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Use of Opposition Method in the Test of High-Power Electronic Converters

François Forest, Jean-Jacques Huselstein, Sébastien Faucher, Mohamed Elghazouani, Philippe Ladoux, T. A. Meynard, *Member, IEEE*, Frédéric Richardeau, and Christophe Turpin

Abstract—The test and the characterization of medium or high-power electronic converters, under nominal operating conditions, are made difficult by the requirement of high-power electrical source and load. In addition, the energy lost during the test may be very significant. The opposition method, which consists of an association of two identical converters supplied by the same source, one operating as a generator, the other as a receptor, can be a better way to do these test. Another advantage is the possibility to realize accurate measurements of the different losses in the converters under test. In the first part of this paper, the characteristics of the method concerning loss measurements are compared to those of the electrical or calorimetric methods, then it is shown how it can be applied to different types of power electronic converters, choppers, switched mode power supplies, and pulsewidth modulation inverters. In the second part, different examples of studies conducted by the authors, and using this method, are presented. They have varying goals, from the test of soft-switching inverters to the characterization of integrated gate-commutated thyristor (IGCT) devices mounted into 2-MW choppers.

Index Terms—Integrated gate-commutated thyristor (IGCT) characterizations, inverter losses measurement, opposition method, reliability test in power electronics.

I. INTRODUCTION

THE OPPOSITION method is probably as old as electrical engineering. Its principle makes it very attractive for a test and a characterization of high-power electrical systems operating under nominal conditions. On one hand, it leads to a significant reduction of the test facility requirements, especially concerning the power of loads and voltage sources, and, on the other hand, it enables more accurate measurements of the power losses. This paper emphasizes the use conditions and the interesting properties of the method, in case of an application to the characterization of power electronic converters. Several power electronic studies, realized by the authors employing the method, are presented to illustrate the advantages of the method for the medium and high power.

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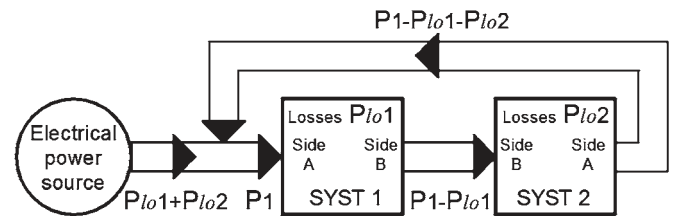


Fig. 1. Opposition method for electrical systems.

II. PRINCIPLES

A. General Principles for Electrical Systems

The opposition-method principle, applied to electrical systems, must be first recalled.

It consists of the connection between two identical systems, supplied by one or more auxiliary power sources; the first one operating as a generator and the second one as a receptor, with the aim to circulate a high power through the two systems while consuming on the line only the losses of both systems (Fig. 1).

Three main advantages can be put forward. First, the method allows minimizing the power source that provides only the total losses $P_{lo1} + P_{lo2}$. Second, it avoids the introduction of a dissipative load. Last, the total power losses can be directly evaluated with a good accuracy. This important feature will be better analyzed in Section II-C, where a review of the possible methods to evaluate the losses in power electronic converters will be presented.

B. Application Rules of the Opposition Method

1) *Reversibility*: If two identical systems are used, one operating as a generator and the other as a receptor, they must be reversible for energy flow. Therefore, as a first approach, the nonreversible electrical systems, such as diode rectifier or single-transistor chopper, cannot be tested with this method.

2) *Symmetry of Operating Modes*: Even when the two systems are identical and reversible, the operating conditions can be quite different in the generator or receptor mode. Therefore, these conditions have to be chosen in order to obtain quasi-balanced losses repartition in the two systems.

These two rules must be obeyed in case of a test concerning two identical noncharacterized systems. In the next section, it will be demonstrated that they can be transgressed if a well-known and characterized system is associated to the system under test.

C. Losses Measurement Methods in Electronic Converters

In the design and the characterization of power electronic converters, loss measurements are essential. The main aim is either to verify loss calculation based on device models or to quantify losses resulting from complex phenomena that cannot be modeled accurately. With this aim in view, if the loss evaluation can be conducted on prototypes partially adapted to that goal, it must use one or several measurement methods well suited to the character of the system under test and easily adaptable to different studies. For example, the output power of a converter can vary in a large range, and the loss estimation in all this range is a frequent need.

On the other hand, when specifying an industrial product, a certain margin must be allowed compared to the measurements realized on a prototype, because of the spread of the different devices. Therefore, in most of the cases, a few percent accuracy is enough for characterizations and sizing.

1) *Electrical Methods*: At first sight, the principle seems trivial since it involves determining the average power (for the periodic systems considered here) based on the measurements of the voltage and current. Nevertheless, its application can be critical with regards to accuracy.

a) *Recall on digital electrical power measurement*: The average electrical power in periodic systems is now systematically measured by digital acquisition and processing of instantaneous current and voltage. Different features influence the accuracy of such measurements in power electronics:

- 1) accuracy and offset of the voltage and current sensors;
- 2) resolution, the quantization noise, the sampling frequency of the analog-to-digital conversion stage;
- 3) ratio between the measured data and the full scales;
- 4) noise induced by the switching mode of the converter (e.g., common mode noise);
- 5) shape of the instantaneous power p and the relation with the average power P_{av} (frequency, harmonics, phase) that can be summarized by the notion of scale power ratio, $R_P = P_{av}/V_M \cdot I_M$ (V_M and I_M being the maximum instantaneous value of voltage and current).

These electrical power measurements can be achieved with power analyzers or with specific acquisition systems, dedicated for example to the evaluation of losses in semiconductor devices. It is difficult to define a generic error formula taking into account the previous features. It depends on the system used and on the shape of the instantaneous power. For dc conditions, the relative error could be close to 0.1%–1%. A low scale power ratio can lead to a significant increase of this error (factor 10 or more).

b) *Digital power measurement across the components*: This method is mainly applied across the semiconductor power devices [1]–[4], [9]. With a correct implementation, the switching losses can be accurately evaluated (error of a few percent), if the switching times are not too low (medium- and high-power devices).

However, these measurements are made on a switching period or a few switching periods with an averaging process. Consequently, they can be correctly conducted in a periodic steady state (e.g., dc-to-dc converters) but they need a large

amount of data in case of low-frequency modulation (e.g., pulsewidth modulation (PWM) inverters), operating conditions that impose to acquire all the switching phases occurring on the modulation period.

