By Philippe Ladoux, Joseph Fabre, and Hervé Caron

Power-Quality Improvement in AC Railway Substations

The concept of chopper-controlled impedance.

THE 25-KV/50-HZ AC SINGLE-PHASE SUPPLY IS a widely used railway system in France with a length of 9,698 km. Overhead lines are supplied by substations drawing power from two phases of a three-phase utility. They behave as nonlinear and time-varying loads and represent one of the most important sources of voltage unbalance for the electricity-transmission network. In the case of weak networks, railway operators are required to install compensation systems in substations to satisfy utility regulations and to avoid penalties regarding voltage unbalance and reactive power consumption. The limits are established by the energy provider with a view to guaranteeing an acceptable power quality to other customers.

In three-phase networks, the most widely used solutions are the classical static var (volt ampere reactive) compensators (SVCs), based on thyristor-controlled reactors (TCRs), and the static synchronous compensator (STATCOM) based on voltage-source inverters (VSIs). The TCR allows the variation of fundamental lagging current by phase control, counterbalancing large leading currents from associated fixed capacitors and allowing continuous compensation of the lagging line. However, this solution generates a high level of harmonics and requires onerous LC filters. On the other hand, VSIs offer several advantages over thyristor-based solutions in terms of compensation dynamics and reduced harmonic distortion. For the last ten

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years, although it requires bulky capacitors on the dc bus, the VSI approach has been widely used for avoiding system unbalance. However, in high-power applications, the semiconductor losses bring forth significant costs both in terms of active energy and cooling system maintenance, which must be taken into consideration by the railway operator.

The concept of the chopper-controlled impedance (CCI), presented in this article, is based on series or parallel associations of ac choppers using high-frequency pulsewidth modulation (PWM) to vary reactances at the network frequency. This approach is a low-power-loss solution and requires a low volume of reactive elements, a fact that makes this solution very attractive in high-power, single-phase systems such as railway networks.

Chopper-Controlled Impedance

Various converter topologies can be applied to provide ac/ac conversion. Direct converters provide a link between the source and the load without additional storage elements, but the input and output frequencies are closely related. Nevertheless, passive filters are always required to filter out the high-frequency harmonics introduced at the input and output sides by the converter switching operation.

Among the ac/ac direct converters, cycloconverters and matrix converters are distinguished by their ability to adjust the output frequency and voltage of a specific ac input voltage source. They also provide bidirectional power-transfer capabilities, allowing the use of active loads (e.g., motors in regenerative mode). On the other hand, the ac chopper topology, which is similar to the well-known dc chopper, provides direct ac/ac conversion between two ac sources at the same fundamental frequency (Figure 1). The ac chopper may be considered as an autotransformer whose turns-ratio can be electronically controlled. Nevertheless, although it can provide instantaneous bidirectional power transfer, it allows power flow in one direction only, according to the type of load. AC choppers are normally designed to transfer power between a fixed ac voltage source (e.g., the utility grid) and a passive ac load. The load voltage [i.e., its root-mean-square (RMS) value] can be adjusted via the duty cycle α to control the power flow, but the power exchange (either active or reactive) is determined purely by the load type (resistive, capacitive, or inductive).

The ideal waveforms are illustrated in Figure 2 (sinusoidal input voltage and sinusoidal output current). In this example, the waveforms are given for the case of a 90° leading current.

It can be easily demonstrated that the RMS value of the output voltage fundamental V_2 depends on the input voltage RMS value V_1 and can be adjusted with the duty cycle α:

$$V_2 = \alpha V_1. \tag{1}$$

Likewise, the relationship between current RMS values is given by

$$I_1 = \alpha I_2. \tag{2}$$

By considering the ideal waveforms, it is clear that the ac chopper topology requires input and output filtering elements. In any case, capacitor C_F and inductor L_F will be designed to filter out the switching frequency from i_1 and v_2. Thus, as shown in Figure 3, the ac chopper can be used as a step-down or a step-up converter, depending on the connection of the network and the load. Assuming a sufficiently high switching frequency f_{sw}, the filtering elements L_F and C_F can be chosen to have a negligible influence at the network frequency. Thus, in terms of fundamental RMS values and relationships of input and output (1) and (2), the structures behave as variable impedances controlled by the duty cycle α. The expressions for input impedance for step-down and step-up configurations are given by (3) and (4), respectively.

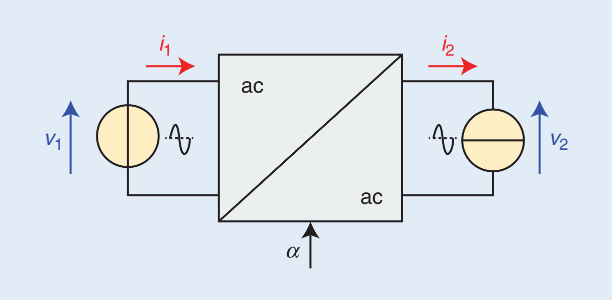

Figure 1. The principle of direct ac/ac conversion.

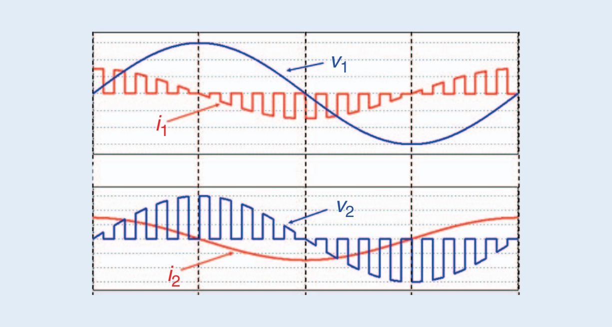

Figure 2. The typical ac chopper current and voltage waveforms for duty cycle $\alpha = 0.5$.

$$Z_{in} \approx \frac{V_{in}}{I_{in}} \approx \frac{Z_{out}}{\alpha^2}, \tag{3}$$

$$Z_{in} \approx \frac{V_{in}}{I_{in}} \approx Z_{out}\alpha^2. \tag{4}$$

For example, if impedance Z_{out} is capacitive at the grid frequency, then the converters act as variable capacitors. Thus, a reactive power compensator can be implemented using the controlled impedance concept. The supplied reactive power can be expressed as (5) for step-down mode and (6) for step-up mode

$$Q = \frac{V_{in}^2}{Z_{out}}\alpha^2, \tag{5}$$

$$Q = \frac{V_{in}^2}{\alpha^2 Z_{out}}. \tag{6}$$

Application of the Controlled Impedance Concept to Reactive Power Compensation

Currently, most of the main-line traffic is from locomotives equipped with thyristor rectifiers. That is why (as traffic and load increase) reactive power compensation is required to reduce reactive power and to keep the voltage from sagging. Basic power-factor correction is realized by fixed capacitors. The problem of such configurations is that when the overhead lines operate at no load, the voltage will rise but may not exceed the 29-kV standard limit. If an increase of compensation is required, then a variable reactive power compensator must be added to the fixed-capacitor banks.

