Reactive Power Compensation in railways using Active Impedance concept

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***Abstract*--In this paper a new active impedance topology, employing AC-Choppers is proposed for reactive power compensation in 25 KV/50Hz railways. The good behaviour of AC-AC converters in terms of losses respect to other solutions like VSI based STATCOM, make this solution really interesting in high power single phase systems like railway networks.**

The concept is applied to a substation in the French Railways. A design method is proposed and simulation results confirm the good working of this low cost and low losses solution. Finally, experimental results, achieved on a 1.2MVAR prototype are presented.

Index Terms— **Rail transportation power systems, AC-AC power conversion, Reactive power control, Static VAR compensators**

I. INTRODUCTION

With a length of 8,256 km, 25 kV – 50 Hz AC single phase supply is widely used in railways in France. Overhead lines are supplied by substations phase to phase connected to a transmission line.

Most of transport traffic is operated with old generation of locomotives, equipped by thyristor rectifiers. Due to the traffic increasing, this converter topology requires the installation of reactive power compensators in substations. This is inevitable in order to respect power quality requirements imposed by the energy provider society. Particularly, penalties have to be paid when tg φ is greater than 0.4.

Previous works [1][2], have demonstrate that AC Choppers converters have good behaviours in terms of losses respect to other solutions like VSI based STATCOM in reactive power compensation. Thus, this solution is really interesting in high power single phase systems like railway networks.

The case study concerns a 60 MVA Substation located at Revest in France. The equivalent circuit [3] of this substation is presented in Fig. 1.

Nowadays, the reactive power compensation is carried out by using fixed LC shunt filters.

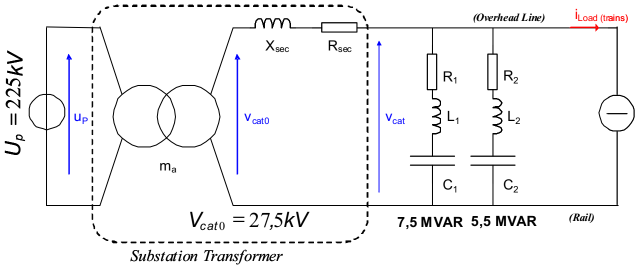

Fig. 1 - Revest Substation equivalent circuit

During the day, these filters can lead to overcompensation when the train traffic is lower and it is not possible to increase the compensation level.

Therefore it is interesting to study the possibility to use the Active Impedance concept in order to get variable reactive power compensation.

In the initial situation, LC filters provide 13MVAR and to avoid penalties when the load current is high, the compensation range has to be increased by ΔQ.

For the Revest substation, the value of ΔQ was chosen by performing an analysis of the reactive energy recorded during 5 month. Fig. 2 shows the invoiced reactive energy versus compensation level ΔQ.

To get a good tradeoff between cost and benefit, ΔQ was set to 3MVAR.

TABLE I. SUBSTATION ELECTRICAL PARAMETERS

Electrical Parameters		
Transform Impedance	***Fixed Compensator 1***	***Fixed Compensator 2***
Rsec=0.43Ω	R1=0.25Ω	R2=0.5Ω
Xsec=2.4Ω	L1=62.5mH	L2=87.5mH
	C1=26μF	C2=19μF

The novel structure proposed in this paper is presented in Fig. 3 (a). Basically the compensator is composed by a LC filter in series with an AC-Chopper.

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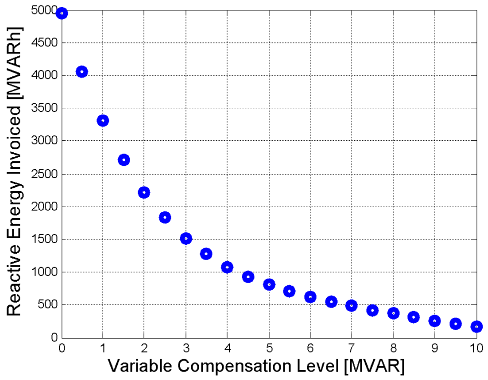
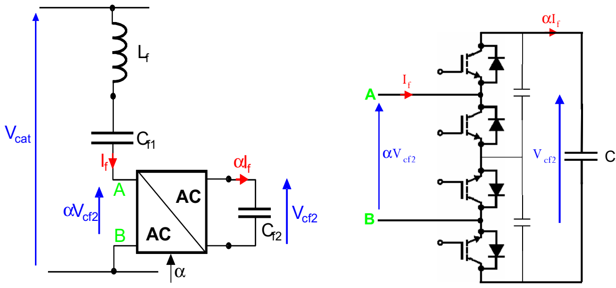