On the other hand, the measurement of ON-state losses in a switching device is a very difficult task because of the great voltage dynamic between the OFF and ON states (factor 100–1000).

c) *Digital power measurement of input and output powers of a converter*: For an electronic converter, loss estimation can be achieved by subtracting the input and output powers, each being measured with a power analyzer. Then, the relative error made on the difference is strongly increased compared to the initial error, for high-efficiency values

$$\frac{\Delta P_{lo}}{P_{lo}} = \left[\frac{1}{1-\eta} \right] \frac{\Delta P_{in}}{P_{in}} + \left[\frac{\eta}{1-\eta} \right] \frac{\Delta P_{out}}{P_{out}}$$

where $\Delta P_{lo}/P_{lo}$ is the relative error on the losses measurement, $\Delta P_{in}/P_{in}$, $\Delta P_{out}/P_{out}$ are the relative errors on input and output power measurements, and η is the efficiency.

For example, applying this method on a system with a 90% efficiency will lead to a relative error on loss measurements twenty times greater than the relative error given by the power analyzer. Nevertheless, the method is applicable for the high scale power ratio (e.g., in dc-to-dc converters).

d) *Digital power measurement in opposition method*: The opposition method described in this paper is a direct-measurement method of the total losses, so the relative error directly depends on the power-analyzer accuracy

$$\frac{\Delta P_{lo}}{P_{lo}} = \frac{\Delta P}{P}.$$

For dc-input electronic converters (high-scale-power-ratio conditions), the relative error made on the total losses is close to a few 0.1%—a few percent range. They include the load-inductor losses (see Section III-A2) but it will be shown in the next part that this point can be solved, keeping the accuracy at the same time.

At last, a loss measurement on a large output power range does not affect the accuracy since the scale can be adjusted for each measurement.

2) *Thermal or Calorimetric Methods*: The calorimetric methods are based on the measurement of the variation of enthalpy of the coolant in a thermal exchanger associated to the device or system under test. The simplified relation giving the power losses versus the thermodynamic parameters is

$$P_{lo} = T_{diff} Q C \rho$$

where

- T_{diff} differential temperature of the coolant between the output and the input of the exchanger system;
- Q flow rate;
- C specific heat capacity of the coolant;
- ρ density of the coolant.

a) *Calorimetric chamber*: The main corresponding method involves enclosing the tested system in a calorimetric

chamber of which the temperature is controlled by a thermal exchanger (air or water) [5]–[8]. If adiabatic conditions are respected in the chamber, the measurement of the coolant parameters, differential temperature, and flow rate leads to the power-loss estimation.

Numerous papers have been written on the subject. They emphasize the high accuracy that can be reached (up to 0.1%) but point out the need for complex experimental benches. To obtain such an accuracy, different features have to be considered:

- 1) accuracy of the temperature sensors and flowmeters;
- 2) parasitic thermal exchange (through the walls and output connections);
- 3) homogeneity of the walls and coolant temperatures;
- 4) variations of physics parameters (specific heat capacity, density);
- 5) dynamic of thermal exchange.

The calorimetric chamber is a very efficient tool to evaluate the power losses in various systems in which the other methods are too inaccurate or inapplicable. It is not really suited to high-power electronic converters, particularly when some parts (semiconductor power devices, for instance) are cooled by water. Unlike other methods, it requires a very specific experimental apparatus including a chamber capable of containing the converter under test.

Finally, another drawback is the decrease of the calorimeter accuracy when the power losses are significantly lower than the typical power the bench is optimized for. Consequently, a loss analysis on all the power range of the converter can be difficult.

b) Measurement based on a water-flow exchanger: For a particular case of converters including water-cooled parts, a simplified version of the calorimetric method consists of measuring the coolant flow rate and the input and output temperatures [21]. The requirements on the sensor accuracy are high (the temperature difference is generally small), and the heat exchange with air has to be negligible.

Relative errors around a few percentage can be obtained. As for the calorimetric chamber, the accuracy decreases with the power losses because of the decrease of the differential temperature. Reducing the coolant rate may be needed to obtain an accurate measurement of the low losses.

3) Partial Conclusion: Table I summarizes the main properties of the different loss measurement methods applicable to the characterization of electronic converters (the calorimetric method had not been considered in the table). These various methods are not exclusive. For example, the opposition method, which is, first, a means to easily conduct the electrical tests, may be used in conjunction with all the others, as this will be illustrated in the last example of this paper.

III. OPPOSITION METHOD APPLIED TO INVERTERS AND CHOPPERS

A. Opposition With Two Identical Converters: Voltage-Source Inverter Legs

1) Structure and Control: The scheme of Fig. 2 shows the association that can be realized to characterize the inverter

legs (the insulated gate bipolar transistor (IGBT) devices are considered here as generic switches).

In keeping with the principle previously described, one of the legs operates as a generator, the other as a receptor. The load is a simple inductor of which the function is to limit the current variations induced by the instantaneous differential voltage between the two legs.

Each leg is driven by a PWM control stage, be it analog or digital. The two control stages have to be synchronized in order to avoid a low-frequency beating interferences but also to minimize the size of the load inductor (an optimal differential modulation requires a synchronization).

The output voltage of the first leg (1) is fixed by an open-loop control. The second leg is controlled by a current regulation of which the reference gives the shape of the inductor current. Therefore, the modulation of leg 2 is close to the modulation of leg 1. Nevertheless, a slight difference is required to compensate for the voltage drop across the inductor. A qualitative illustration is given in Fig. 2, with the example of symmetrical PWM applied to the legs.

This operating mode leads to a much lower value of the load inductor, compared to the test configuration of the same inverter with a classical dissipative $R-L$ load. This is another advantage of the opposition method.

In the next section, an example of a digital PWM control stage, dedicated to the opposition method, is described.

2) Operating Modes and Losses Measurement: With this general topology, different operating modes can be tested depending on the references applied to the control stages. A chopper operation is obtained with continuous current (iref) and voltage (vref) references. The injection of ac references at low frequency (a few hertz to a few hundreds hertz) leads to ac operations that better represent inverter applications like motor drives, uninterruptible power system (UPS), or active filters. In that case, the control stage must include an ac generator able to deliver synchronous references with adjustable frequency, amplitude, and phase. More elaborated tests can be conducted, reproducing operating modes corresponding to a real process [11] that describes the operational test of high-power three-phase voltage-source inverters.

Some passive components (L , L_{in} , C_{in}) are present in the power stage of Fig. 2 and contribute to the power losses. The low input power guarantees that the losses in L_{in} and C_{in} are negligible.