Today, French National Railways [Société Nationale des Chemins de fer Français (SNCF)] use some lines equipped

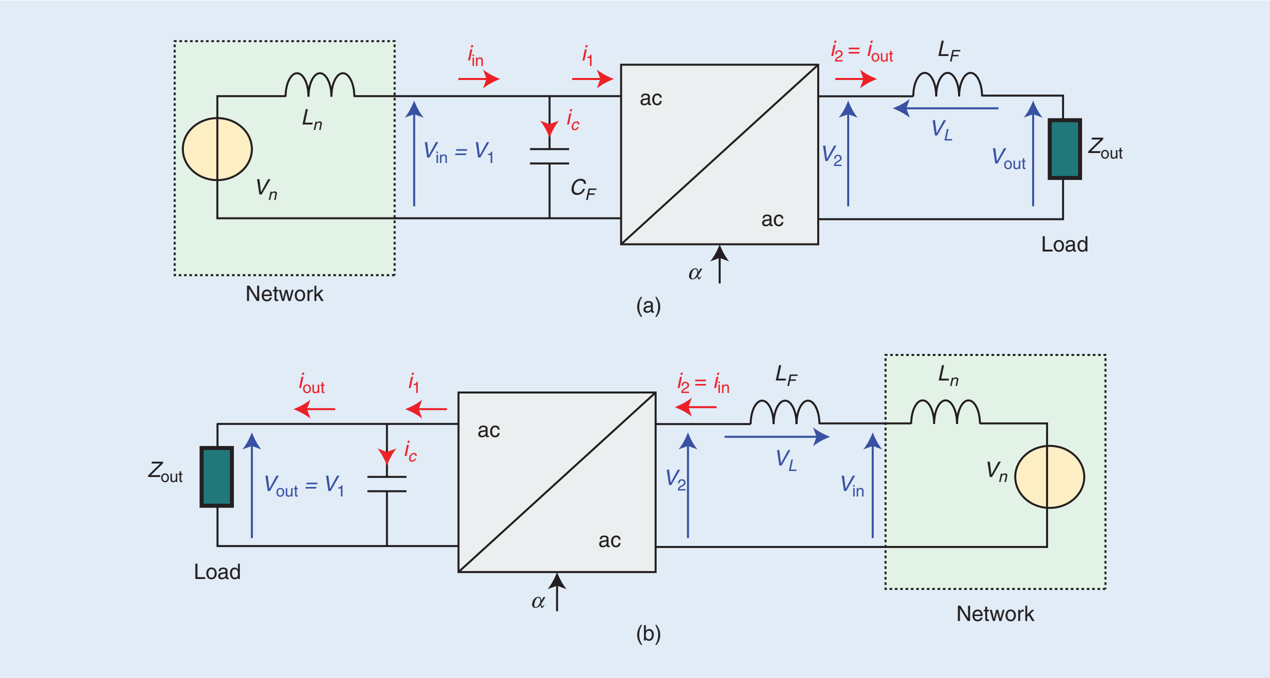

Figure 3. The CCI with buck or boost ac/ac converter: (a) the step-down configuration and (b) the step-up configuration.

with thyristor-based SVCs. However, the TCR draws a nonsinusoidal current, and in single-phase systems, these have a high level of third harmonic (up to 34% of the fundamental). As a result, this topology requires a bulky LC shunt filter tuned to the third harmonic. To avoid this drawback, a new structure, based on CCIs was proposed. The case study is a 60-MVA substation close to Paris. The substation is phase-to-phase connected to a 225-kV three-phase transmission line. The initial circuit, presented in Figure 4, includes two fixed compensation banks with antiharmonic inductors (L_1 and L_2).

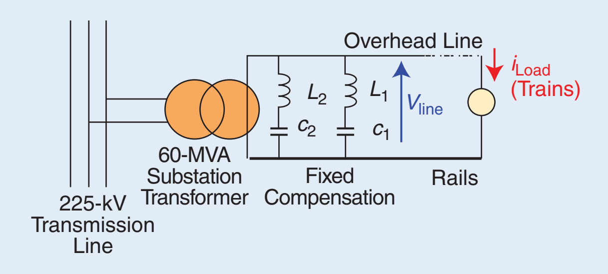

Figure 4. A 25-kV, 50-Hz ac railway line power supply.

