

Using Active Filters to Reduce THD in Traction Systems

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Abstract.

DC underground traction systems are a powerful source of harmonic distortion, and so, suitable corrective actions have to be taken. For the design of these corrective actions simulation has proved to be a very useful tool. In this paper, the simulation of an active filter for the reduction of the current harmonic distortion of an underground traction system is presented.

Keywords

Total Harmonic Distortion, Active Filter, Computer Simulation, Underground Traction Systems

1. Introduction

The main requirement of any electric power system is the supply of electricity with a determined power quality and reliability to the minimum possible cost. Due to the increased quality of life, it has taken place a spectacular increase of the number and installed power of non-linear loads, especially of electronic devices used mainly in the control of systems and power hardware.

These devices produce currents with high harmonic content. Because of this, distortion makes a double and negative effect since it doesn't only affect to the own loads, but also to the loads of other consumers, reducing the useful life of their equipment. Therefore it is necessary to have the legislation concerning voltage harmonic distortion in order to settle down corrective actions. Among these corrective actions, active filters are one of the most novel and effective solutions [1,5].

But, previous to taking any measure it is necessary to evaluate the distortion introduced by the installation into the distribution network and the reduction expected when the active filter is in use. For this step, simulation has proven to be an useful tool when evaluating the harmonic distortion. Firstly, it allows to quantify the harmonic distortion created by a system and secondly, when a corrective action is introduced in the system, the simulation process shows the reduction of the distortion.

In this paper, the simulation of a traction substation using MATLAB/SIMULINK program is presented with the aim of evaluating the THD produced.

2. Modelling of the traction substation

A. Substation description

The configuration of a traction substation consists, basically, on several power transformers for traction units which convert AC electricity to DC. Rectification is made through three phase diode rectifiers connected to the secondary of the power transformers. DC terminals of the rectifiers are connected in parallel to a positive and a negative DC bus, respectively. The positive bus is connected to the line and the negative to the rail. Supply to the line is in pi configuration, that is to say, the section of the line between two substations is supplied in each end by a substation.

The main components of the substation are shown in the Figure 1 and they are the following ones:

- Four rectifier groups with 3R+1 configuration. That is to say, three rectifiers are connected at the same time and one is always in reserve. Each rectifier group is composed of a 30/1,295 kV transformer (TGR) with 2.250 kVA rated power and a three-phase rectifier. The rectifiers convert the voltage at the output winding of the transformers group into DC voltage of 1750 V when they work without load and into 1650 V when they work with 2000 kW rated power.
- Two 30/13,8 kV power transformers (TSE) with 2.500 kVA rated power each one, for station services.
- One 30/0,4 kV transformer (TSA) with 1.000 kVA rated power for auxiliary services.

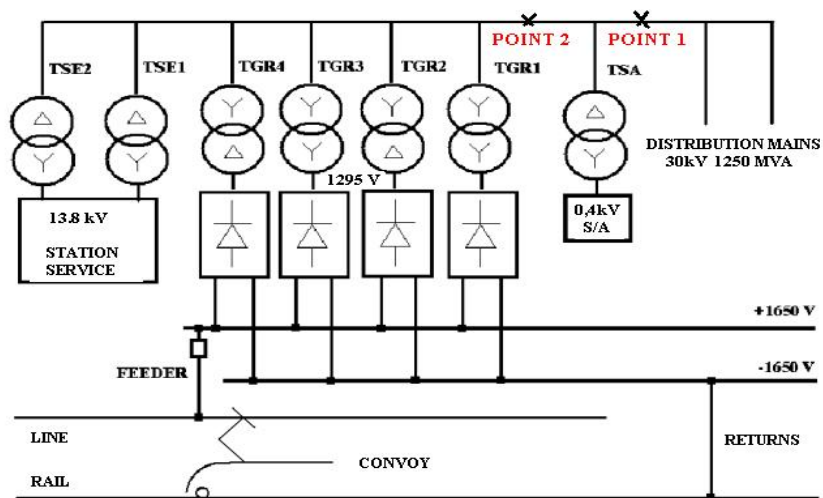


Figure 1. One-line diagram of the substation

To evaluate the rate of the total harmonic distortion in the substation, two measurement points have been located, as Figure 1 shows. The "point 1" is located in the connection with the distribution system and the "point 2" is located in the feeding to the non-linear load (traction unit).

