A high current multicell converter using InterCell Transformer

Modelling and design of a 1200 amps module - 12 cells prototype

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ABSTRACT. *In this paper, the study and implementation of DC/DC power converter is presented. It is a 12 cells interleaved buck converter with magnetic coupling using InterCell Transformer (ICT). The aim of this application is to use the converter as a regulated current source. Its principle is based on a transient heating of HVDC cable or the outer conducting screen by Joule effect for generating a thermal pulse which, by crossing the insulation, generate a capacitive current measured by a current amplifier. An experimental prototype was built in order to validate the application principle directly on aged power cable loops. Both cases of inner and outer heating were validated and the thermal step current was measured by current amplifier.*

RÉSUMÉ. *Cet article présente l'étude et la réalisation d'un convertisseur DC/DC de forte puissance. Il s'agit d'un convertisseur multicellulaire entrelacé constitué de 12 cellules en parallèle dont les inductances de liaison sont couplées entre elles en utilisant un transformateur intercellule (ICT). Le but est de faire fonctionner le convertisseur comme une source de courant régulé. Le système est conçu pour générer des impulsions de courant de 1200 A durant une à deux secondes, à injecter dans l'âme conductrice (et/ou l'écran extérieur) d'un câble haute tension afin de générer une onde de température qui va diffuser dans l'isolant et donner naissance à un courant capacitif dit « courant d'onde thermique ». Un prototype expérimental a été conçu afin de confirmer et valider le principe de l'application sur des tronçons de câbles haute tension. Les deux cas de figures (chauffage par l'âme et chauffage par la gaine) ont été traités et les courants d'onde thermique ont été mesurés à l'aide d'un système de mesure très faible courant.*

KEYWORDS: *interleaved buck converters, magnetic coupling, Thermal Step Method (TSM), InterCell Transformer (ICT), HVDC cable.*

MOTS-CLÉS : *convertisseurs multicellulaires entrelacés, couplage magnétique, transformateur InterCellule (ICT), câbles HVDC, méthode de l'onde thermique (MOT).*

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1. Introduction

Space charge measurement on DC power cable insulation can be performed by using the Thermal Step Method (TSM), which consists to generate a low temperature rise by injecting a high current in the cable core (Cernomorcenco *et al.*, 2008; Notingher *et al.*, 2009). The resulting thermal wave diffuses into the insulation, and the induced displacement current through the dielectric is measured after the heating current has been turned off. The electric field distribution across the insulation is then extracted from the acquired displacement current (Notingher *et al.*, 2009). In (Agnel *et al.*, 2001), a method based on an AC heating transformer is presented. Such a setup has been successfully used to assess long-term ac aged cable loops (Castellon *et al*., 2009).

However, for long cables of strong section, the inductive reactance of the conductor becomes very important, and a huge apparent power is needed to produce the required heating current. Thus, the inductance of the conducting core does not allow to reasonably considering the use of such a principle on more than several meters of high voltage cable. Another way to produce a high current during a short period of time is to use a DC/DC converter in transient regime. Therefore, in medium term, we aim to set up a measurement installation including a robust, efficient and compact DC/DC converter which must be able to inject 12 kA to be used for characterization of one hundred meter of high voltage cable with a conductive core of 2500 mm².

