is necessary to make a preliminary study of each line, in the different circulations modes (peak, off-peak, current circulations, future circulations, frequencies…) that will be necessary for defining consumption for trains traction, auxiliary services consumption, catenary losses, substations losses, energies burned in the resistors and even those losses that cannot be generated, and therefore, to define better the conditions to improve efficiency. That is, we should know the possibilities to improve efficiency of every elements involved so we can define the action plan.

3º We cannot use all the loss energies (because it is burned in the resistors or it could not be produced). Energy is produced along all the track path, while the equipment that receives it (trains or DC to AC converters), have losses in transport and in as well in conversion, so it is necessary to define the best location reversible substations and its evacuation power too.

4º Finally, we have to keep in mind that not all the existing software, related to electrical sizing, have the analysis tool to control the recovery braking energy or the reversible energy in substations.