B. Traction units

The traction units consist on four wagons, two with cabin and two intermediates. The electric AC motors are fed by a PWM inverter.

Each convoy has a traction power of 2.880 kW and a nominal voltage of 1.500 Vdc. Each wagon leans over two bogies with two motors each, this is, each convoy has 16 induction motors of 180 kW supplied by a PWM inverter connected directly to DC line voltage.

The model that has been used in the convoy simulation, has been developed by means of only one inverter and only one 2.880 kW equivalent motor, as it is shown in Figure 2.

The inverter converts the DC voltage of the line in alternating voltage that feeds the induction motors of the traction units. Also, it can control the voltage in width and in frequency by means of the pulses PWM generator. The characteristic harmonics injected by a 6-pulse inverter are harmonics of 5th and 7th order.

A condenser with high capacity is placed in the inverter input to maintain the voltage level as constant as possible, with the idea of not harming neither the conversion of voltage process nor the asynchronous machine operation.

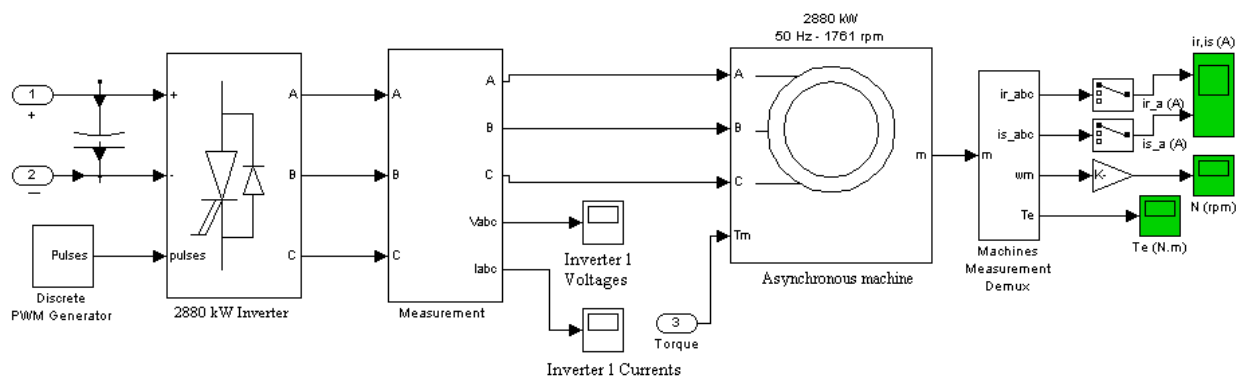


Figure 2. The whole model of the convoy (inverter + asynchronous machine)