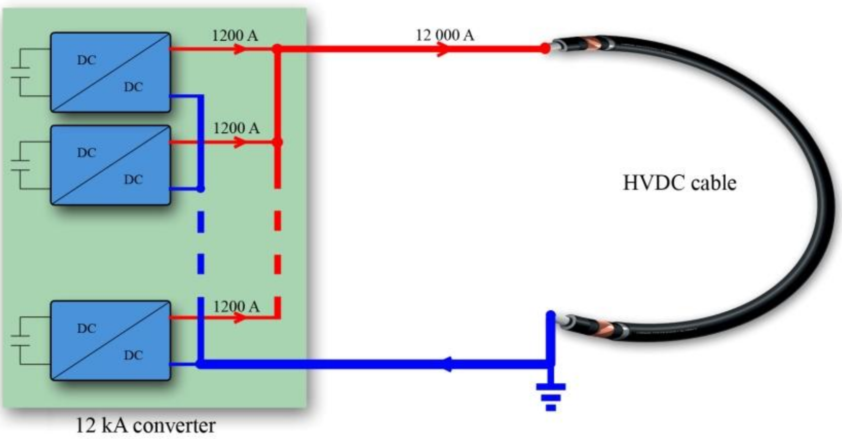


Figure 1. 12 kA converter topology

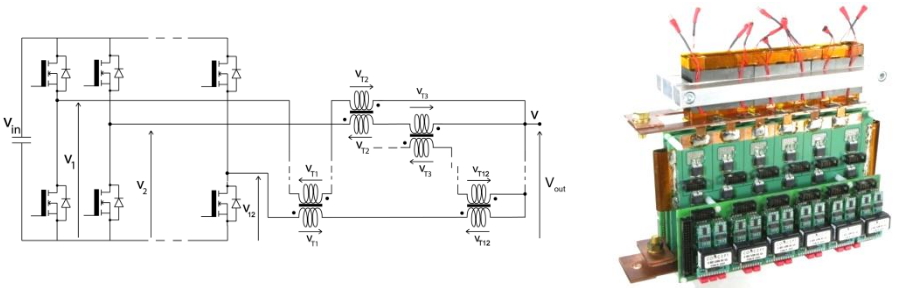
Designing and integrating such a converter is a challenging task, both in terms of power electronics and low signal instrumentation. Accordingly, the 12 kA converter (Figure 1) will consist to a modular system that will be composed by ten “low voltage/high current DC/DC converters" (ten 1200 A modules), supplied separately by super-capacitors (48 V, 165 F). Each module is a 12-phase interleaved buck converter with magnetic coupling by means of ICT. A current control loop will impose the total current waveform in the power cable conductive core. We aim to set up this application by using interleaved converters, since they are an interesting alternative for many applications due to their advantages in terms of power density, dynamic response, output ripple cancellation, thermal management and optimized design. However, the drawback of this technique is the current ripple in each channel that increases with the number of parallel phases. Recent works (Li *et al.*, 2012; Wibowo *et al.*, 2008; Gonzalez *et al.*, 2010) have shown that to overcome this drawback, coupled inductors can be used and the converters effectiveness can be improved. The magnetic coupling can be achieved by means of single monolithic transformer or separate transformers. The use of InterCell Transformers topology greatly improves input/output waveforms quality, and increases converter compactness (Zumel *et al.*, 2005; Forest *et al.*, 2007; Labouré *et al.*, 2008). The total current ripple filtering is naturally made by the ICT coupler without any additional passive filter. In this paper a 12-phase/1200 A current controlled converter is presented. It is an enhanced version of the first 600 A / four phase module presented in (Darkawi *et al.*, 2012). Firstly, the hardware setup is presented, and secondly the application principle and results are then presented in order to validate the experimental prototype for aged power cable loops diagnostic by mean of the thermal step method. The main purpose of the installation is to be a "portable installation for space charge measurements on full-size high voltage cable loops".

2. System overview and operation

2.1. Description

The main objective of the proposed setup is to allow energy transfer from the energy source (Ultracapacitors) to the power cable conducting core and to generate the thermal step by Joule effect. As the final converter will be used for space charge measurement on cable with lengths up to a hundred meter and conductors sections up to *2500 mm²*, the heating current injected will be close to *12 kA* during one or two seconds. The elementary module should produce up to *1200 A*. Each module consists of twelve commutation cells and will be supplied by ultracapacitors (165F, 48V), which provide the necessary energy to produce the thermal step. As is said in the introduction, this *1200 A* module is an enhanced version of the 600 A, its principle is based on the parallel association of twelve commutation cells (buck converters) with magnetic coupling by means of intercell transformers mounted in cyclic cascade as it can be seen in Figure 2a. As the first prototype, this module was realized with magnetic circuits made from standard E58/11/38 Planar. A circuit E is considered as two adjoining U. The number of turns per winding was set to $N = 2$. This number allows a simple construction with copper sheet, cut to optimize the electrical connections between the different transformers as shown in Figure 2b.

Knowing that each phase will provide up to *100 A* during a *2 s* transient phase, and to reduce conduction loss and making compact the power converter, high power density MOSFETs (IRLS3036, *60 V - 240 A* with very low $R_{DS(on)}=1.5m\Omega$) have been chosen.



(a) (b)

Figure 2. 12-phase parallel multicell converter using ICT (a) simplified equivalent electrical circuit, (b) designed experimental prototype (2l, 2,5kg).