A previous parametric characterization of the load inductor is realized (the influence of the switching current ripple is neglected). The direct power measurement on the dc link gives the total losses of the system. The legs' losses are then determined by subtracting the load-inductor losses from these total losses. Because of the minimization of the inductor size, its losses are around 10% of the total, so the error on its characterization is not critical (up to 10% is acceptable) for the final precision. Finally, the losses of one leg can be derived if the symmetry condition (see previous section) is respected.

In order to evaluate the symmetry level, the simplified chronograms of Fig. 3 can be used (with a very low switching frequency in order to make the representation easier). They give an example of sinusoidal modulation with two values of

TABLE I
METHODS OF MEASUREMENTS OF POWER LOSSES FOR HIGH-POWER ELECTRONIC CONVERTERS

	ELECTRICAL METHODS			THERMAL METHODS	
	measurement of instantaneous voltage and current	Input and output Powers measurement	Opposition Method	water flow exchanger	Calorimetric chamber
Principle	Calculations of the instantaneous power then of the average power across any component.	Difference between input and output power $P_{lo} = P_{in} - P_{out}$	Direct electrical power measurement See section II-A	Flow and differential temperature measurements $P_{lo} = \Delta T \cdot Q \cdot C \cdot p$	Not suitable to high power electronics converters
parts involved	Mainly power semi-conductor devices	All the converter	All the converter	Mainly semi-conductor power devices (all components water cooled)	
Characteristics of Experimental test bench	Specific Introduction of current sensors into the lay-out	Not specific	Requires two power stages (each not specific). Specific control stages.	Introduction of sensors on the water flow exchanger	
Instrumentation	High accuracy voltage and current sensors. High precision and high speed acquisition system	Very high accuracy power analysers compatible with the total power	Power analyser compatible with the total losses	Flowmeter and thermal sensors Acquisition system	
Difficulties	Insulation of sensors Noise measurement	full power measurements (rating of current sensors)	No particular difficulties	Accuracy on the differential temperature measurement	
Accuracy	Very dependent on the switching frequency and switching times. Good with low speed devices	Intrinsically bad 1 to few 10%	Very good on the total losses with input continuous power 0.1 to Few per cent Independant of load	Very good on the concerned part at full load 0.1 to Few percent, decrease with load (low losses)	
Application conditions	Power devices with low and medium switching times Periodic steady-state	Usable in case of continuous instantaneous power	See section II-B	Other thermal exchanges negligible (e.g. problem of a partial water cooling on a component like inductor)	
Main advantages in power electronic context	Quasi-direct losses measurement	Very simple	direct loss measurement Applicable in any system. No power source and load required	Direct loss measurement Directly applicable in water cooled systems	
Main drawbacks	Modification of the lay-out	Indirect loss measurement Low accuracy	Used of two power stage	Limited to water cooled systems	
Losses separation	Additional losses measurement depending of the test bench used for full power operation	Additional losses measurement depending of the test bench used for full power operation	Additional losses measurements on passive components and load inductor	Additional losses measurement depending of the test bench used for full power operation	
Comments	The problem of full power operation (source, load) must be solved.	The problem of full power operation (source, load) must be solved.	<i>Not only a loss measurement method. Global testing method allowing also full power testing.</i>	The problem of full power operation (source, load) must be solved.	
Preferred Goals and concerned Converters	Switching losses measurement for semi-conductor devices DC-to-DC converters/any cooling system but difficult with high speed devices	Efficiency measurement Low and medium power DC-to-DC converters/any cooling system	Measurement of efficiency and total losses. Any converter (DC-to-X conversion)/any cooling system	loss measurement for semi-conductor devices Any converter/water cooling system	

the current/voltage phase. The duty cycles on the two legs are supposedly quite identical, and the current ripple in the load inductor is neglected.

a) *Conduction losses*: The duty cycle applied to leg 1 is set by the sinusoidal voltage reference v_{ref} . The conduction sequence of the semiconductor devices, IGBT, and diodes depends on the phase φ between the current and voltage references. If $\varphi = 0$, the maximal current values in the IGBT devices (leg 1) appear for the greater duty cycles, therefore, their ON-state losses are maximal and the diodes' ON-state losses are minimal (conversely for leg 2). The losses' configuration is opposite for $\varphi = \pi$. The ON-state voltage of the diodes and

IGBT are being generally different, the only case of symmetry corresponds to $\varphi = \pi/2$.

Therefore, the method cannot be directly applied here for any value of the phase. This problem can be solved by an evaluation of the ON-state losses derived from the devices' datasheet, or better, by a preliminary static characterization of the devices. It should be noted that the recent generations of devices, especially standard IGBT, present relatively low spread for the ON-state voltage, probably due to the increase of the quality process. If the manufacturers do not define correctly the spread range in their datasheet, the experimental values are generally lower than 10%. Therefore, in the present case, an

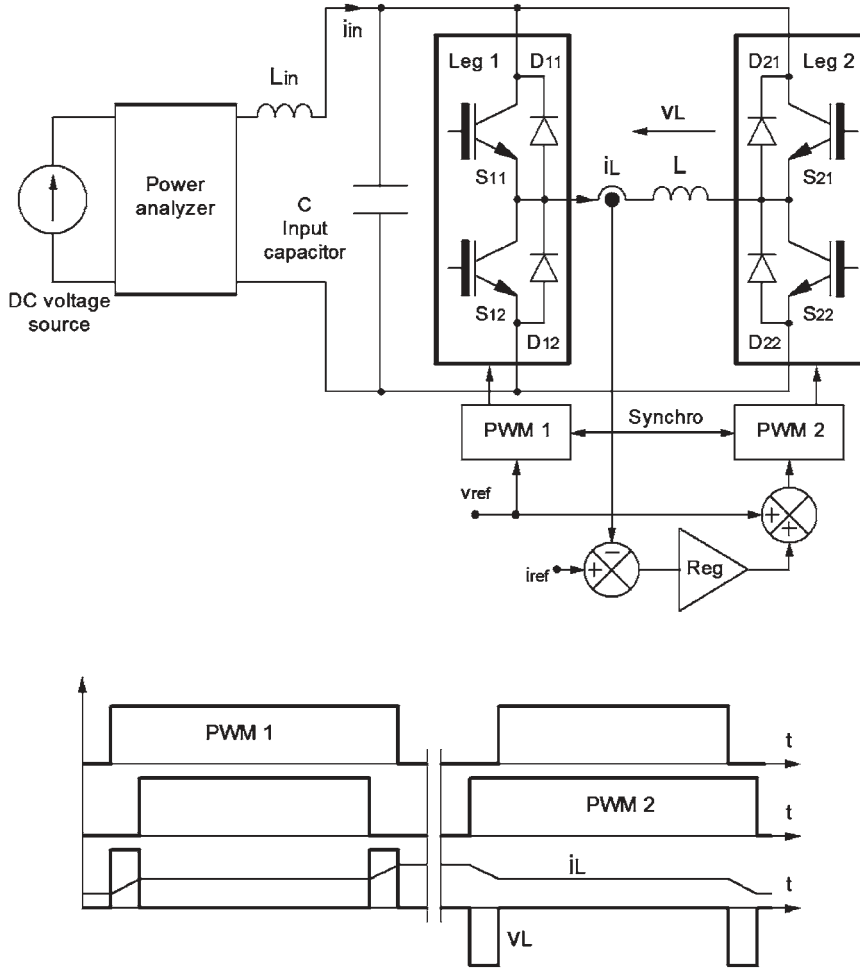


Fig. 2. Opposition of two inverter legs.