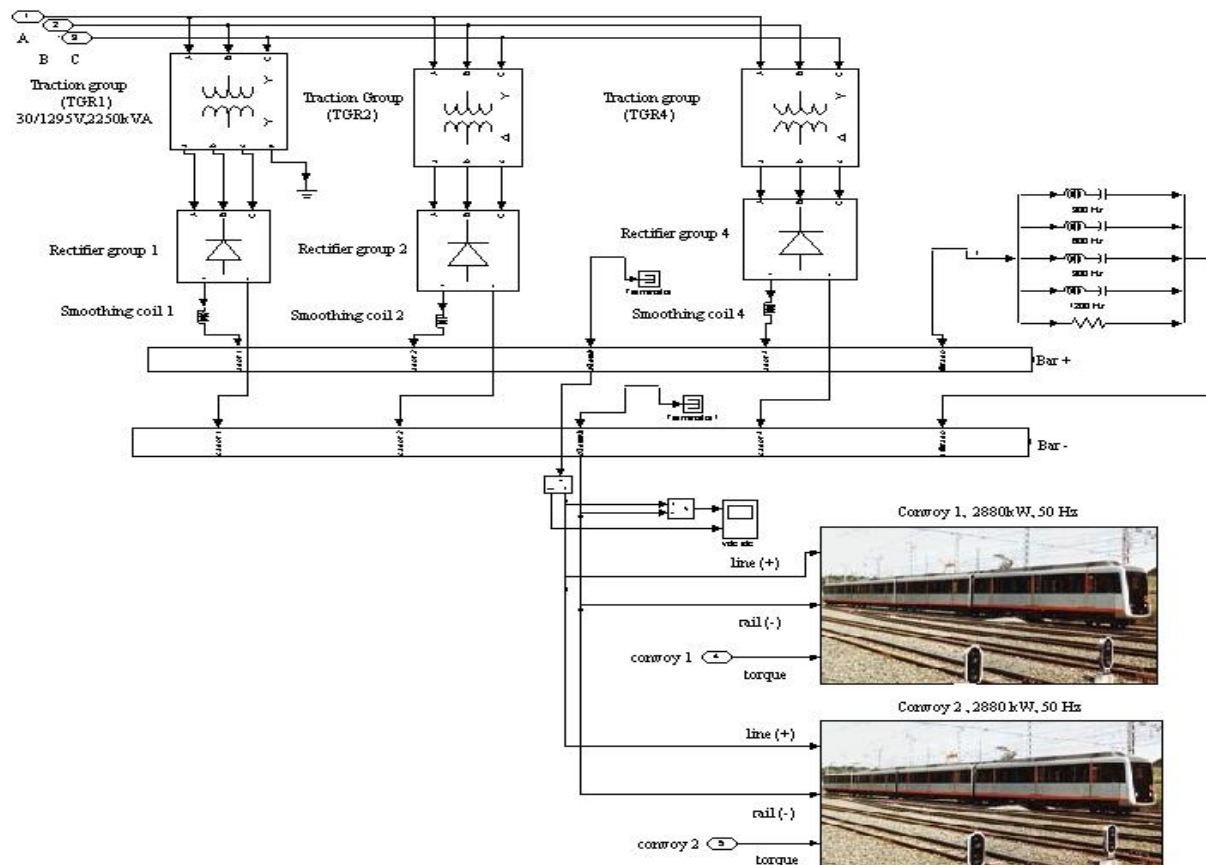


Figure 3. Non-linear load subsystem with two convoys

The circuit that simulates the electric diagram of the traction system consists in a source with 1.230 MVA of short-circuit power that feeds a linear load and another non-linear.

The linear load has been considered as a pure resistance and represents the station and auxiliary services. For modelling considerations, the two underground station service transformers and their load have been grouped into a single constant load of 5.000 kVA supplied at 30 kV and the auxiliary services transformer and its load as a constant load of 1.000 KVA supplied at 30 kV.

The non-linear load is shown in Figure 3. This is formed by 3 traction groups that feed 2 meter units. The rated power of the non-linear load is 6 MW and it is adjustable through the convoys torque. In the simulation, the torque measurements are real.

3. Modelling of the active filter

Once carried out diverse simulations and proven the existence of harmonic distortion, it has been inserted an active filter in the simulation model. This shunt active filter is formed by an inverter with the configuration of voltage source. The filter injects the harmonic current that the non-linear load consumes in each moment but 180° out of phase, so the current of the source is sinusoidal.

The filter is composed of a power circuit and a control circuit, as it is shown in Figure 4. The power circuit is fed with the low voltage of the fourth transformer that is in reserve and that has 2.500 kVA power. This transformer can also support 1.000 A rated current in the secondary winding. This value is higher than the maximum RMS current that the inverter will generate, therefore, this power is enough to face the harmonic power necessary to compensate the distortion generated by the non-linear load.