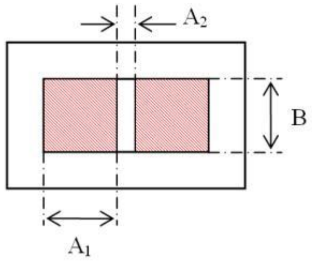


Figure 3. Elementary transformer winding configuration

In order to predict the output current ripple, we can evaluate the total leakage inductance *(L_{tot})* of the 12-cells Inter-Cell transformer in simplified 2D scheme (Figure 3) by:

$$L_{tot} = \frac{1}{12} L_{cell} = \frac{1}{12} l_{mean} \mu_0 \frac{N^2}{B} \left[A_2 + \left(\frac{2A_1}{3} \right) \right] = 19.6nH \qquad (1)$$

Where N is the number of turns, μ_0 the air permeability, l_{moy} the winding mean length, A_1, A_2 and B are defined in Figure 3. ($N = 2$, $A_1 = 9\ mm$, $A_2 = 2\ mm$, $B = 6.5\ mm$, $N = 2$, $l_{mean} = 38mm$). Taking account to the relation (1), the maximum output current ripple could be evaluated by relation (2) without any additional output filter:

$$\Delta I_{out_{\max}} = \frac{V_{in}}{4\times 12^2 L_{tot} f_{sw}} = 85A \tag{2}$$

Where V_{in} is the input voltage and f_{sw} the switching frequency *(V_{in} = 48 V and f_{sw} = 50 kHz)*. In this case the maximum the output current ripple ration when I_{out} *= 1200 A* is theoretically $\Delta I_{out}/I_{out}$ = 7%.

With the analytical model of cyclic ICT for multiphase coupled converters design, applicable for any number of cells, developed and described in (Darkawi *et al.*, 2012), the magnetic field matrix can be determined in order to find out the flux density peak value that can saturate ferromagnetic-core. It has been demonstrated that the value of the flux density B_{max} (obtained for a duty cycle of 50%) increases with the number of phases. Accordingly, care must be taken in the power converter design parameters definition. However, a significant reduction of the induction peak value can be obtained by applying permuted mode described in (Forest *et al.*, 2007).

Modelling the ICT allows to determine the transformers voltage matrix, the flux and the magnetic field for any number of cells (even or odd). It also leads to predict the inductors behavior. Hence, the magnetic coupler parameters such as the switching frequency, the magnetic core geometry and the number of turns of the windings can be correctly calculated. Accordingly, in the case of an even number of commutation cells, particularly for k=12, the transformer voltage matrix is given by relation (3).

$$\begin{bmatrix} v_{T1} \\ v_{T2} \\ \vdots \\ v_{T12} \end{bmatrix} = \frac{1}{24} \begin{bmatrix} m_1 & m_2 & \cdots & m_{12} \\ m_{12} & \ddots & \ddots & m_{11} \\ \vdots & \ddots & \ddots & m_2 \\ m_2 & m_3 & \cdots & m_1 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_{12} \end{bmatrix} \tag{3}$$

$$m_i = 2\left(6-i\right)+1 \tag{4}$$

$v_i = V_{in} \quad for \quad t \in \left[\frac{i-1}{12}T_{sw}; \left(\frac{i-1}{12}+D\right)T_{sw}\right]$ and zero elsewhere, Here, D is the duty cycle and $T_{sw} = 1/f_{sw}$ and f_{sw}, the switching frequency.

If A_{eff} is the magnetic core effective area, the flux density expression for a 12-cell ICT is given by (5). And for a duty cycle of *50%*, the maximum magnetic induction can be expressed as indicated in relation (6).

$$B = \frac{1}{24NA_{eff}} \int \left[\sum_{i=1}^{12} \left(2\left(6-i\right)+1\right).v_i \right].dt \tag{5}$$

$$B_{\max} = \frac{9V_{in}/2}{24NA_{eff}\,f_{sw}} \qquad (6)$$

In order to validate this model, the voltage measured across the transformers windings were compared to calculated voltage waveforms both for standard mode and permuted mode according to the following parameters: f_{sw}*=45 kHz*, with *N = 2*, A_{eff} *= 154 mm²* , V_{in} *= 4 V and D=0.5*. Figure 2 shows that both experimental and simulation results are extremely closed, we have exactly the same waveforms calculated and measured. It is shown that the peak to peak value of the transformer voltage is *4 V* by applying the permuted mode instead of *12 V* in standard mode. This reduction by three is also available for the flux density through the magnetic core.