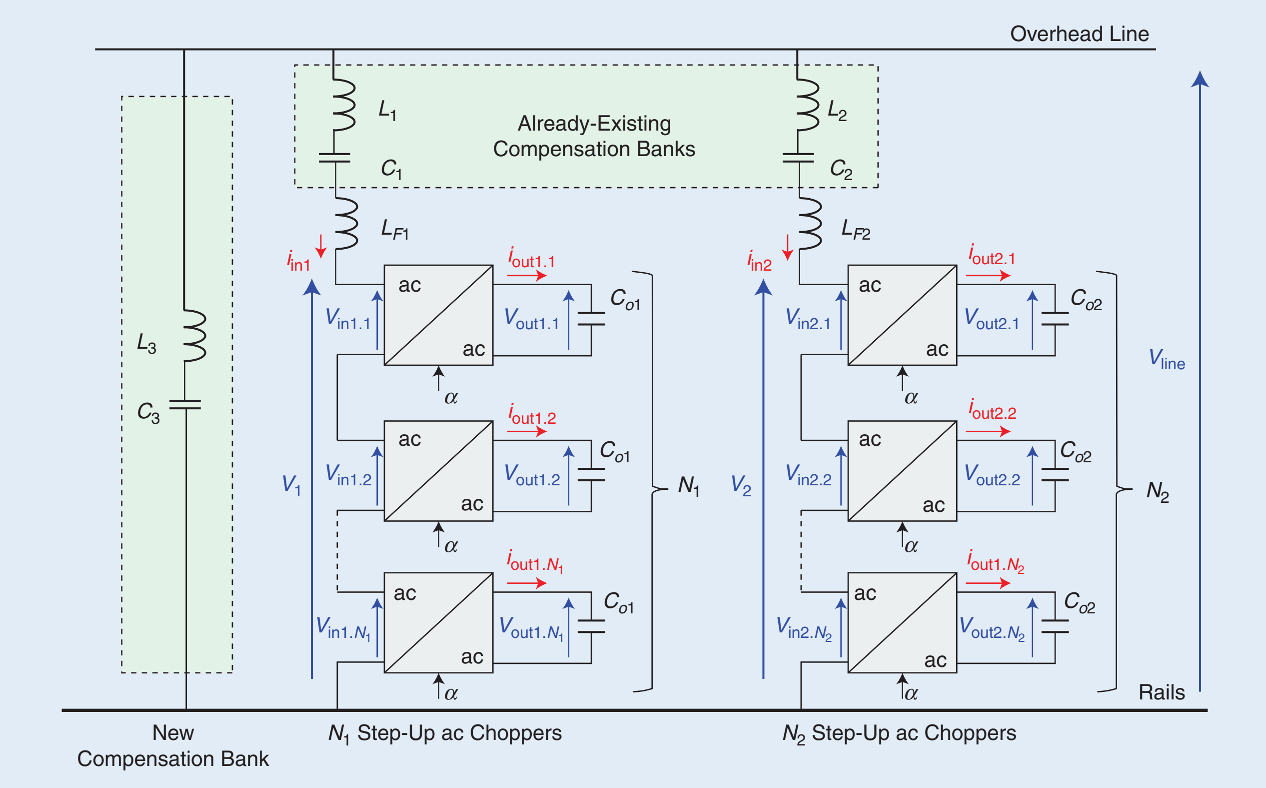

Figure 5. A new topology of a reactive power compensator.

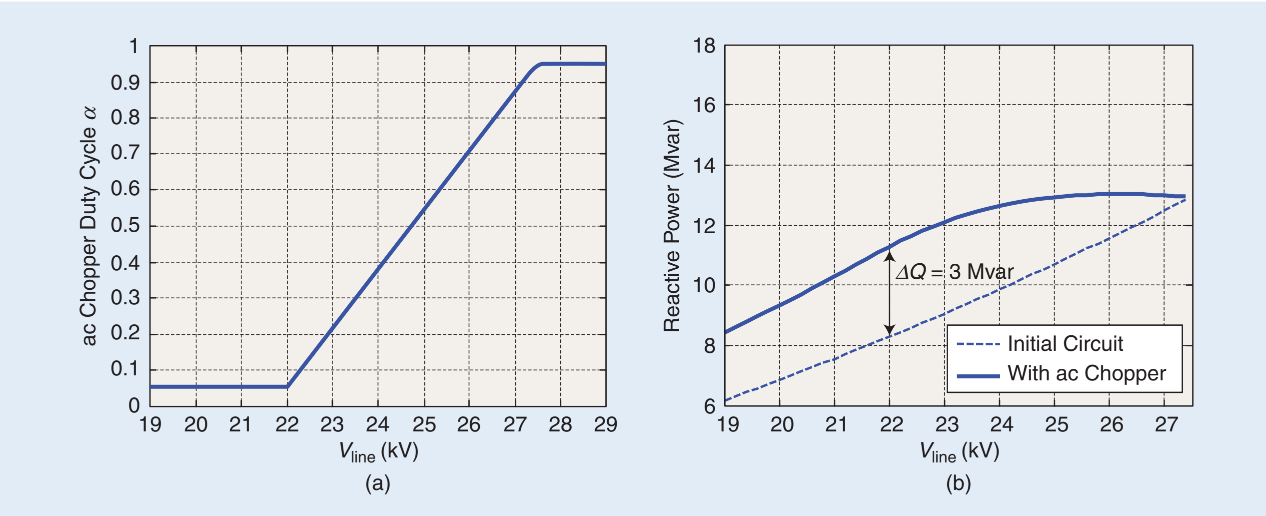

Figure 6. The (a) duty cycle and (b) reactive power are plotted versus the line voltage.

At the substation, a study of active and reactive energy consumption was performed over a five-month period. It was thus demonstrated that the invoiced reactive energy could be reduced from 5,000 Mvarh to 1,500 Mvarh by adding variable compensation of 3 Mvar.

The new compensation circuit is presented in Figure 5. AC choppers are connected in series with the existing fixed compensators. A filtered shunt capacitor bank ($L_3 - C_3$) is added and sized to provide an additional reactive power of 3 Mvar at 22 kV (for a total maximum of 13 Mvar). The controlled impedance part allows reactive power control by variation of the duty cycle according to Figure 6 as a function of the line voltage and the maximum compensated reactive power, limited to 13 Mvar.

The peak voltage on each ac chopper is limited to 3.6 kV for a line voltage of 27.5 kV (no-load operation). As a result, four series-connected ac choppers are required. The advantage of the voltage divider with regard to semiconductor stress is shown in Figure 7, where the maximum input current is reached when the output voltage is close to 1 kV.