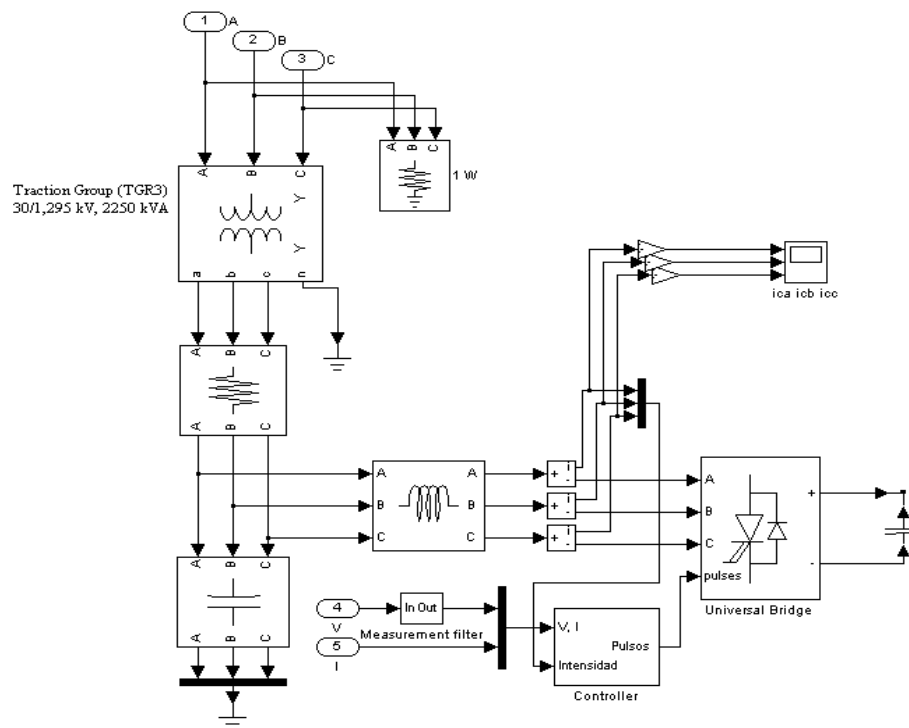


Figure 4. Shunt active filter model

The control circuit is divided in two blocks. The control technique, where the Akagi's theory p-q is used in the temporary domain [3,4], and the current control circuit based on a pulse-width modulation (PWM). This last one, together with the inverter, works like a current source that injects the compensation current in each moment to eliminate the harmonics and correct the reactive power variations.

The final model, including the meters, can be observed in Figure 5. Here, the points 1 and 2 of measurements are pointed out with an arrow and they are located in the same position that they were indicated in Figure 1 (without filter).

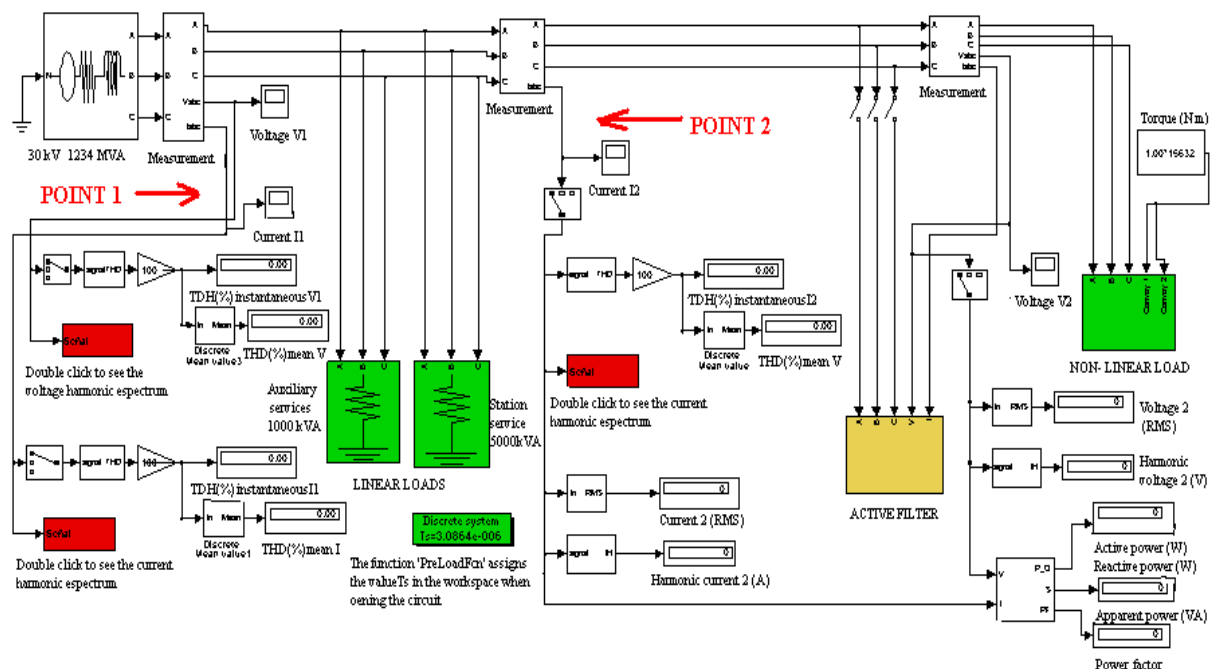


Figure 5. Substation model including filtering and meters

4. Harmonic analysis

In order to perform the harmonic analysis of the voltage and current signals present in the traction system, a Simulink block has been developed. This block calls an M-file that makes the required calculations and shows graphically the harmonic spectrum of the analysed signal (Fig. 6). The 1st harmonic is out of scale so that the rest of the harmonics can be visualized properly. The calculated values correspond to peak values.