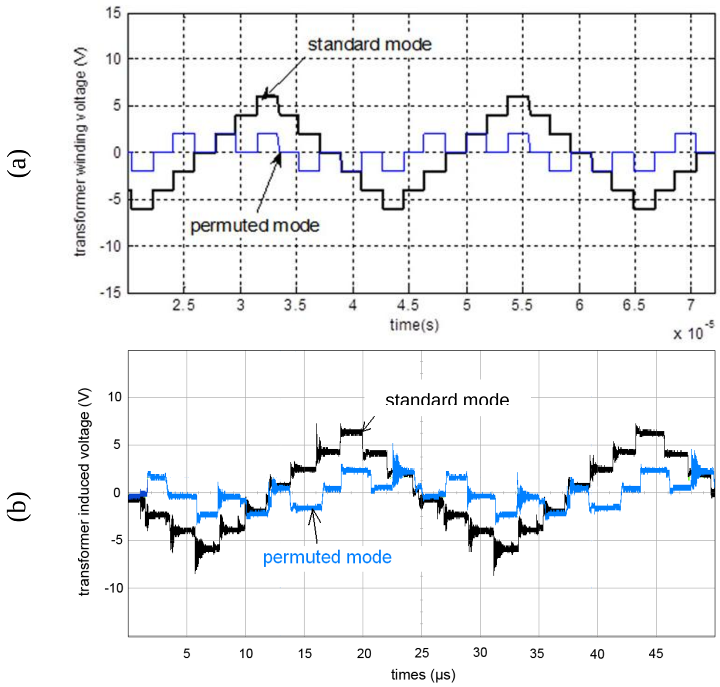


Figure 4. Transformer voltage (V) – standard mode and permuted mode (a) Simulation using the analytical model, (b) Experiments

Firstly, the experimental prototype has been tested for injecting up to *1100 A* DC current during *1 s* in a *3* meters power cable. The test has been done without any current control loop. Consequently, because of the discharging of the ultracapacitors, the current decreases from *1100 A* to *700 A* during the test as it is shown in Figure 5a. However, the use of the ICT coupler guarantees the waveforms improvement without any aditional passive element particularly the output current ripple minimization. Figure 5a and Figure 5b show that the measured output current ripple is quasi equal to zero (less than *1%)*. To maintain the output current constant during the test, a sensorless method based on a linear compensation of the duty cycle has been tested. Therefore, for a current pulse of *200 A* during 0.5 s as it is shown in Figure 5b, the output current decay (decrease of 25 A) has been compensated by applying the numerical duty cycle linear compensation technique.

(a)

(b)

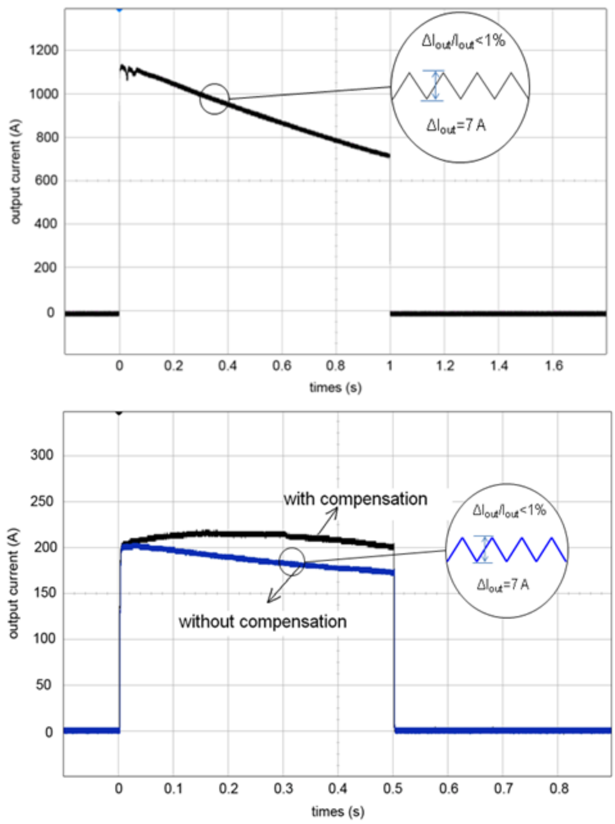


Figure 5. Output current (a) 1.1 kA *heating current generation without any regulation, (b)* 200 A *heating current generation with duty cycle compensation*

Its principle is illustrated in Figure 6a and Figure 6b. The linear compensation is based on calulation of the two values of the duty cycle, at the begining and the end of the current pulse duration. Knowing the load characteristics (inductancce and resistance), and the input voltage, a duty cycle of D_0 is chosen in order to obtain the desired outuput current, since $I_{out} = V_{out}/R$, and $V_{out} = DV_{in}$. Initially at (t=0), $V_{out1} = D_0 V_{in1}$. While, the ultracapacitors are discharging, V_{in} decreases and at the end of the pulse duration, V_{out2} = D'*V_{in2}. If t_{pulse} is the pulse duration in second, D(t) = D_0 + kt, where k = (D'-D_0)/t_{pulse}. This method works well while either the "current pulse duration" or the "current decay" are not significant because of the ultracapacitors discharging is exponential (V_{in}(t) = V_{in1}exp(-t/tau), where tau is the time constante of the equivalent circuit composed by the ultracapacitors ESR, the power converter and the load). The parabolic shape of the output current is due to the output voltage V_{out} = D(t)*V_{in}(t).