Fig. 2 - Reactive Energy vs Variable compensation level

At the fundamental frequency, this structure behaves as fixed capacitive impedance connected in series with variable capacitive impedance.

L_f and C_{f1} are chosen in order to have a capacitive behavior at the fundamental frequency.



(a) (b)

Fig. 3 - Active Impedance Compensator basic scheme

The AC/AC converter, presented in Fig. 3 (b), has a capacitor C_{f2} at the output and it is series connected at the input with the LC filter. The resulting system is an Active Impedance controlled by the duty cycle α.

$$Z_f(\alpha)=\omega L_f-\frac{1}{\omega C_{f1}}-\frac{\alpha^2}{\omega C_{f2}} \tag{1}$$

$$\Delta Q_f=\frac{V_{cat}^{\ 2}}{Z_{tot}(\alpha_{\max})}-\frac{V_{cat}^{\ 2}}{Z_{tot}(\alpha_{\min})} \tag{2}$$

Equation (1) gives the value of the impedance respect to the duty cycle α and the reactive power variation is given by equation (2). The impedance module increases with α while the provided reactive power decreases.

II. NOVEL COMPENSATION SYSTEM

The new topology introduced in the previous section can be employed in the substation by modifying the existing fixed compensator. The structure proposed is presented in Fig. 4. AC choppers are connected in series to fixed compensators already existing. A fixed shunt filter is added. Thus, by increasing the duty cycle, the total reactive power supplied is reduced. In this way, the complete compensation system shows a variable reactive power denoted ΔQ.

Due to the high voltage application, it is possible to consider an association of AC-Choppers in order to split the voltage across N converters. In this case an interleaved modulation in the switching pattern generation has to be used.

The considered switching devices are 6.5 kV/600A IGBTs modules. Moreover, for the circuit sizing a resonance frequency (4) variation between 100Hz and 150Hz is accepted. In fact, measurements of load current, at Revest substation, have shown that this frequency band is clear of harmonics [4].

Equation (3) and (4) describe the reactive power variation and the resonance frequency variation versus the duty cycle α. According to these relations a system of 2 equations can be solved in order to find the capacitor values C_{V1} and C_{V2}. Besides, inductors L_{V1} and L_{V2} must be added in series to the already existing LC shunt filters, in order to get 2 degrees of freedom in the calculation.

$$Q_{1,2}(\alpha)=\frac{V_{cat}^{\ 2}}{\left(L_{1,2}+L_{V1,2}\right).\omega-\frac{1}{C_{1,2}.\omega}-\frac{N_{1,2}.\alpha^2}{C_{V1,2}.\omega}} \tag{3}$$

$$f_{r1,2}(\alpha)=\frac{1}{2.\pi.\sqrt{\left(L_{1,2}+L_{V1,2}\right)\cdot\frac{C_{1,2}.C_{V1,2}}{C_{V1,2}+C_{1,2}\cdot N_{1,2}\cdot\alpha^2}}} \tag{4}$$