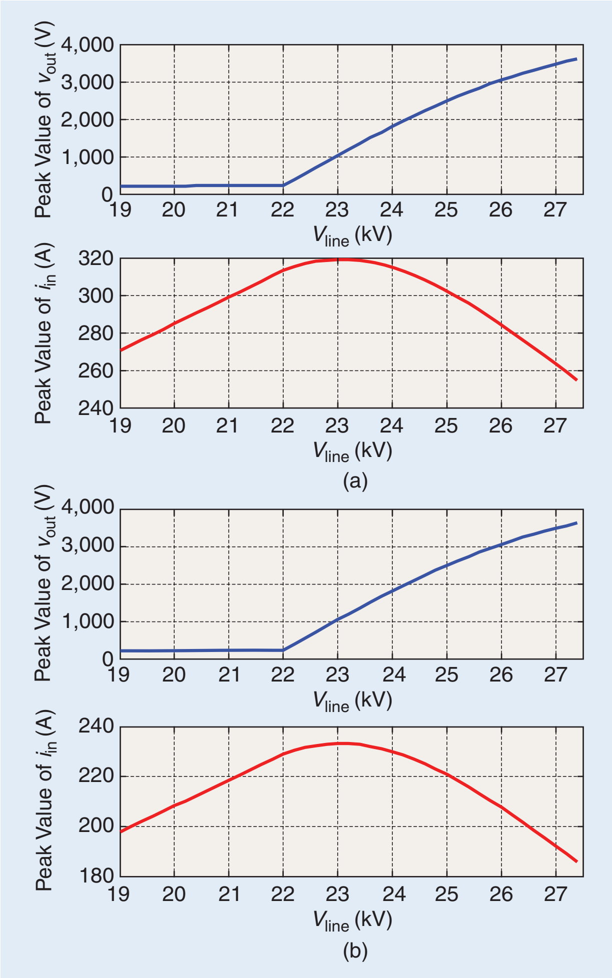

Figure 7. The ac chopper output voltages and input currents versus line voltage for (a) bank 1 and (b) bank 2.

Experimental Results: Reactive Power Compensation with Step-Up AC Chopper

A prototype was developed to demonstrate the feasibility of the solution presented in Figure 5. The maximum reactive power level was set to 1.2 Mvar. The ac chopper was built at the Plasma and Conversion of Energy Research Laboratory (LAPLACE) in Toulouse, France, and tested on the SNCF test platform in Vitry (Paris), France. The experimental setup, shown in Figure 8, is based on the series connection of an ac chopper and an LC filter, which has a capacitive response at 50 Hz. For safety reasons, resistors R_{dis1} and R_{dis2} are installed to discharge the capacitors when the circuit is turned off.

The RMS value of the ac supply used during the test is 2,450 V. The semiconductor devices used for the ac chopper converter are 3.3-kV/1,500-A insulated-gate bipolar transistors (IGBTs) switching at 1 kHz. The maximal reactive power provided is about 1.2 Mvar, and the reactive power variation, ΔQ, is 320 kvar. An air-cooled system based on heat pipes is used. The control part and the generation of IGBT switching patterns are achieved by using a mixed-environment digital signal processor and field-programmable gate array. The experimental setup is shown in Figure 9, and the waveforms are presented in Figure 10. It can be seen that the current i_{in} is sinusoidal; voltage v_{cell} corresponds to the voltage across capacitor C_0 when V_{out} is positive. The current in switch K1_C is chopped with a polarity opposite to i_{in}, and the voltage across C_0 increases with duty cycle α. All experimental measurements match well to the previously calculated values. The reactive power variation $Q(\alpha)$ is plotted in Figure 11.

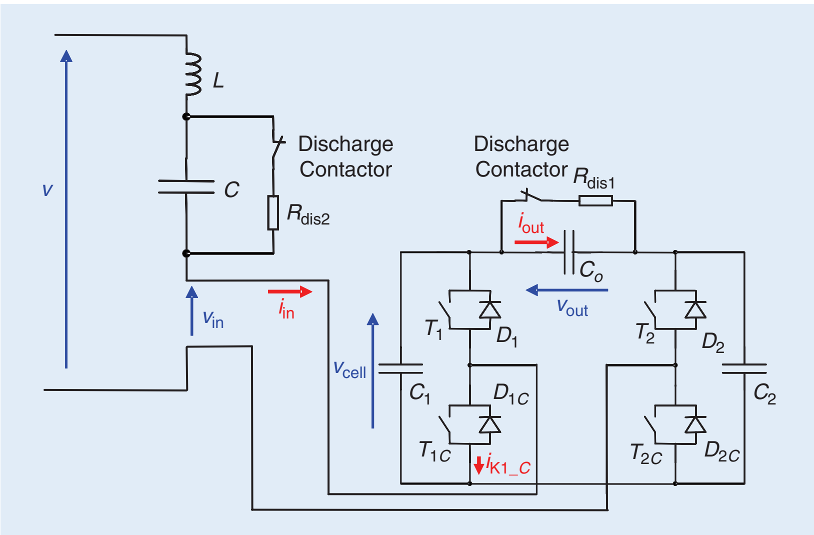

Figure 8. The reactive power compensator based on a step-up ac chopper.

Chopper-Controlled Steinmetz Circuit for Voltage Balancing in Railway Substations

Chopper-Controlled Steinmetz Circuit for Voltage Balancing

Figure 12 shows a classical railway substation supplied by a three-phase network. At the point of common coupling, to avoid penalties from the utility, the railway company is forced to meet a maximum voltage unbalance factor (UF) averaged over 10 min. The UF is defined as the ratio of the negative sequence component V_- and the positive sequence component V_+ of the line voltages (v_a, v_b, and v_c).

Figure 13 shows the basic principle of the active Steinmetz compensator with ac choppers realizing controlled impedance, both capacitive and inductive, as required. These impedances, connected across two lines of the three-phase network, draw currents with a negative sequence, which compensates the current unbalance and, consequently, the voltage unbalance produced by two-line loading.

Only the real part of the negative sequence component drawn by the substation is compensated, which is the main drawback of the active Steinmetz circuit. Nevertheless, modern locomotives are equipped with active front-end rectifiers, which draw a sinusoidal current in phase with the line voltage. In the future, locomotives using thyristor rectifiers will no longer be used; therefore, it will not be necessary to consider low-power-factor operation during development. Moreover, the railway operator is not interested in an instantaneous compensation since penalties are applied on the basis of a 10-min average. In this case, a very simple control strategy can be implemented: the duty cycle of the ac choppers will be controlled as a function of the active power consumed by the substation.

Chopper-Controlled Steinmetz Circuit Design in a Typical Substation of the French National Railways

The case study is a 16-MVA substation located in Évron, Pays de la Loire, France. The primary of the transformer is connected across two of the three 90-kV/50-Hz transmission lines, and a 2.7-Mvar reactive power compensation bank is connected on the 25-kV side. The rating of the compensator was chosen to guarantee a UF of 1.5% when the substation is loaded at 10 MW and for the lower short-circuit power $S_{cc} = 295$ MVA. The power rating of the unbalance compensator is given by

$$S_{comp} = S_L - \mathrm{UF}\, S_{cc}. \tag{7}$$

Thus, the power of each CCI is equal to S_{comp} divided by $\sqrt{3}$ and set to 3.3 Mvar. The converter is designed with standard 3.3-kV/1.5-kA IGBT modules with a switching frequency $f_{sw} = 1$ KHz. For the design, the following specifications were developed.