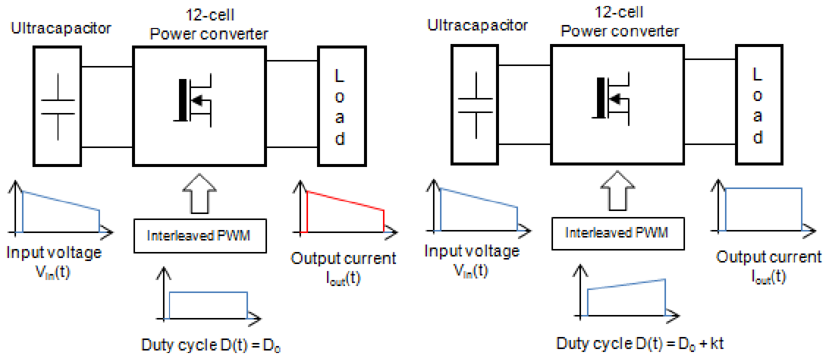


Figure 6. Output current regulation based on Duty cycle linear compensation principle

To maintain the output current constant, we propose an automatic numerical current control loop. We aim to maintain the mean value of the output voltage by automatically adjusting the duty cycle as it is presented in Figure 7, since the heating current is the ratio of output voltage by the cable core resistance.

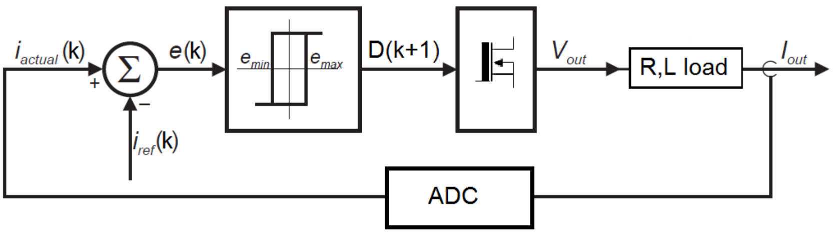


Figure 7. Automatic compensation current controller bloc diagram

The measured current is firstly converted to a digital value by means of a 12-bit Analogical to Digital Converter. The current is regulated using the fully digital automatic compensation current controller which has been designed and implemented in a DE2 FPGA board. The numerical duty cycle varies from 0 to 1000 (0 to 100%). This current controller is special regarding its operation mode. Its principle is described in Figure 8, while the actual current is lesser than the upper limit (the output voltage is lesser than the required V_{out}) the duty cycle is incremented *(D(k+1)= D(k) +1) in order to increase the mean value of* V_{out}, and while the actual current is greater than the lower limit (the output voltage is greater than the desired V_{out}), the duty cycle is decremented *(D(k+1) = D(k)-1) in order to decrease the output voltage mean value.*