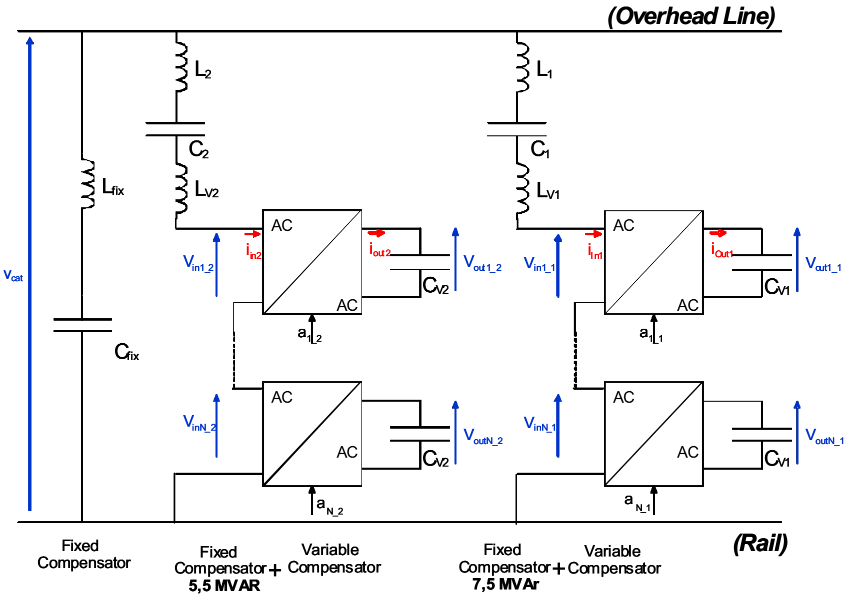


Fig. 4 - Novel reactive power compensation topology

The actual LC shunt filters are designed considering a voltage of 27.5kV. In order to have at least the desired reactive power variation of 3MVAR, even when the traffic is high, an overhead line voltage of 24kV was considered for the dimensioning. Moreover, the requested reactive power is shared between the two variable compensators as reported in the following design specifications:

V_{CAT}=24kV; $\Delta Q_1(\alpha_{max})$=2MVAR; $\Delta Q_2(\alpha_{max})$=1MVAR; $f_{res1}(\alpha_{max})$=138Hz; $f_{res2}(\alpha_{max})$=138 Hz

The number of AC choppers in series, N1 or N2, is evaluated considering the maximum overhead line voltage (29kV) and the maximum duty cycle.

Regarding the fixed compensation branch, it is sized considering that the maximum reactive power provided at minimum duty cycle, is equal to the critical reactive power Q_{crit}.

This last parameter represents the limit reactive power, over which the overhead voltage can reach the maximum allowed V_{CAT}=29kV, as reported in (5). Moreover a resonance frequency of 135Hz is considered of the fixed compensator design.

$$Q_{crit} = \frac{\left(29kV - V_{cat0}\right)\cdot 29kV}{X_{sec}} = 17.6MVAr \qquad (5)$$

The calculation results are reported below:

L_{V1}=10.7mH; C_{V1}/N_1=54.4μF; N_1=4
L_{V2}=1.3mH; C_{V2}/N_2=63.97μF; N_2=3
L_{fix}= 57.9mH; C_{fix}= 24μF

On this base, Fig. 5 shows the reactive power variation versus the overhead line voltage for the initial configuration and for the new system. Thus, the area of controllable reactive power can be highlighted.

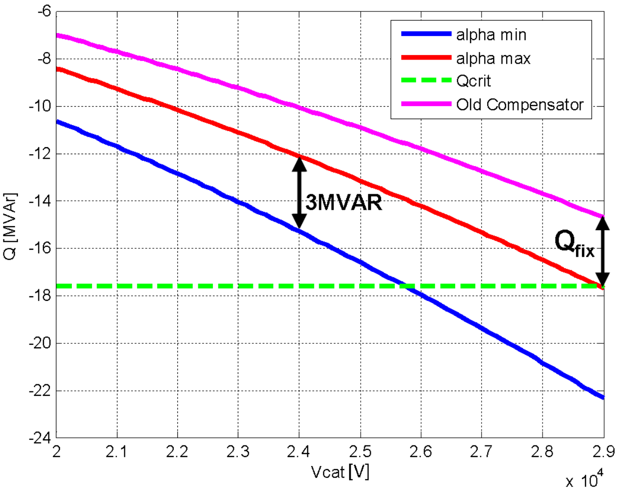


Fig. 5 - Reactive Power Vs overhead line voltage

III. NUMERICAL ANALYSIS

Specifications of the compensators are presented in Fig. 6. Calculations are done for an overhead line voltage of 24kV and considering the impedances of which expressions are given below:

$$Z_{tot}(\alpha) = \frac{1}{\dfrac{1}{Z_1(\alpha)} + \dfrac{1}{Z_2(\alpha)} + \dfrac{1}{Z_{fix}} + \dfrac{1}{Z_{in}}} \qquad (6)$$

$$Z_{1,2}(\alpha) = \omega\left(L_{1,2} + L_{V1,2}\right) - \frac{1}{\omega C_{1,2}} - \frac{\alpha^2 N_{1,2}}{\omega C_{V1,2}} \qquad (7)$$

$$Z_{in} = \omega X_{\sec} \qquad (8)$$

$$Z_{fix} = \omega L_{fix} - \frac{1}{\omega C_{fix}} \qquad (9)$$

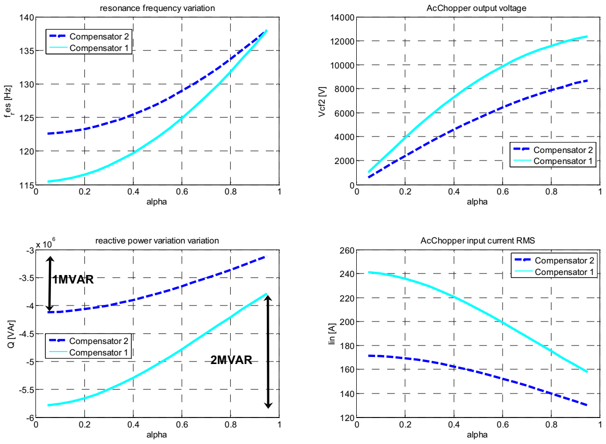


Fig. 6 - Calculation results for Vcat=24kV

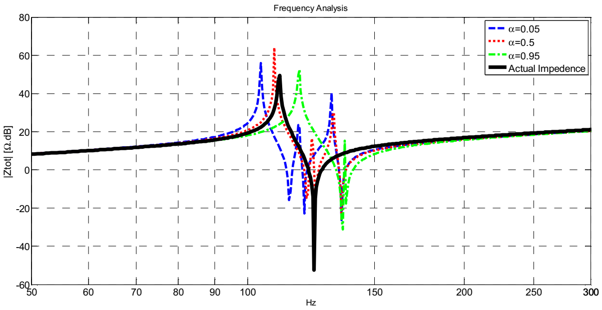


Fig. 7 - Frequency Analysis

Regarding figure 6, it is interesting to focus on the maximum AC-Chopper input voltage and current variation. When the former is minimum the second is maximum and so there is the minimum voltage when the maximum current is flowing. This working condition leads to low switching losses in the devices.

Finally, Fig. 7 shows the module of the total impedance [5] described by expression (6). The module of Z_{tot} is reported for three different values of the duty cycle. Moreover, the initial value of the substation impedance is superimposed.

IV. SIMULATION RESULTS

In order to validate the novel compensator behaviour, the system is been modelled and simulated in Psim. In the simulations, current records have been used as current load source, in order to observe the behaviour of the system in real condition.

Condition considered for simulations, refers to a worst working case for the substation when the traffic is very high and the overhead line voltage is very low.

Fig. 8 shows simulation results with the real current waveforms corresponding to the maximum amplitude of the 3rd harmonic. At this operating point, the overhead line voltage is 21 kV and the reactive power provided by the compensator is 9.2 MVAR. Let us note the distorted current waveforms in each branch of the compensator.

In the same way, Fig. 9 shows simulation results when the duty cycle is minimum (α=0.05). In this case compensators currents are maximum, thus the system provides the maximum reactive power to the overhead line.

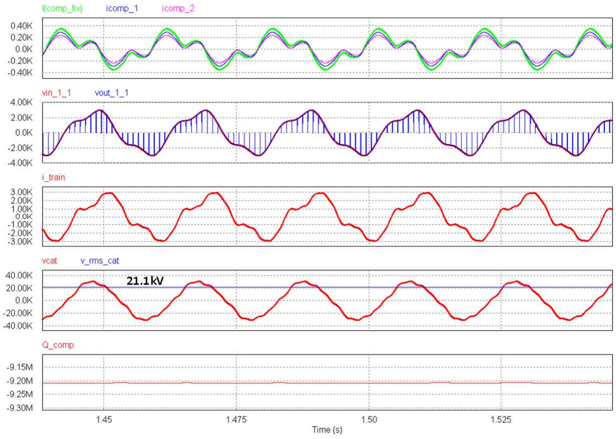


Fig. 8 - Psim simulation results. Load current (i_train) with the 3rd harmonic at its maximum amplitude (α=0.95).