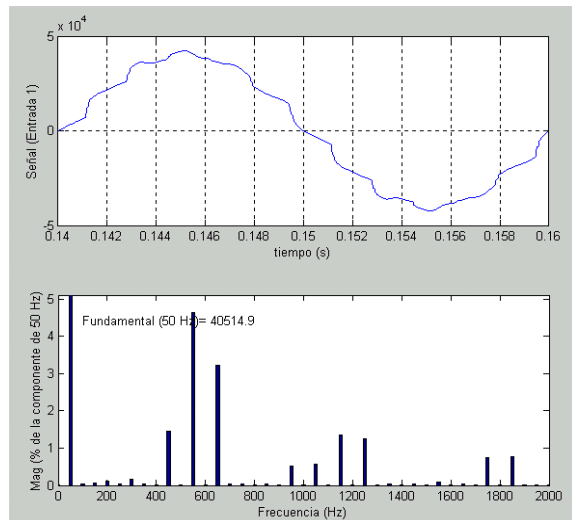


Figure 6. Harmonic analyser result

A real time harmonic analyser that show the peak values of the first 20 harmonic components as the circuit is being simulated has been developed too. This block has been developed using Simulink blocks. The results format is shown in Fig. 7.

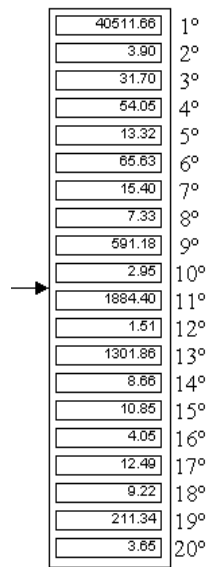


Figure 7. Real time spectrum analyser

5. Simulation and results

Once developed the substation model, its behaviour has been simulated without and with active filter in diverse situations. In this section, the graphic results of the following cases are presented:

Case 1: Two convoys working in steady-state and developing a 100% of the nominal torque each one.

Case 2: Two convoys working in steady-state and developing a 10% of the nominal torque each one.

Besides, in the point 1 of measurement (connection with the distribution system) the graphs of voltage harmonic spectrum are shown, while in the point 2 (feeding to the no-linear load) the graphs of current harmonic spectrum are shown.

A. Case 1

The results obtained in the harmonic distortion analysis of voltage at the connection “point 1” without the active filter are shown in Figure 8. The THD value corresponding to the current is 4.85% while the voltage THD is 0.43 %.

It can be observed that the harmonic voltage, generated by the substation, hardly have weight. This is due to the non-linear load consumption which is about 6 MVA in front of the 1234 MVA short circuit power of the source.

The highest harmonics are the 5th (250 Hz) and the 7th (350 Hz) and they are repeated at the 11th (550 Hz) and the 13th (650 Hz). These harmonics are characteristic of non-linear loads that include three-phase rectifiers of six pulses.

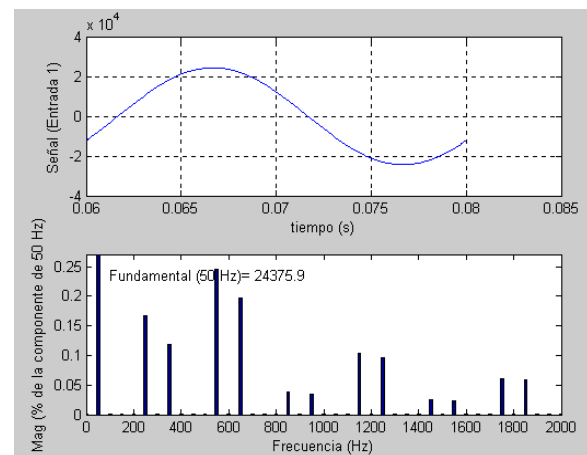


Figure 8. Voltage harmonic spectrum in the point 1, without filter

If the harmonic analysis is performed including the active filter the results change (Figure 9). The THD of the current is reduced from 4.85% to 0.10% and the voltage THD from 0.43% to 0.31%. The values of the highest harmonics have been reduced considerably. But some new components of low value (harmonics due to the injection of the filter) can be observed.