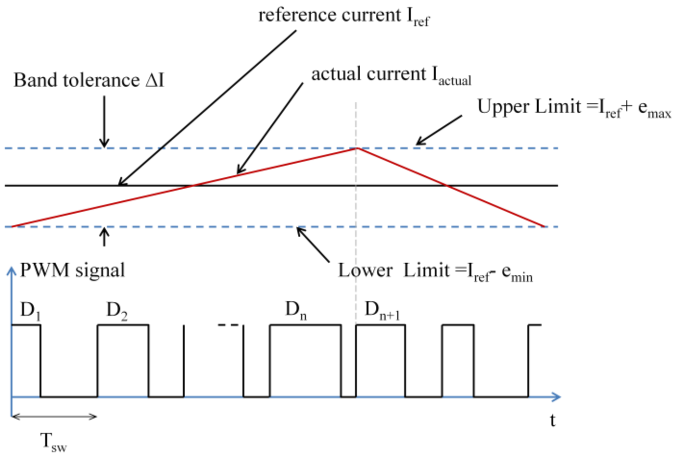


Figure 8. Automatic compensation current controller waveforms

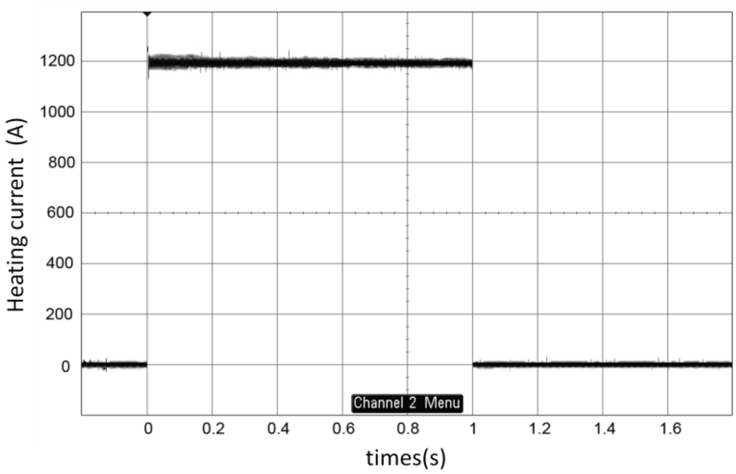


Figure 9. Pulse of 1200 A *regulated heating current during* 1 s

The resulting current controller works well and the output current is well regulated, then the output current could be now maintained to the value of 1200 A even if the ultracapcitors are discharging. Figure 9 shows a pulse of 1200 A – 1s regulated current delivered by the power converter. The ability of the multicell power converter to generate regulated transient current has been validated by multiple experiments. Such a high current could be used for cable heating.

3. Application: power cable transient heating and thermal step current measurement and validation

3.1. Application principle

To generate the temperature gradient in the dielectric by Joule effect, the energy is transferred from the energy source (ultracapacitors) to the cable core or conducting screen. The ultracapacitor module is a Maxwell *BMOD0165048 (48 V – 165 F)* consisting of eighteen *3000F – 2.7 V* ultracapacitors connected in series. The maximum energy (E_{tot}*=190kJ)* that the module is able to store is:

$$E_{tot} = \frac{1}{2} C V^2 \tag{7}$$

The energy required to produce a quick temperature rise ΔT_0, of is:

$$Q = m C_p \Delta T_0 = R I_h^2 t_h \tag{8}$$

where m is the mass of the cable conductor, C_p its heat capacity, R its résistance, I_h the heating current and t_h the heating time (supposed short enough to trigger an adiabatic regime).

The capacitive signal issued by the cable insulation when crossed by the thermal wave produced by the heating current is a function of:

– the electric capacitance C_{diel} of the radial heated region;

– the electric field repartition within the material in the radius direction *E(r);*

– the temperature distribution across the insulator in the radius direction: $\Delta T(r,t)=T(r,t)-T_0$ (T_0 is the cable temperature before applying the thermal step).

The equation governing the dependence of the measured capacitive signal, called thermal step current, is:

$$I(t) = -\alpha C_{diel} \int_{R_i}^{R_e} E(r) \frac{\partial \Delta T(r,t)}{\partial t} dr = k(t) \Delta T_0 \tag{9}$$

where α is a material constant related to the insulation contraction (or expansion) and to its permittivity variation with temperature, R_e and R_i are the external and internal radii of the insulator, and ΔT_0 the temperature rise.

We have therefore checked the proposed buck converter set up for its ability to provide thermal step currents, which are base for the determination of the electric field repartition E(r). The parameters of the used power cable are detailed in Figure 10. Before the measurements, the cable loop has been dc conditioned under thermal gradient in order to allow the appearance of a residual electric field across the insulation. Thus, the two ends of the cable loop have been connected to constitute a single turn secondary of a heating transformer, then an RMS ac current of *220 A* has been set up through the cable to generate a thermal gradient of *40°C* between the cable core and the outer semiconductor (*90°C* on the core and *50°C* on the external semiconductor). In the same time, *a 30 kV* dc voltage has been applied to the cable core.

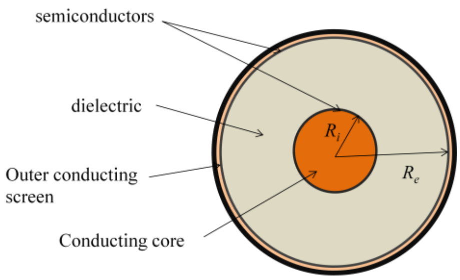


Figure 10. Description of the 12/20kV power cable used for the experiments (cable length: 3 m, section of the conducting core: 50 mm2 R_e =10.25 R_i mm= 5.2 mm)

After three days, the ac current has been switched off and the cable has been left to come back to room temperature with the dc voltage still applied, in order to keep as much as possible of the charge accumulated in the insulation and to “freeze” the polarization gradient. Then, the cable has been transferred to the power converter bench for thermal step measurements.