- *Transformer ratio*: N_{T1} and N_{T2} limit the semiconductor voltage to 1,800 V.

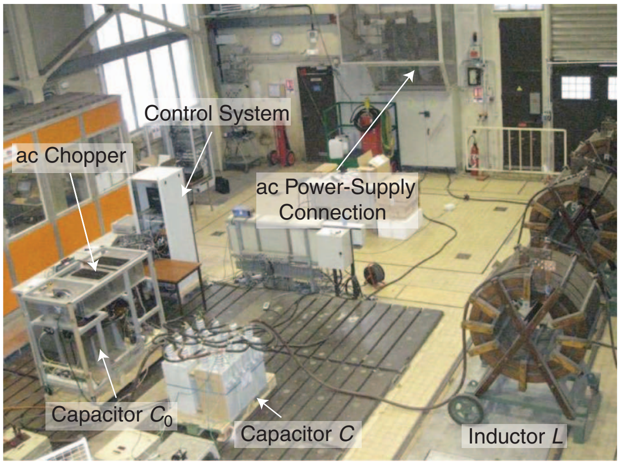

Figure 9. The reactive power compensator under test.

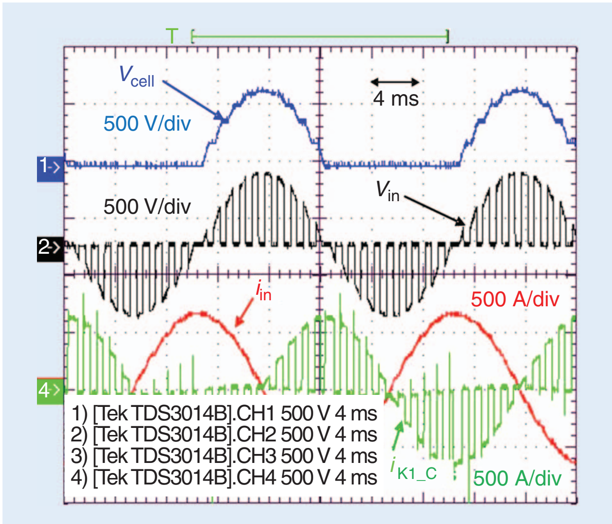

Figure 10. The ac chopper waveforms ($V = 2450$; $V_{RMS} - \alpha = 0.5$).

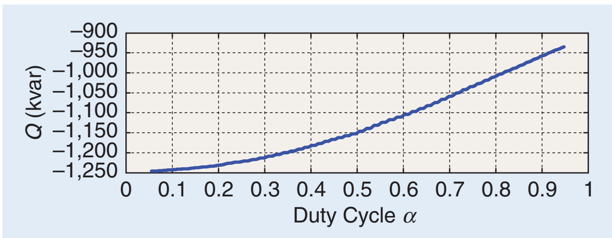

Figure 11. The experimental results: leading reactive power versus duty cycle α.

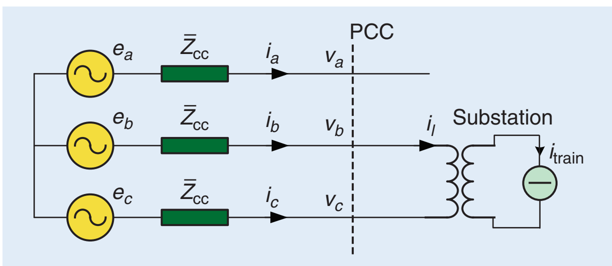

Figure 12. A single-phase substation connection.