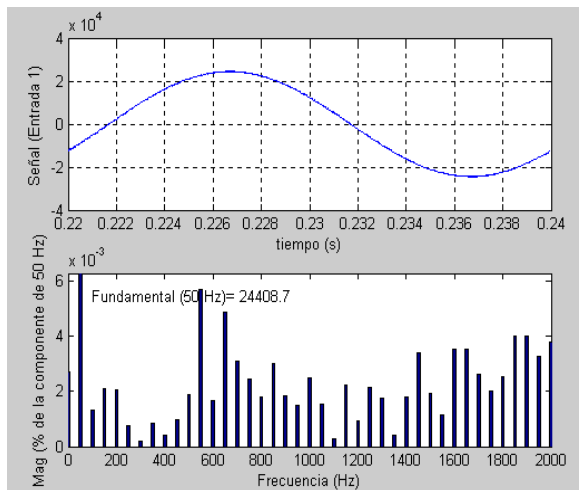


Figure 9. Voltage harmonic spectrum in the point 1, with filter

As for the “point 2” of measurement, the results obtained in the harmonic distortion analysis of current without active filter are shown in Figure 10. It is observed a higher deformation of the waves than in the case measured in the point 1. This distortion is due to the characteristic consumption of the non-linear load that contains electronic power elements. The THD value corresponding to the current is 9.16% while the voltage THD is 0.31%.

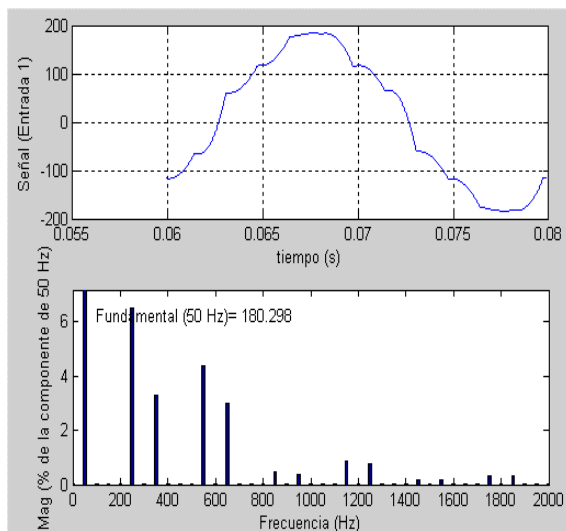


Figure 10. Current harmonic spectrum in the point 2, without filter

If the harmonic analysis is performed including the active filter (Figure 11), the THD of the current is reduced from 9.16% to 0.35% and the voltage THD from 0.43% to 0.31%.

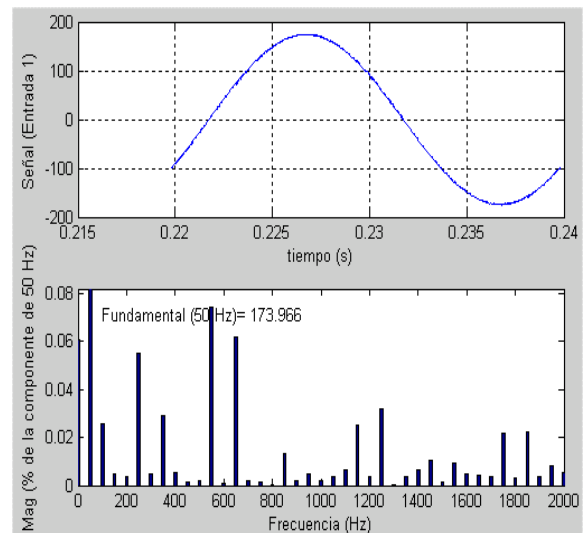


Figure 11. Current harmonic spectrum in the point 2, with filter

B. Case 2

The results obtained in the harmonic distortion analysis of voltage at the connection “point 1” without active filter are shown in Figure 12. The THD value corresponding to the current is 1.72% while the voltage THD is 0.11%, due to the drop in value of the non-linear load.