3.2. Thermal step measurements by heating the cable core (inner heating)

Space charge measurements by the thermal step method using the Joule effect are classically made by injecting the heating current in the cable conducting core. Thus, the thermal wave diffuses radially from the inside part of the insulation toward the outer region. This method, called “inner heating”, has been presented in (Agnel *et al.*, 2001), where an AC current has been used; in (Darkawi *et al.*, 2012), we have demonstrated the benefit of using DC/DC converters to produce DC heating current.

Figure 11 presents the diagram of the thermal step measurement installation used in the present work, including the designed power converter (which generates the thermal wave by transient Joule heating) and the current amplifier (for measuring the thermal step signal). Because of EMC reasons, the pico-ampermeter ground is connected to the cable core.

Measurement results obtained with a heating dc current of *1,2 kA* are shown in Figure 12. It comes out that the amplitude of the measure signal is proportional to the thermal gradient (heating duration), as predicted by Equation (9). Indeed, the signal amplitude is about *250 pA* for a heating duration of *1 s* and of *500 pA* for a heating duration of *2 s*.

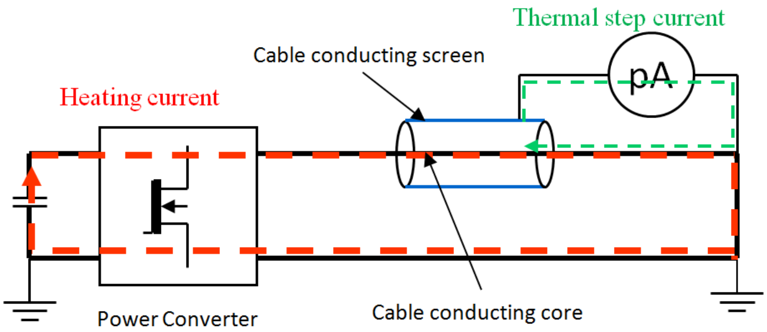
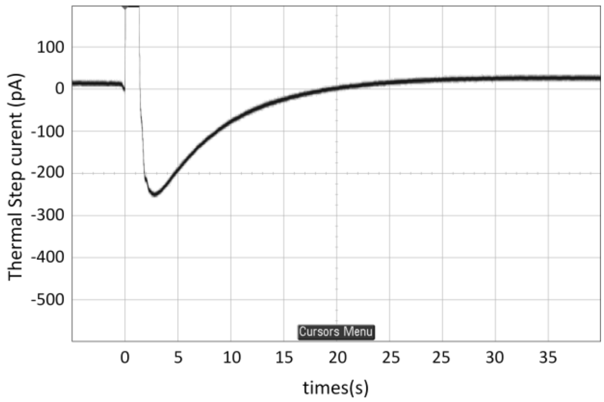


Figure 11. The heating current provided by the controlled discharge of the ultracapacitor is injected in the cable core to generate a radial thermal wave across the insulation, then the thermal step current is measured by the current amplifier

(a)



(b)

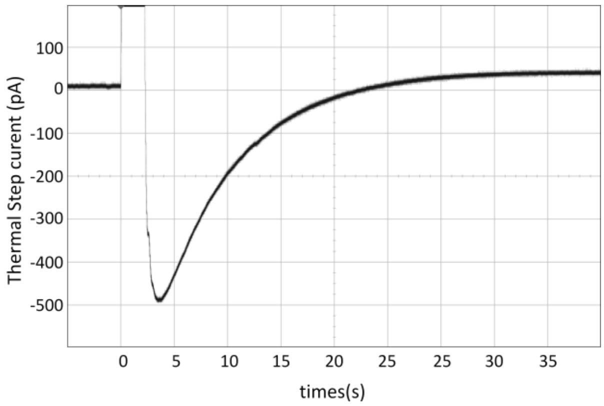


Figure 12. Thermal step currents issued from the dc-conditioned cable (case of inner heating) with:(a) 1200 A heating current during 1 s; (b) 1200 A heating current during 2 s

3.3. Thermal step measurements by heating the outer conducting screen (outer heating)

Another way of producing the thermal stimulus is to inject the heating current in the outer conducting screen. In this case, the thermal wave diffuses radially from the outside region of the insulation towards its inner region. The benefit of this setup is an enhanced sensitivity of the measurement near the outer semi-conductor. The capacitive current due to the space charges is measured as previously, except that in this case the ground of the current amplifier is connected to outer screen, as shown in the diagram from Figure 13.