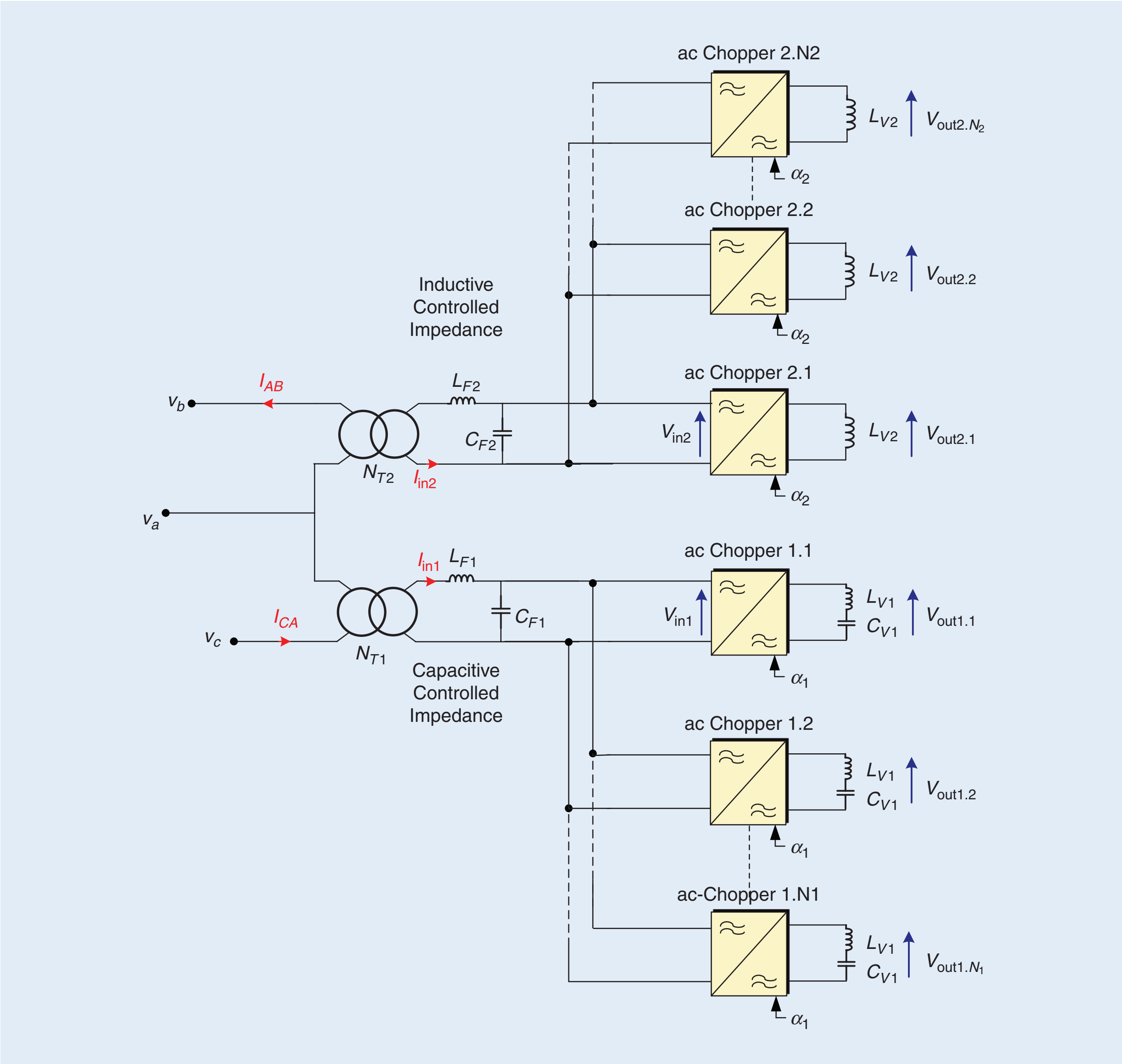

Figure 13. An active Steinmetz compensator.

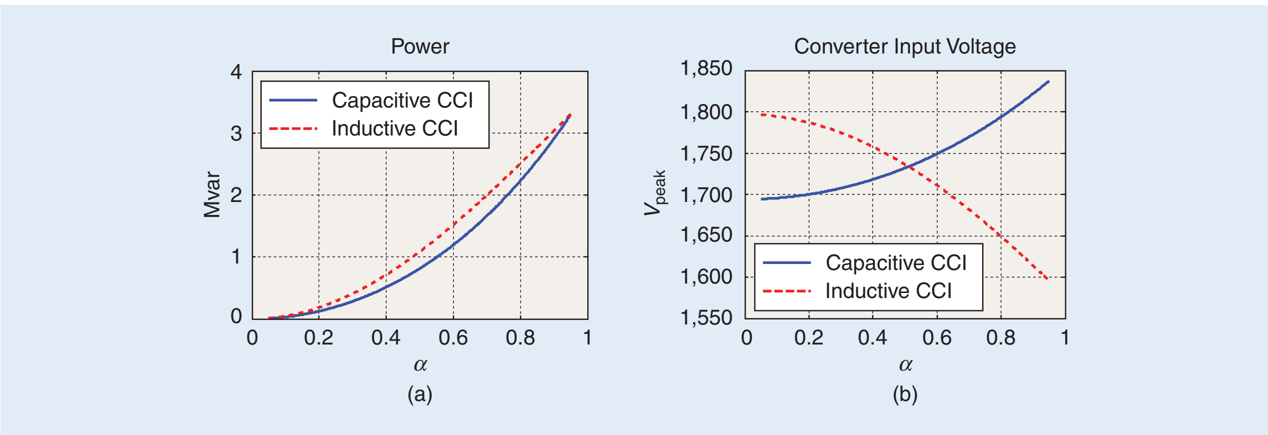

Figure 14. The (a) reactive powers and (b) input ac choppers' peak voltage are plotted versus duty cycle $\alpha_{1,2}$.

- *Input filter*: To balance the substation even when it is not loaded, the already existing 2.7-Mvar reactive power compensator was replaced with one that was 900 kvar, and the input filter capacitor of the CCI was chosen to provide a reactive power $Q_F = 900$ kvar. In this way, when no trains are supplied by the substations, the circuit is seen from the three-phase network as a balanced load. Moreover, $L_{F1,2}$ is simply the leakage inductance of the 3.3-MVA transformer.
- *Maximum ac chopper output current*: The number of modules in parallel (N_1 or N_2) was chosen according to the thermal limits of the IGBTs (case temperature: $T_C = 100\,^\circ$C, and junction temperature: $T_J = 125\,^\circ$C) with a maximum RMS current I_{MAX} of 735 A.
- *Maximum power*: Output impedance parameters obtain 3.3 Mvar at the maximum duty cycle (0.9). Moreover, a 10% maximum current ripple at the switching frequency was chosen to determine the output impedance of the capacitive ac choppers.

The reactive powers and peak input voltages (V_{in1} and V_{in2}) of the controlled impedances versus duty cycles α_1 and α_2 are shown in Figure 14.

Comparison of VSI Versus Active Steinmetz

On the basis of the design presented in the previous sections, Figure 15 summarizes the power losses for different voltage-balancer topologies. Losses are referred to a working condition for the compensators when the load phase is $\phi_L = 0°$. Comparing the two solutions based on VSI converters, the three-level neutral point clamped (NPC) solution is characterized by lower losses. In addition, if the active Steinmetz compensator is compared with the three-level NPC topology, a reduction in the power losses of about 60% is achieved.

The energy stored in the reactive elements is used as a qualitative index of the components space volume. The peak values for current $\hat{I}$ and voltage $\hat{V}$ in the inductors

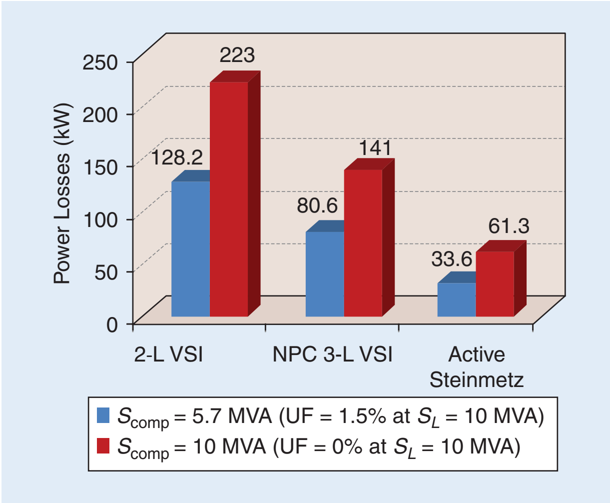

Figure 15. A comparison between voltage-balancer topologies in terms of power losses.