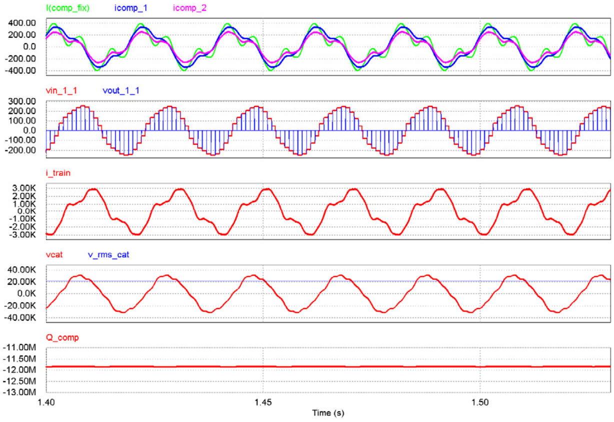


Fig. 9 - Psim simulation results. Load current (i_train) with the 3rd harmonic at its maximum amplitude (α=0.05).

V. EXPERIMENTAL RESULTS

To validate the Active Impedance concept, a 1.2MVAR prototype was built in the LAPLACE laboratory in Toulouse and tested at the SNCF test platform in Vitry (Paris). The experimental setup, shown in Fig. 10, is based on a series connection of an AC chopper and a LC filter (Fig. 3).

Component values for the compensator are reported below:

$$L_f = 3.7mH \quad C_{f1} = 526.5\mu F \quad C_{f2} = 1.6mF$$

The rms value for AC voltage used during the test is 2450V. Moreover, semiconductor devices used for the AC Chopper converter are ABB IGBTs 3.3kV 1500A model 5SNA 1500E330300. Finally, a switching frequency of 1kHz has been chosen.

The command part and the generation of switching pattern for IGBTs is achieved by using a mixed environment DSP and FPGA.

Theoretical electrical parameters variation for the prototype are presented in Fig. 11. The maximum reactive power provided is about 1.2MVAR and the reactive power variation ΔQ is 320kVAR.