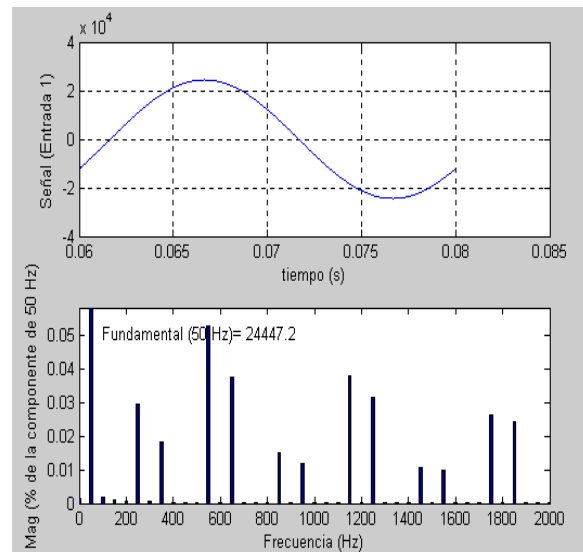


Figure 12. Voltage harmonic spectrum in the point 1, without filter

If the harmonic analysis is performed including the active filter (Figure 13), the THD of the current is reduced from 1.72% to 0.08%, while the voltage THD is increased from 0.11% to 0.22%. In this case, the THD raises due to the injection of the filter, but its value is very low.

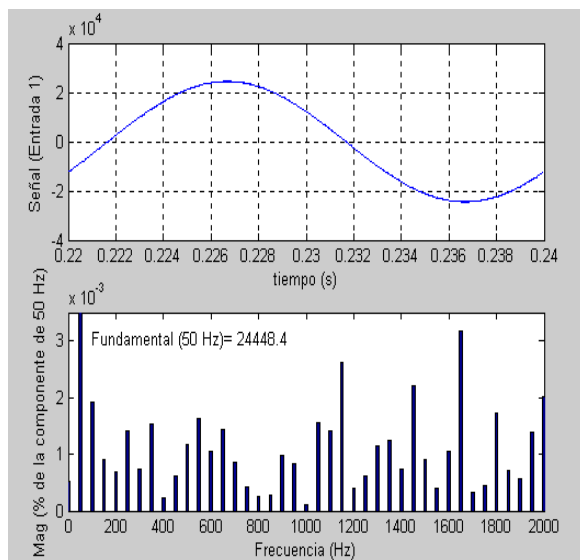


Figure 13. Voltage harmonic spectrum in the point 1, with filter

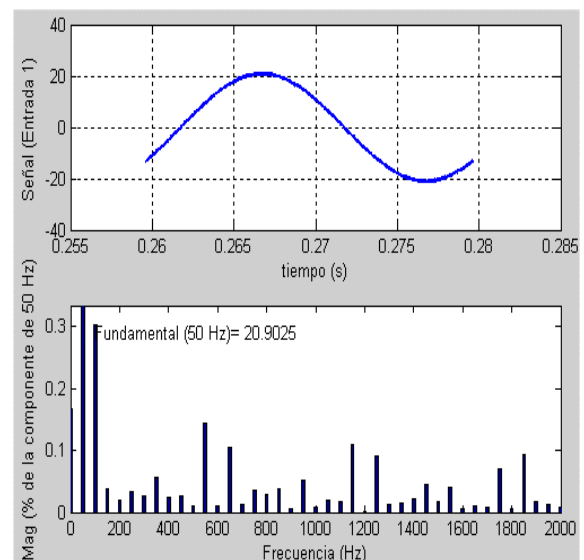


Figure 15. Current harmonic spectrum in the point 2, with filter

The results obtained in the harmonic distortion analysis of current at the point 2 without active filter is shown in Figure 14. The THD value corresponding to the current is 15.08% while the voltage THD is 0.11%.