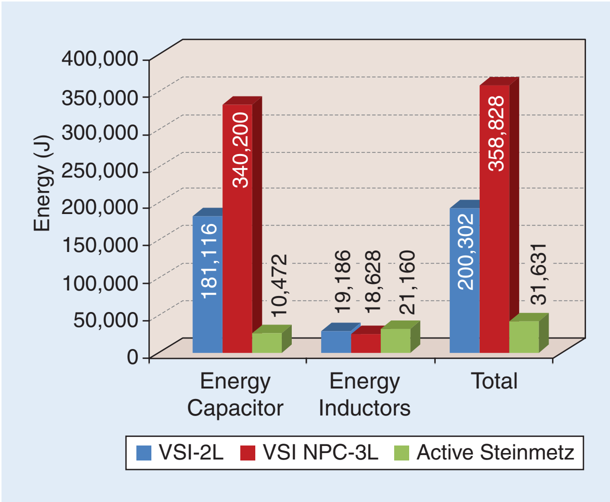

Figure 16. A comparison in terms of energy stored in reactive elements ($S_{comp} = 5.7$ MVA).

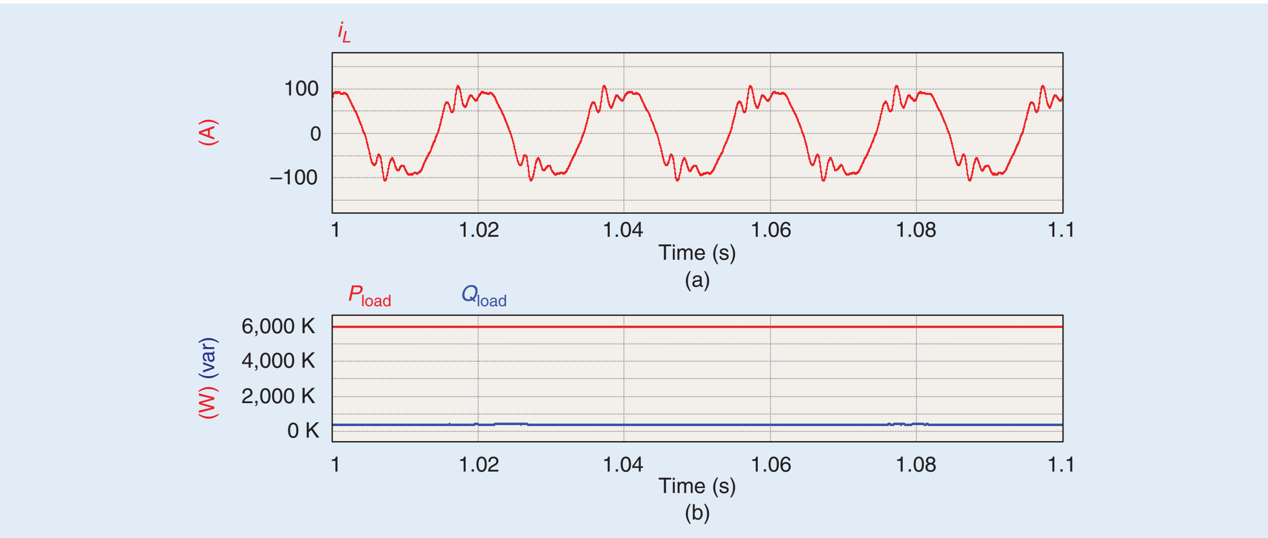

Figure 17. (a) The substation current waveform and (b) active and reactive power.

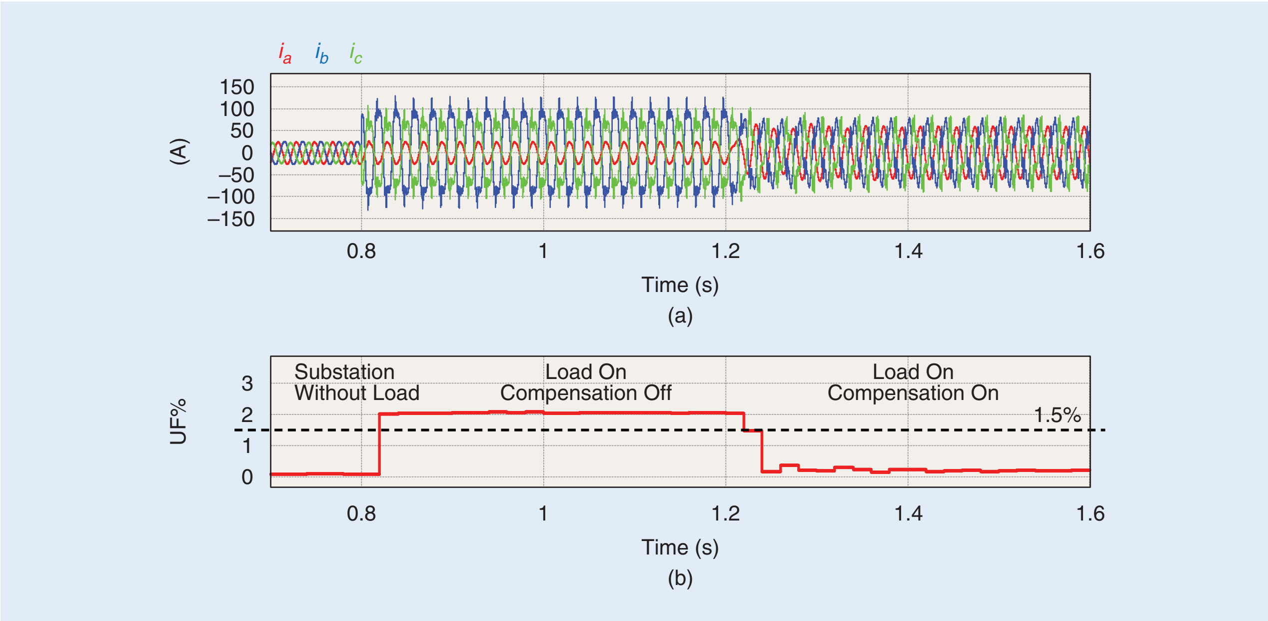

Figure 18. (a) The line currents and (b) the voltage UF%.

and capacitors of the three studied topologies are evaluated and used in

$$E_{\text{cap}} = \frac{1}{2}C\hat{V}^2 \quad E_{\text{ind}} = \frac{1}{2}L\hat{I}^2. \tag{8}$$

Figure 16 shows a comparison of the total energies for the three solutions. Comparing the energy stored in the reactive elements for the three topologies, a huge difference exists between the proposed compensator and the classical solutions based on VSI converters. Particularly for the size of the dc-link capacitors, the capacitive stored energy in these conversion structures is significant. In fact, as the converter is injecting a purely negative sequence three-phase current, the fluctuating power makes it necessary to install large capacitors to limit the voltage ripple at the dc side.