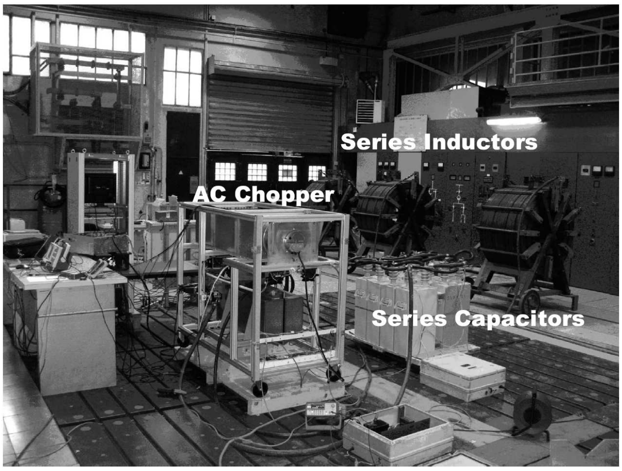


Fig. 10 – Test Bench

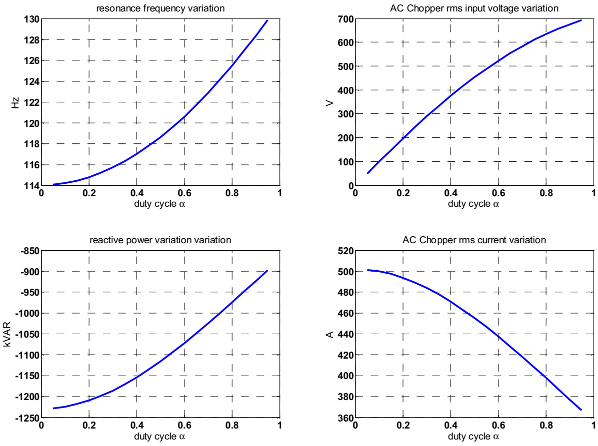
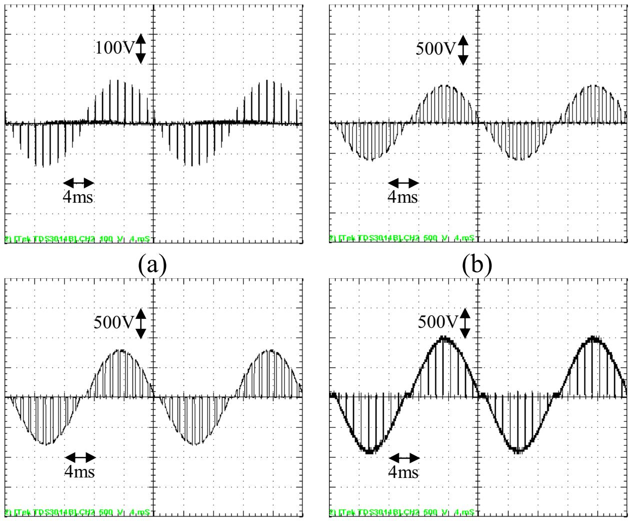


Fig. 11 – Variation expected for V=2450V

In Fig. 12, chopped voltages measured by the oscilloscope at the converter input have been reported. In the same way, Fig. 13 reports measured compensator currents. Four values for duty cycle have been considered.

The reactive power variation Q(α)has been plotted in Fig. 14. All experimental measurements match quite well the value previously calculated.

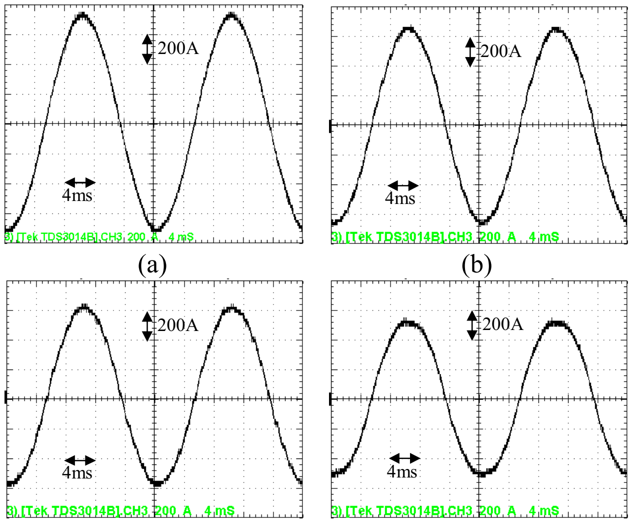
Spectral analyses have been performed for all measurements. This is necessary with the purpose of analyze the interaction of the compensator with the grid.



(a) (b)

(c) (d)

Fig. 12- AC Chopper input voltage for duty cycle: a)0.1 b)0.5 c)0.7 d)0.95



(a) (b)

(c) (d)

Fig. 13 – Compensator currents for duty cycle: a)0.1 b)0.5 c)0.7 d)0.95

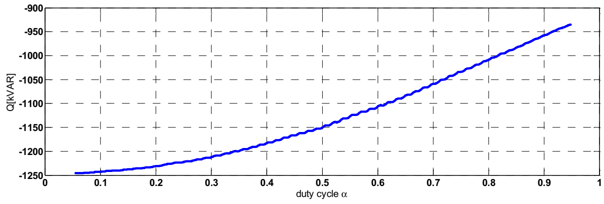


Fig. 14 – Provided Reactive power measured versus Duty cycle

FFT for voltage source is presented in Fig. 15 to Fig. **18**. To evaluate the influence of the compensator in the electrical circuit, it’s interesting to compare voltage spectrum analysis before and after the compensator insertion. At this effect, Fig. 15 shows the supply voltage spectrum when the compensator is disconnected. Finally, Fig. 16, Fig. 17 and Fig. 18 report the spectral analysis after the prototype connection, for duty cycle 10%, 50% and 95%.