analytical estimation is acceptable because the resulting error concerns only the ON-state losses (see the following section).

b) Switching losses: The tendency is quite different for switching losses. Indeed, for fixed switching frequency and current amplitude, the number of switching and the shape of the switched current are the same (typical switching frequency is much greater than illustrated in Fig. 3). Therefore, the switching losses are independent of the phase φ and the system is symmetrical regarding this feature.

In addition, the accuracy of the total-loss measurement allows an easy evaluation of the switching loss dependence versus the switching frequency, if all the other parameters (dc voltage, current and voltage references, phase) are set.

Therefore, by introducing the ON-state voltage correction derived from the devices' data sheet, it can be considered that the application conditions of the method to the inverter legs are very close to the ideal ones, concerning the symmetry. Then, an accurate estimation of the different losses, function of operating parameters, can be easily obtained.

B. Opposition With Two Different Converters

In the previous section, the generic use of the method, by associating two identical stages, had been illustrated. The application conditions can be greatly simplified if a converter,

already characterized, can be associated to the system to be tested.

This reference converter has to be reversible and its electrical characteristics have to be compatible with those of the studied system. The subtraction of the known losses of the reference converters and passive components from the total input losses gives directly the losses of the tested converter. As in the previous configuration, the principle avoids using a dissipative load.

In the next section, one of the applications described will be based on this variant.

IV. APPLICATION EXAMPLES

For ten years, the authors have widely applied this method in research studies concerning medium and high-power devices and converters. Some examples, having various goals, are presented in this section.

A. Soft-Switching Inverters

The first application domain corresponds to successive works made by the authors concerning soft-switching converters and, more particularly, soft-switching inverters [13]–[15]. In this context, the possibility to easily compare classical and

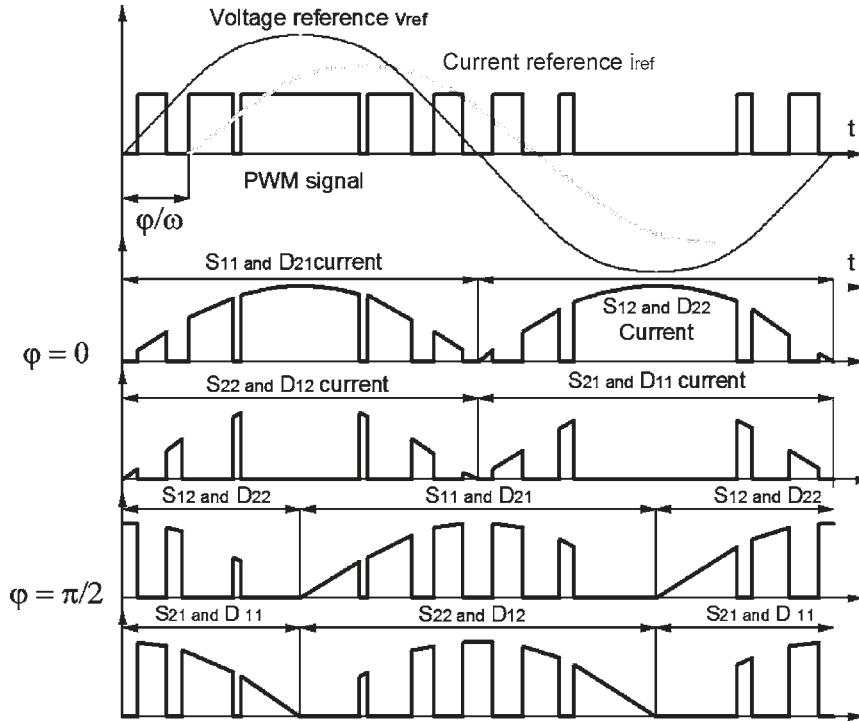


Fig. 3. Conduction modes versus the phase between the references.

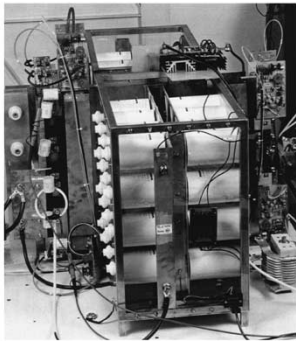
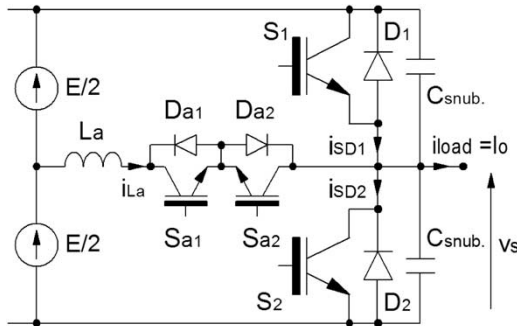


Fig. 4. Basic scheme and layout of the ARCP inverters.

soft-switching inverters performing the same function can be added to the advantages previously emphasized.

1) *Auxiliary Resonant Commutated Pole (ARCP) Inverters:* The method had been first applied to the characterization of IGBT inverters (Fig. 4) using the ARCP topology [12].

The aim was to evaluate this solution in high-power drives (1 MW), with gate turn off (GTO) or IGBT power devices. Two

identical legs had been realized (see Fig. 4) in order to respect the configuration of Fig. 2.

They had been tested under a 600-V dc voltage and a maximal output current of 600 A. The parallel structure of the ARCP cell allows stopping the soft-switching operating mode by inhibiting the auxiliary switches and disconnecting the snubber capacitor. Therefore, the losses, with and without the ARCP cell, can be directly compared. The experimental layout included this function in order to evaluate the loss reduction provided by the ARCP principle. The global results were qualitatively quite similar to those presented in Fig. 6.