As it can be seen from Figure 14, the proposed set up also works in the outer heating configuration. It can be noticed that the thermal step current measured by outer heating are, for identical test conditions, higher than those measured by inner heating (Figure 12). Thus, for a *1200 A* heating current during *1 s*, the amplitude of the measured signal is about *500 pA* versus *250 pA* in the case of inner heating.

This is due to the screen resistance: the effective section of the screen is less than that of the conducting core one, so the temperature rise by Joule effect is more important. Furthermore, the electric field is not the same near the core as near the screen. If the heating duration is doubled (*2 s*), the amplitude is also multiplied by two; the proportionality described in (9) are thus verified for outer heating. One may note that the signal forms are slightly different from one method to other, due to the difference in the temperature profile across the dielectric.

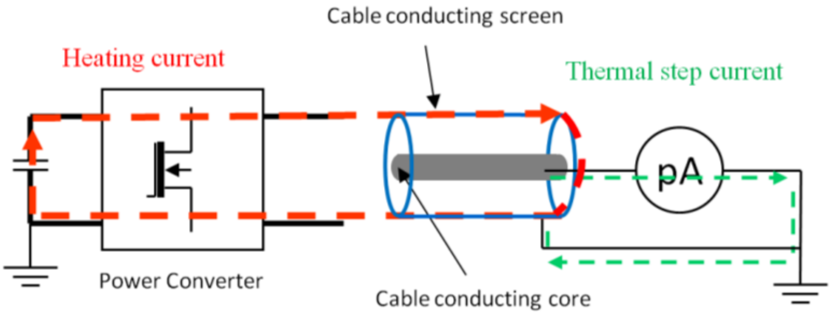
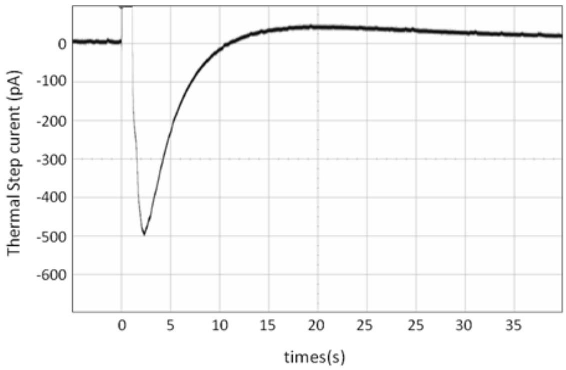
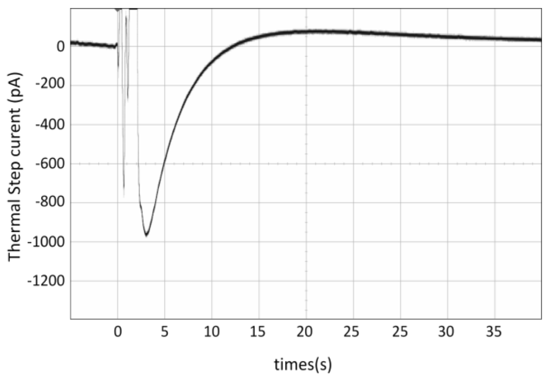


Figure 13. The heating current provided by the controlled discharge of the ultracapacitor is injected in the outer conducting screen to generate a radial thermal wave across the insulation from the outer region of the insulation toward the cable core. The thermal step current is measured by the current amplifier



(a)



b)

Figure 14. Thermal step currents issued from the dc-conditioned cable (case of outer heating) with: (a) 1200 A heating current during 1 s (b) 1200 A heating current during 2 s

The experiments described in these sections highlight that the designed power converter can be integrated in a measurement chain allowing to obtain thermal step currents in view of determining the residual electric field in long cables. The use in parallel of several power modules as the one described in this paper should allow increasing the heating current and therefore characterizing cables with significant core sections, up to *2500 mm*^{2}.

4. Conclusion

This paper presents the modeling and design of high power density multi-cell buck converter to be used for space charge measurements in full-size HVDC cables. A 12-phases power converter prototype allowing to deliver up to *1200 A* during several seconds has been presented. The converter operation mode has been validated through simulations and experimental work. Two different techniques of current control loop have been compared to find the most appropriate method to regulate the output current during the pulse duration. The use of the converter in a thermal stimulus measurement chain for space charge measurements on cable lengths by inner and outer heating has been assessed experimentally, showing its capability for being integrated in measurement benches allowing insulation characterization of long cables with strong sections.

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