Same consideration can be carried out for the compensation current. Figures 19 to 22 show the spectral analysis for duty cycle 10%, 50%, 70% and 95%. As expected, increasing duty cycle, the compensator resonance frequency increases and comes close to the 3rd harmonic frequency. That is why the 150 Hz component amplitude is increasing with the duty cycle.

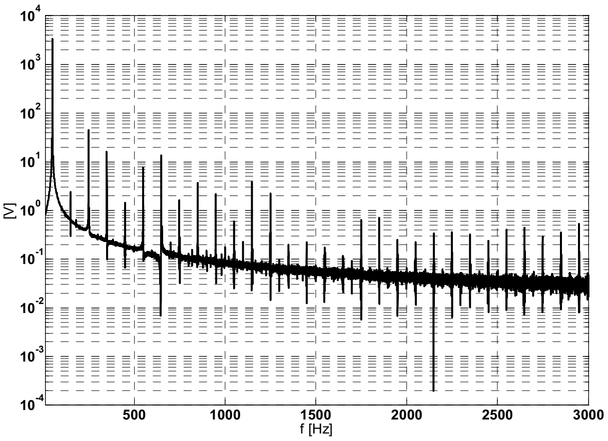


Fig. 15 - Supply voltage FFT in case of disconnected compensator

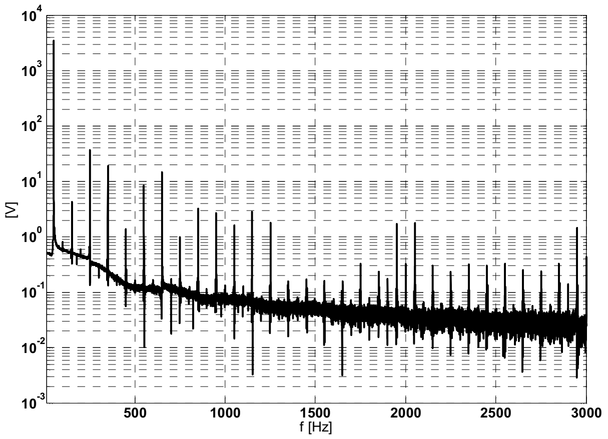


Fig. 16 - Supply voltage FFT in case of connected compensator with duty 0.1

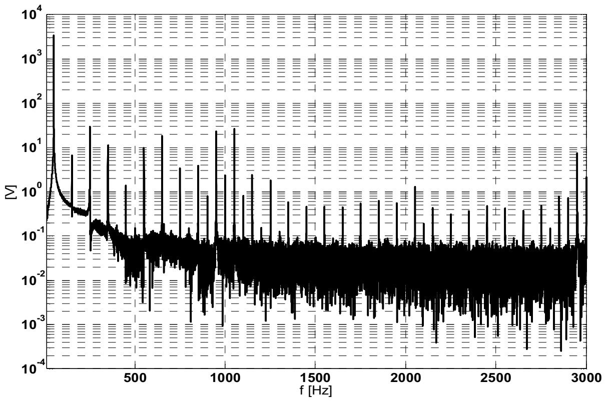


Fig. 17 - Supply voltage FFT in case of connected compensator with duty 0.5

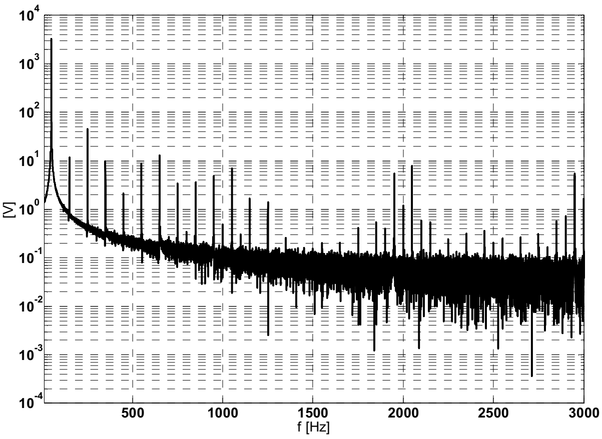


Fig. 18 – Supply voltage FFT in case of connected compensator with duty 0.95

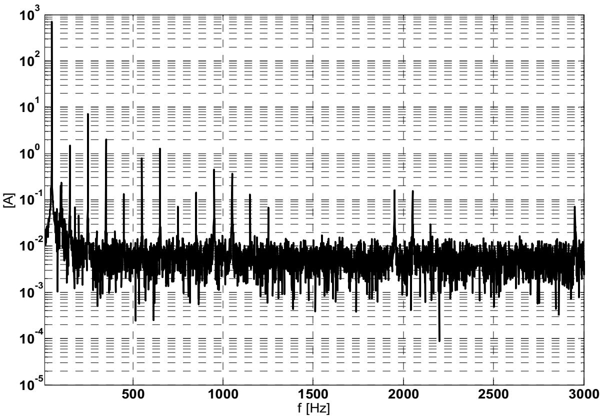