The IGBT devices were mounted on a water-cooled heatsink. A second way to evaluate the losses was given by a basic coupled measurement of the temperature and the water flow in the heatsink.

The experimental development had clearly demonstrated the efficiency of the opposition method with the obtaining of accurate total-loss measurements on the power devices (error of a few percent). The thermal method proved to be more difficult to use (estimated error around 20%–30% in that case) because of the limited accuracy of the used sensors and the low differential temperature existing in the high-flow heatsink system. In addition, it had been confirmed that the nominal operation without dissipative load (economy of a bulky load and of its electrical consumption) constitutes a very significant experimental advantage in such a power range.

2) *Multilevel/ARCP Inverter:* A second application example, in the soft-switching context, is associated to an extension of the previous study of which the goal was the mixing of the ARCP cell and multilevels flying-capacitor topologies [17], [18]. In that case, the original specification (1800 V, 100 A) and the complexity of the inverter leg (three cells, Fig. 5) made the realization of the two patterns not easy.

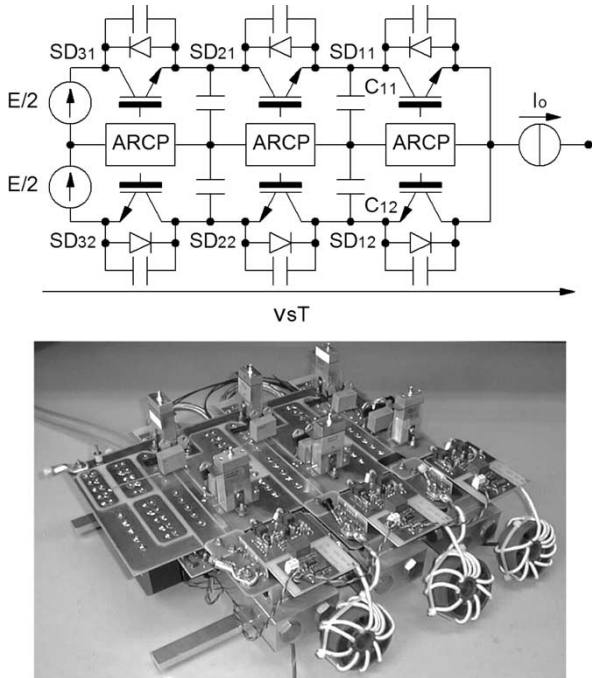


Fig. 5. Basic scheme and layout of the Multilevel/ARCP inverter leg.

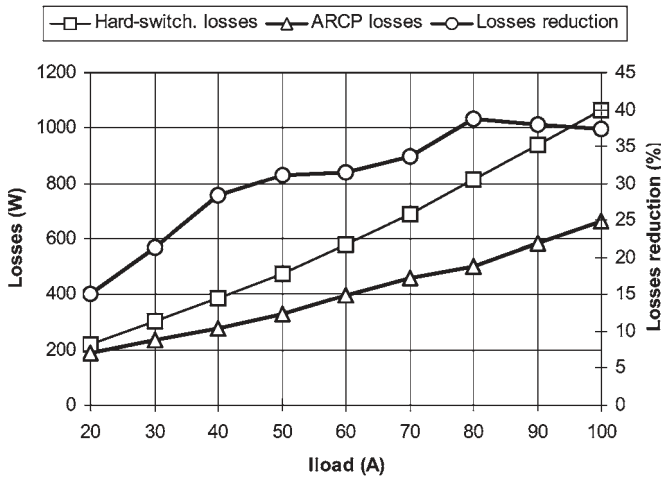


Fig. 6. Loss comparisons derived from the opposition between a hard-switching inverter leg and an ARCP inverter leg.

Therefore, the variant using a reference converter had been used. A three-cell multilevel inverter leg, with similar specifications, operating in hard-switching mode, and characterized in the previous study, had been introduced as the reference leg. Once again, this association had made it possible to obtain directly a measurement of the total losses and a comparison between the hard switching and the ARCP configurations (Fig. 6).

B. Reliability Testing Bench

More recently, a different need had led the authors to apply again the opposition method. This third example concerns reliability test bench [19] designed to stress IGBT-Diode modules in nominal conditions with controlled parameters (voltage, current, temperature, switching frequency). This example will

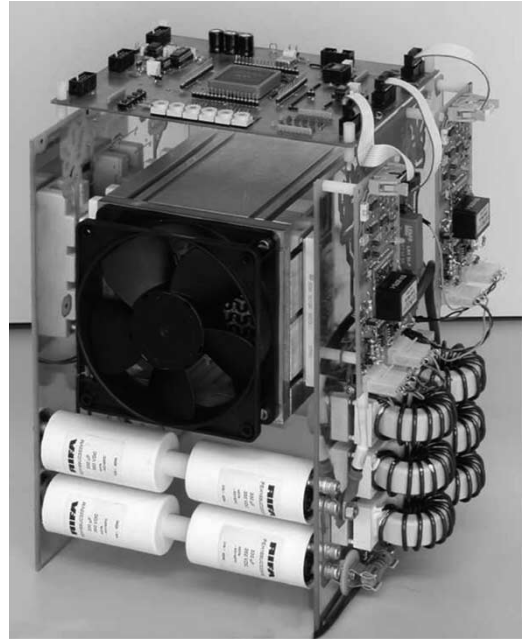


Fig. 7. Layout of the reliability testing bench.

be used to describe more precisely the control strategy that can be applied in the particular operating mode induced by the method.

The reliability tests need to place numerous devices under controlled operating conditions for a long time. The opposition method allows realizing these conditions with minimal power consumption and without any load.

The basic test bench (Fig. 7) includes two full-bridge inverters, of which IGBT modules (devices under test) are mounted on the same heatsink. Each bridge operates in the opposition mode.

They are controlled so as to reproduce the operating conditions of PWM inverters, used in drives or UPS: the current in the load inductor is sinusoidal, with a low frequency (1–200 Hz) and a variable amplitude (0–50 A). The control stage is based on a field-programmable gate array (FPGA) that includes all the functions required (PWM, regulation, reference generations).

When two high-side devices or two low-side devices are simultaneously in the ON state, the current variation is low (voltage V_L equal to the ON-state voltages). Conversely, when diagonally opposite devices are in the ON state, the current variations are much higher ($di_L/dt = \pm U/L$). The control strategy is based on a precise setting of the diagonal ON-state duration, performed by a closed-loop regulation of the load-inductor current.