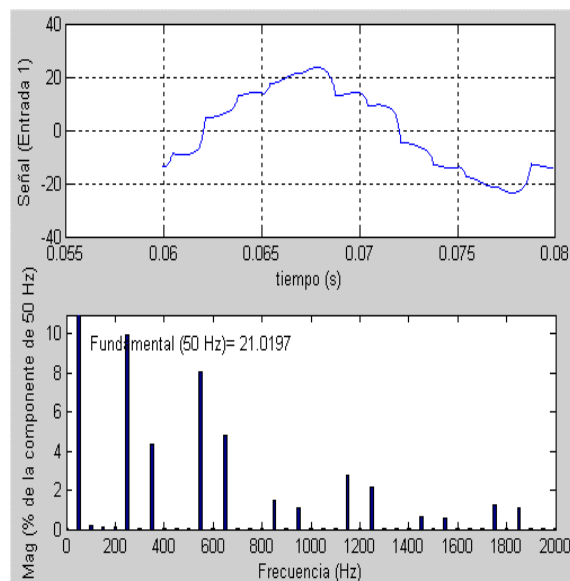


Figure 14. Current harmonic spectrum in the point 2, without filter

If the harmonic analysis is performed including the active filter the results change (Figure 15). The THD of the current is reduced from 15.08% to 1.83%, while the voltage THD is increased from 0.11% to 0.22%. Again the THD raises due to the injection of the filter.

6. Results analysis

From the simulated cases results without filter and with filter, it can be made a comparative analysis. Besides, in this analysis, it is also included the case of two convoys working in the steady-state and developing a 50% of the nominal torque each one.

- The THDI decreases more than 86% in anyone of the three cases, which implies a high effectiveness of the active filter (tables I and II).

TABLE I. – Results for measurement point 1 (substation interconnection)

Traction load level	Current distortion (THD %)	Current distortion with active filter (THD %)	Reduction of current distortion (%)
100 % (case 1)	4,85	0,09	98,14
50 %	4,07	0,09	97,79
10 % (case 2)	1,72	0,08	95,35

TABLE II. – Results for measurement point 2 (traction load)

Traction load level	Current distortion (THD %)	Current distortion with active filter (THD %)	Reduction of current distortion (%)
100 % (case 1)	9,16	0,35	96,18
50 %	11,51	0,63	94,53
10 % (case 2)	15,08	2,01	86,67

- The harmonics are decreased almost completely and the highest value becomes the 11th and 13th order, instead of the 5th and 7th order in the case without filtering. Even harmonics are also observed (included the 0 order harmonic which is the DC component). These harmonics are introduced by the active filter, but they take worthless and highly variable values.

- The active power (P) demanded by the non-linear load increases due to the active filter consumption (table III). This value is 0,8% inferior of the demanded power by the non-linear load.

TABLE III. – Results for the filter consumption

Traction load level	P (MW) Non-linear load	P (MW) Non-linear load with filter	Filter consumption (%)
100 % (case 1)	6,316	6,369	0,8
50 %	3,174	3,199	0,8
10 % (case 2)	0,7623	0,7664	0,5

- The reactive power consumption (Q) of the non-linear load diminishes, what means that the power factor will be the unit or very close (table IV).

TABLE IV. – Results for the reduction of reactive power

Traction load level	Q (MVar) consumed by the non-linear load	Q (MVar) consumed by the non-linear load with filter	Reactive power reduction (%)
100 % (case 1)	1,88	0,098	95
50 %	0,68	0,05	93
10 % (case 2)	0,1143	0,0138	88

- The peak factor is close to the value $\sqrt{2}$ (value that takes the peak factor when the wave is pure sinusoidal).

7. Conclusions

By means of the simulation carried out, the current harmonic distortion created by a traction substation has been obtained. Moreover, the reduction of the distortion by an active filter has been simulated. The simulation tool allows to design the filter so that the required harmonic reduction is obtained.

The introduction of an active filter allows:

- To decrease the effective current consumption (it implies smaller heating in the wires).
- To compensate the reactive power until obtaining a power factor next to the unit. (The filter is a PFC element).

- To diminish the apparent power consumption.
- To adapt to the changes of the configuration system automatically.

The harmonic amplitude decreases considerably, the highest rate become the 11th and 13th order, instead of the 5th and 7th order. Even harmonics are also observed, they are introduced by the active filter and they are highly variable, although worthless in the simulation.

On the other hand, it is observed that the voltage harmonics that the substation generates are practically worthless, this is because of the non-linear load consumption is small in front of the short circuit power of the source.

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