Fig. 19 - Compensator current FFT for duty cycle 0.1

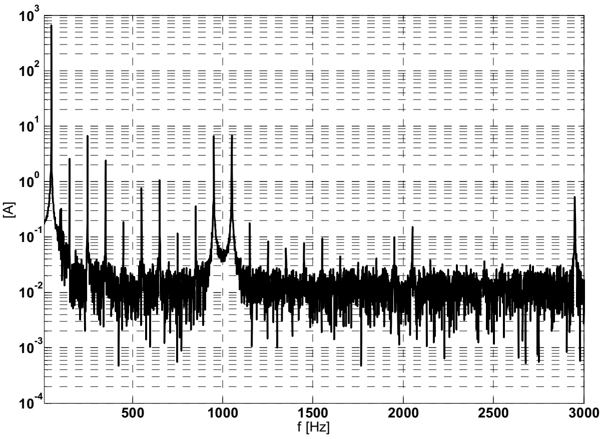


Fig. 20 - Compensator current FFT for duty cycle 0.5

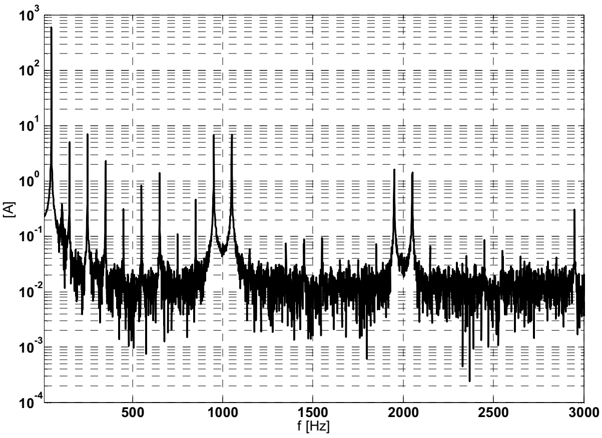


Fig. 21 - Compensator current FFT for duty cycle 0.7

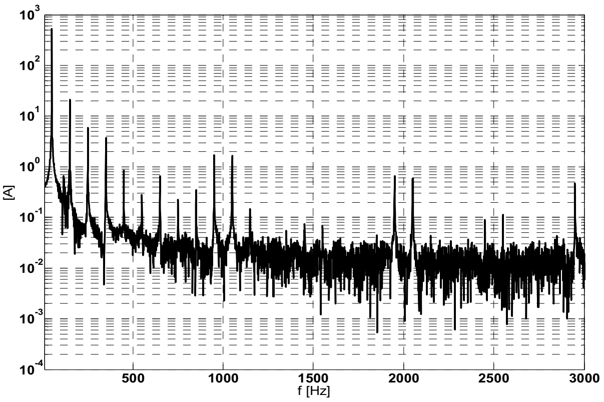


Fig. 22 – Compensator current FFT for duty cycle 0.95

VI. CONCLUSION

In this paper, a low losses reactive power compensator based on Active Impedance concept has been proposed. A real case of study has been considered.

Simulation results validate the correct working of the novel topology even when real waveforms are considered. Moreover, a 1.2 MVAR prototype of the compensator has been realized and tested at the test platform of SNCF. Experimental results confirm the analytical study and the good behaviour of the system.

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