The scheme of the control stage is given in Fig. 8. It allows adjusting different operating parameters such as the switching frequency, the dead times, the modulation frequency, the output current and voltage amplitudes, and the output current/voltage phase.

The first part of this stage generates the low-frequency references of the current and voltage (sinusoidal in that case). They are provided by memorized tables, read with an adjustable time base, and they can also be phase shifted. Their amplitudes can be adjusted by means of multipliers.

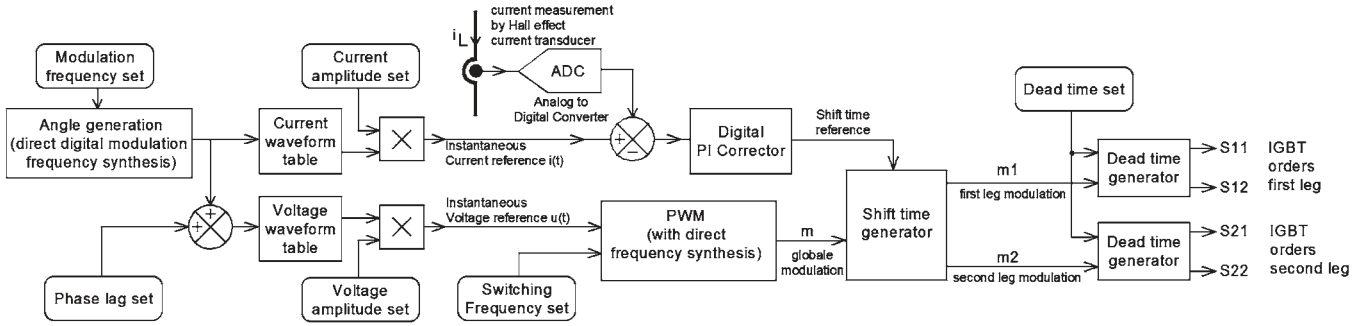


Fig. 8. Digital controller diagram.

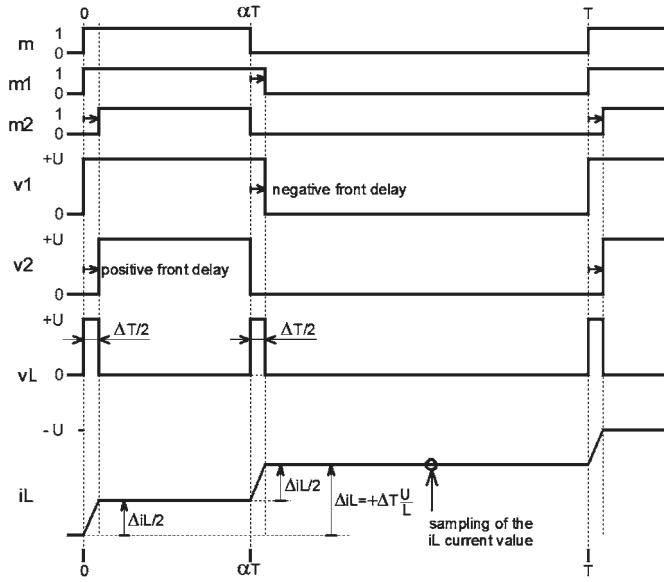


Fig. 9. Modulation signals, inductor voltage, and current evolution.

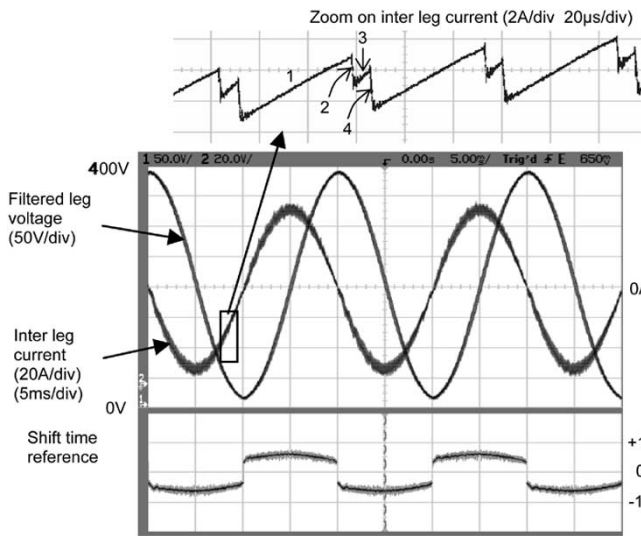


Fig. 10. Experimental waveforms in the test bench.

The main control signal $m(t)$ is generated by a PWM stage using the voltage reference (Fig. 9).

As it had previously been mentioned, the diagonal ON-state configurations create high current variations ($\pm 10 \text{ A}/\mu\text{s}$ with $U = 400 \text{ V}$ and $L = 40 \mu\text{H}$). In order to respect the current

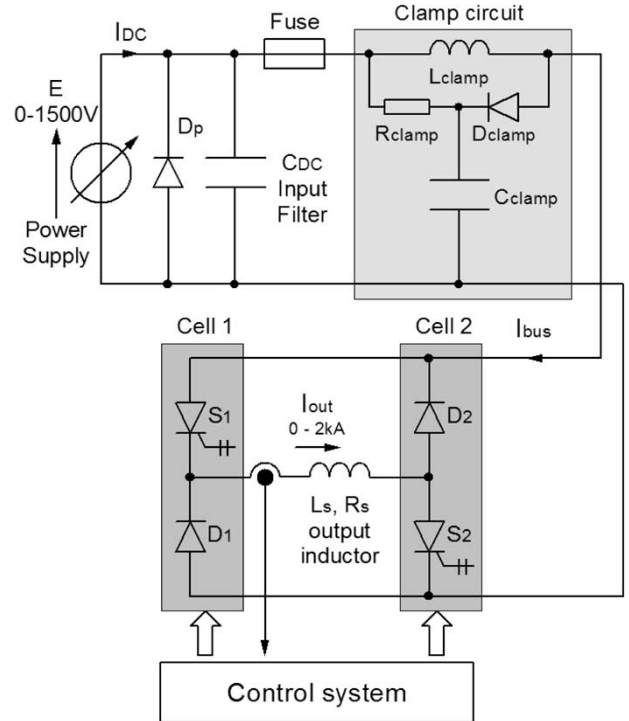


Fig. 11. Test-bench power-stage circuit.