The semiconductor power losses and energy-storage requirements compared to the widely used VSI topology make the proposed solution very attractive for railway operators.

Simulation Results of the Chopper-Controlled Steinmetz Circuit

The worst-case condition, i.e., at lowest short-circuit power, $S_{cc} = 295\,\text{MVA}$, is considered. The chopper-controlled Steinmetz circuit is connected in parallel to the substation. In the circuit, the substation and the trains were replaced by a controlled current source. Then, simulations with PSIM software were carried out using measured current waveforms. The substation current waveform is given in Figure 17 and presents a third harmonic of about 20 A. Resulting line currents and UF% are presented in Figure 18, in which three working periods can be distinguished in the simulation corresponding to three modes of operation:

- The substation is not loaded and appears as a balanced load to the power network.
- The substation is loaded, and the UF reaches 2%.
- The chopper-controlled Steinmetz circuit is turned on and UF is close to zero, well under the limit of 1.5%.

Figure 19 shows a zoom on the three-phase line-currents and the currents drawn by the compensator. It can be seen that currents i_{ca} and i_{cb} are quasi-sinusoidal, which confirms that harmonic interactions are avoided, as expected, with the frequency analysis presented above. Furthermore, the line voltage drop corresponding to the negative current sequence is strongly reduced, and the substation voltage is boosted by 1.7 %.

Conclusion

In this article, reactive power and voltage unbalance compensators based on PWM ac choppers were proposed. In multilevel structures, current or voltage sharing is naturally ensured by the choice of impedance values. A very simple control of reactive power can be achieved by varying only the duty cycle; no control loops for internal variables are required. Compared to a TCR solution, the ac chopper does not generate any low-order harmonics, thanks to its PWM operation.

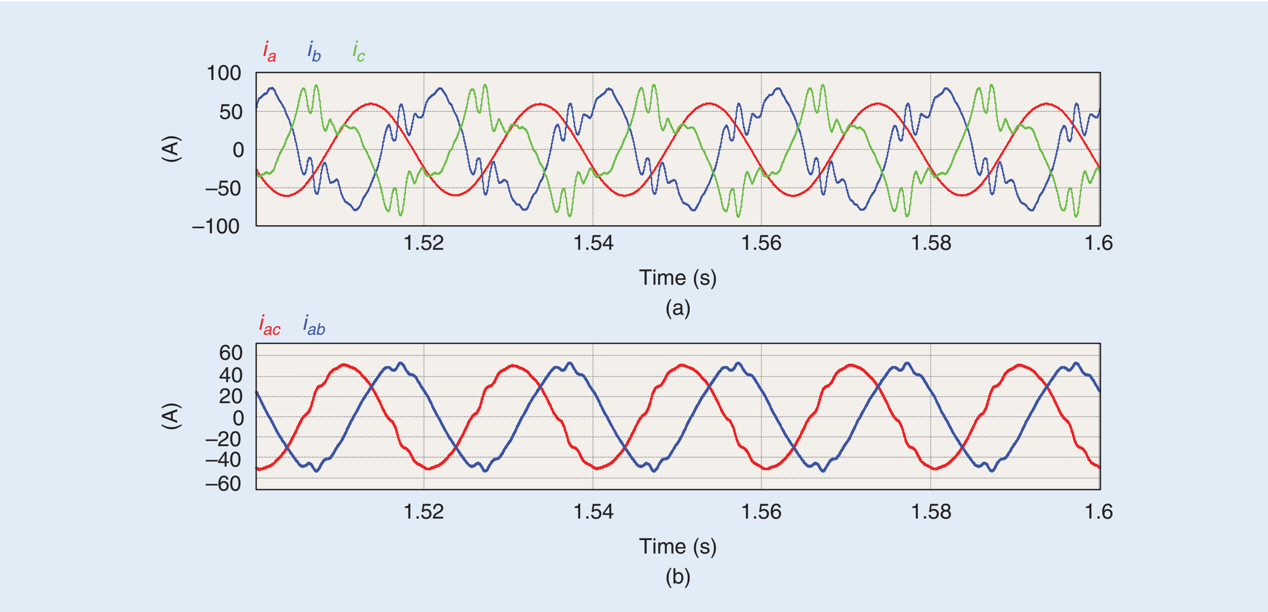

Figure 19. (a) The line currents and (b) the injected currents i_{ab} and i_{ca}.

Nevertheless, to avoid over-voltages, it is necessary to choose the filtering elements with regard to preexisting harmonics in the network.

As far as the application in ac traction lines is concerned, simulation results validated the operation of this novel topology, and a 1.2-Mvar prototype of the compensator was built and tested at the SNCF's test platform, confirming the analytical study and system performance. Although a STATCOM solution using cascaded VSIs could be considered, the ac chopper topology, presented in Figure 5, exhibits lower semiconductor losses. Furthermore, a low-loss voltage-unbalance compensator based on the CCI concept was proposed, and the case study of a real French substation was undertaken. Despite the limited compensation domain of the presented topology, the study highlights its feasibility in railway substations. In fact, in this kind of application, average compensation is sufficient to respect the utility's requirements. The semiconductor power losses and energy-storage requirements compared to the widely used VSI topology make the proposed solution very attractive for railway operators. A very simple control can be achieved by varying only the chopper duty cycles, without the need for control loops for other variables. The simulation results confirmed the operation of the novel topology under real conditions. At present, an industrial solution of the chopper-controlled Steinmetz circuit is under development and will be tested in 2016.

Direct converters provide a link between the source and the load without additional storage elements.

For Further Reading

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Biographies

Philippe Ladoux (philippe.ladoux@laplace.univ-tlse.fr) is a full professor at the Plasma and Conversion of Energy Research Laboratory, University of Toulouse, France.

Joseph Fabre (joseph.fabre@laplace.univ-tlse.fr) is a postdoctoral researcher at the Plasma and Conversion of Energy Research Laboratory, University of Toulouse, France.

Hervé Caron (herve.caron@sncf.fr) is an engineer at the Department of Fixed Installations for Traction Power Supply in the French National Railways Company.