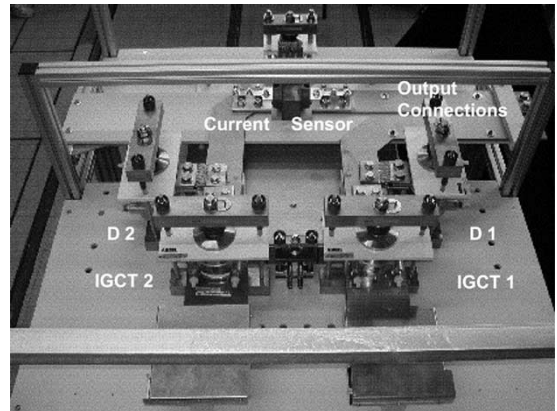


Fig. 12. Test-bench layout.

reference, the closed-loop regulation ensures an accurate setting of the diagonal ON-state duration with a time-resolution of 50 ns and an amplitude resolution of 0.5 A. To avoid the introduction of a low-pass filter, the sampling is realized

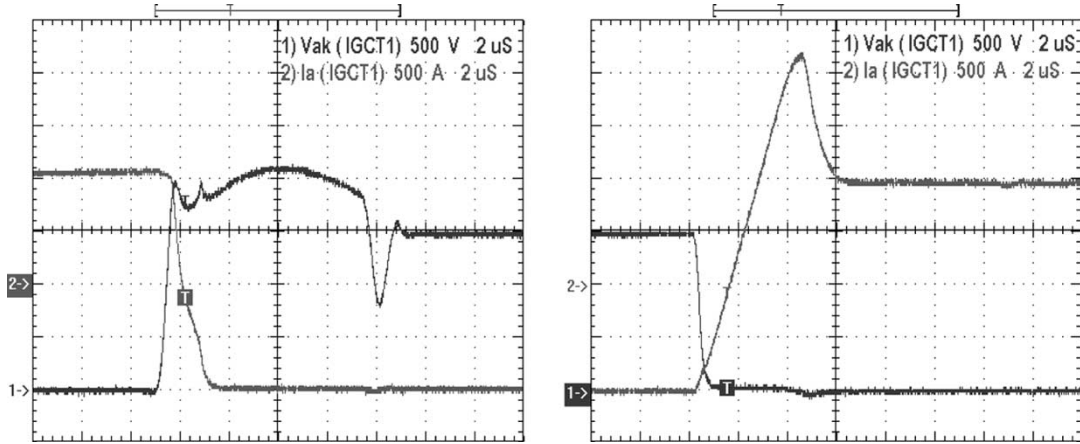


Fig. 13. IGCT turn-off and turn-on waveforms (dc-link voltage 1.5 kV, dc output current 2 kA).

between the two more distant switching points (Fig. 9), when the current variations are very low.

From the closed-loop error, a digital PI corrector calculates the shift time to apply between the switching of the two legs and, therefore, to control the diagonal ON-state durations. The classical distortion, resulting from the dead times around the zero crossing of the current, is corrected by setting the sign of the integral action equal to the sign of the current.

The theoretical control signals m_1 and m_2 , dedicated to the legs, are built by combining the calculated shift time and the main signal $m(t)$. At last, the introduction of the dead time on the signals m_1 and m_2 gives the final signals transmitted to the IGBT drivers.

The oscillograms of Fig. 10 show an operating point, corresponding to a 400-V dc-link voltage and to a sinusoidal modulation. The current (50 A–50 Hz) is phase shifted to 90° with respect to the voltage fundamental (see filtered voltage). On the top, a temporal zoom emphasizes the current waveform, with the successive low (1, 3) and high (2, 4) current variations. On the bottom, the shift-time reference clearly shows the correction of the dead-time effect, synchronized with the current sign.

At present time, this bench allows the test of 50 A–600 V IGBT modules operating in the real conditions of a few 10-kW power stage, with an overall consumption close to 1 kW (total losses of the two bridges).

The aim of these test benches is to stress in real conditions the devices up to the first failure (controlled conditions) in order to build parametric reliability models. To detect potential aging indicators, the main characteristics of the devices are regularly measured. New test benches are progressively realized but the tests are still in progress and must be extended to obtain full results that can be published.

C. High-Power Test Bench for the Characterization of Experimental Low-Voltage Integrated Gate-Commutated Thyristors (IGCTs)

The last example also concerns the characterization of power devices. In this case, it is mainly the power rating of the considered devices (IGCT) which makes, one more time, the opposition method very attractive.

1) *Test-Bench Presentation:* The switching and ON-state characteristics of power semiconductors are usually obtained by means of several standard tests (continuous conduction and single or double switching tests) that drive the components to their nominal ratings but not in the real working conditions (i.e., switching frequency, cooling systems). Usually, the test conditions (junction temperature, dc-bus voltage, di/dt conditions, and so on) do not match the real working conditions of semiconductors in power converters, so the designer must get an estimate of the semiconductors' real losses by extrapolation methods. A test bench using the opposition method for power converters has been developed to characterize the ABB's experimental low-voltage IGCTs and diodes (3.3 kV) in real working conditions (continuous switching operation, rated current, and voltage). The topology of the power converter (Fig. 11) consists of two PWM-controlled switching cells (IGCT–diode) in an opposition configuration to manage the energy transfer between the input capacitor, C_{dc} , and the output inductor L_S [20], [21]. An RLCD clamp circuit is used for both switching cells to limit the di/dt at the turning on and the over-voltage at the turning off of the IGCTs. Each switching cell is controlled independently.

The first switching cell works in PWM mode controlled by the dc output current control loop (duty cycle $D_1 > 0.5$ in steady state), and the second switching cell works in an open loop at a constant duty cycle ($D_2 = 0.5$).

The dc-link voltage can be adjusted between 0 and 1.5 kV by means of the voltage-controlled input-power supply while the dc output current closed-loop control allows the switching current selection from 0 to 2 kA. Furthermore, the switching frequency can be set up from 375 to 2 kHz in several steps by means of the FPGA-based PWM modulator of the control system (dip-switches selection). Also, the cooling conditions of semiconductors (water flow) can be changed; thanks to a water pump supplied by an open-loop speed drive. The test bench is instrumented to perform oscillographic measurements (oscilloscope and PC interface, high-bandwidth current probes and voltage differential probes), as well as calorimetric measurements (temperature probes, flowmeters), to allow semiconductor switching and ON-state characteristics evaluation at the selected conditions. Also, a power analyzer is used to measure

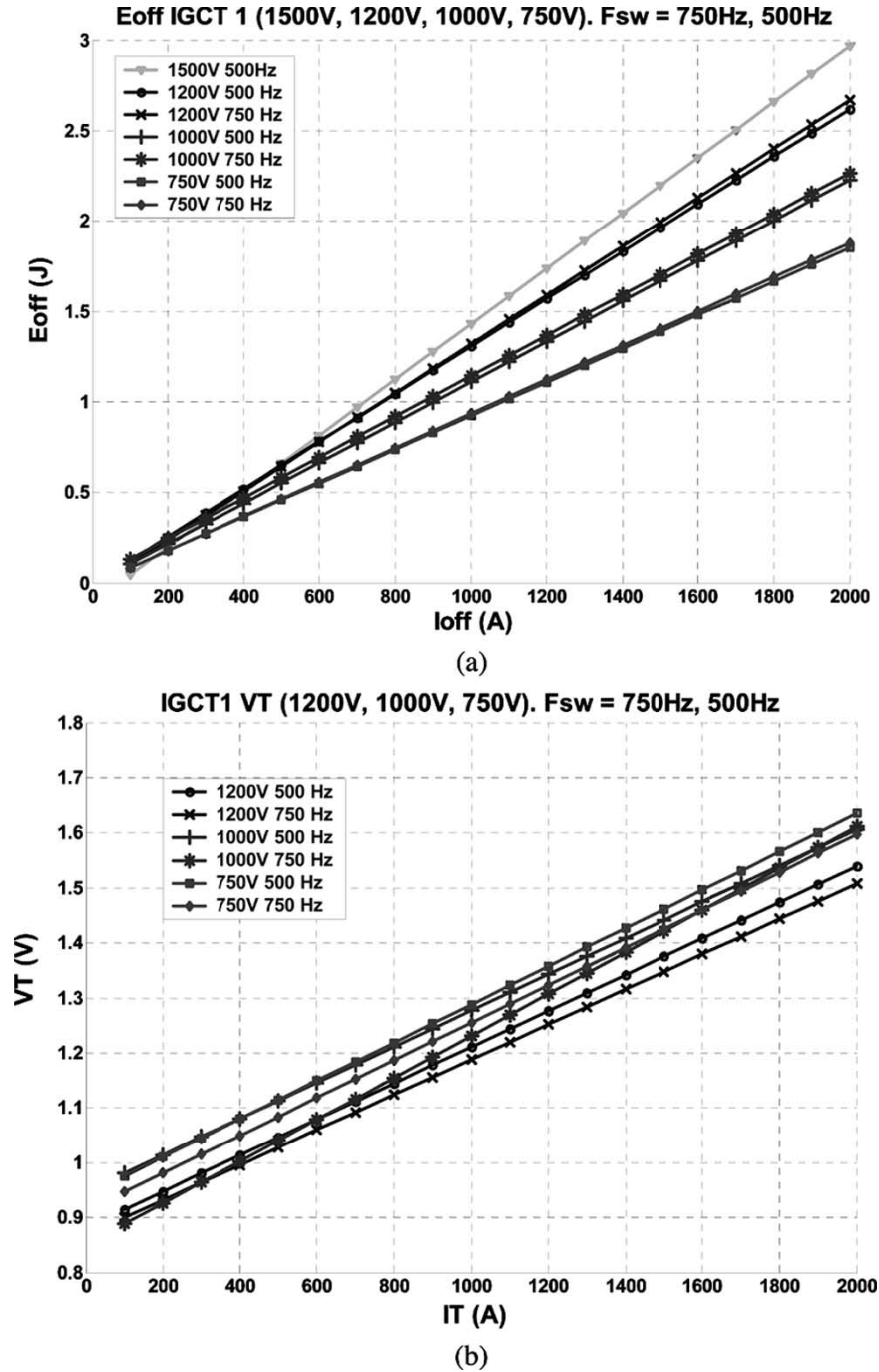


Fig. 14. IGCT characteristics. (a) Turn-off energy versus turn-off current. (b) IGCT ON-state characteristics.

the total power consumption of the test bench to identify the power losses in other components of the test bench (clamp components, output inductor, current sensor, and so on).

Fig. 12 shows the test-bench layout. The main semiconductors (ABB experimental 3.3-kV 5SHY 45L3300 IGCTs and 2.5-kV 5SDF 10H2500 diodes) are arranged to allow simple mount/dismount procedures when semiconductor replacement is required (one semiconductor per mechanical clamp). Furthermore, a solution provides thermal isolation between semiconductors for a loss evaluation by the calorimetric method.

2) *Characterization Method:* Two water circuits are established in the test bench. One of them is used to cool the main

semiconductors (one branch for each switching cell with the IGCT and its freewheeling diode in series in the water circuit).

The other one is used to cool the clamp-circuit components and the output inductor (a branch for the clamp diode and resistor and a branch for the output inductor). The water flow on each branch can be adjusted by means of the water-pump speed drive or manual valves. Moreover, several flowmeters and temperature probes are connected in both water circuits to allow the total-loss evaluation on each water-cooled component by measuring the water input and output temperatures and the water flow applying the calorimetric method. To obtain the switching energies, first, the voltage and the current waveforms

are transferred from the oscilloscope to a PC. Then, the waveform data are processed to remove the offset level of the signals. Finally, the power and energy waveforms are mathematically obtained and the switching energies are derived.

Fig. 13 shows the steady-state operation waveforms for the 1.5-kV dc-link input voltage and 2-kA dc output current at 500 Hz of switching frequency. Parameter identification of the defining coefficients for the switching and ON-state characteristics was obtained from both electrical and thermal measurements. A calorimetric method is applied to evaluate the ON-state characteristics of the low-voltage IGCTs and their diodes.

First, the total losses of the semiconductor are obtained for the given working conditions, and then the conduction losses are mathematically derived by subtracting the electrically measured switching losses from the total losses.

Alternatively, the conduction losses may be obtained by performing two tests at different switching frequencies keeping the rest of the working conditions constant (dc-link voltage, dc output current, duty cycle). If the variation of the conduction loss variation versus the junction temperature (due to higher switching losses) is neglected and the switching losses are considered proportional to the switching frequency, the conduction losses can be mathematically separated. Fig. 14 shows the experimental results obtained with the test bench. For a 1.5-kV dc bus voltage, a 2-kA output current, and a switching frequency of 750 Hz, the total input power is only 30 kW.

V. CONCLUSION

After a recall of the opposition-method principles and their adaptation to the test of power electronic converters, this paper has described some typical examples of application corresponding to varying projects in which the authors have been implicated. The goals are quite different and concern either the converter characterization or device (IGBT or IGCT) characterization. In each case, the simplification of the experimental environment and the quality of the achieved characterizations demonstrate the global interest of the method, which is still, one century after its first applications to the test of electric motors, a powerful experimental tool.

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