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# Influence of aging on electrolytic capacitors function in static converters: Fault prediction method

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**Abstract.** The failure of electrolytic capacitors is the cause of most breakdowns of static converters. The function of these capacitors is to filter and to store electrical energy. Accelerated aging tests showed that the increase of the internal resistance *ESR* of the capacitors is a good indicator of their faulty state. The filter function is affected by the capacitors wearout on the one hand. At high frequency, the voltage ripple at the terminals of the capacitors increases according to *ESR* rise. On the other hand, the storage function is not much influenced by the capacitors aging. As static converters work most of the time at variable load, high transient values of the voltage ripple occur when output current changes that can induce false alarms. These transients are verified theoretically and experimentally. In order to avoid these transients effects, we suggest to monitor the fundamental component of the voltage ripple. This latter waveform is the best signature of the capacitors state. The *ESR* of the capacitors and the time before their failure are deduced from the processing of this waveform with other converter parameters such as input voltage, output current and ambient temperature.

**PACS.** 84.30.Jc Power electronics; power supply circuits – 84.32.Tt Capacitors – 84.37.+q Electric variable measurements (including voltage, current, resistance, capacitance, inductance, impedance, and admittance, etc.)

## 1 Introduction

About 30% of breakdowns of electronic equipment are caused by static converters which represent essential sub-systems for such devices. Since more than half of faults of static converters are due to electrolytic capacitors [1,2], the monitoring of these passive components is necessary.

To avoid the risks caused by the failure of the capacitors, and in order to establish an efficient prevention against sudden stoppages, a predictive maintenance method is applied to the static converters.

The main functions of the electrolytic capacitors (filter and storage of electrical energy) are similar in a great majority of converters.

Thus, this method is presented for capacitors used in two types of static converters (AC/DC and DC/DC switching mode power supplies provided by static converters manufacturer).

After a presentation of the converters taken in example, we analyze the influence of thermal aging on the electrolytic capacitors. The equivalent series resistance (*ESR*) is a good indicator of their faults and its evolution *versus* aging time and temperature fits a well known law.

Then, we study how the aging of input and output capacitors affects the capability of the latter to filter and store electrical energy. We demonstrate that the voltage ripple applied to the capacitors varies almost proportionally to the *ESR* [1].

To monitor the increase of *ESR*, some authors [3,4] suggest to use the rectified average signal of the voltage ripple as an image of the latter. As static converters usually work at variable load, we verify theoretically and experimentally that high transient values of the voltage ripple are generated by the load variation. These transients may lead to wrong predicted lifetimes of the capacitors.

To get rid of these transient values and have a better image of *ESR*, we suggest to extract the fundamental component of the voltage ripple.

We established a method to predict the fault of electrolytic capacitors. Since the input and the output voltages ripple does not depend only on *ESR*, but also on the output current  $I_o$ , the input voltage  $V_i$  and the ambient temperature  $T_a$ , all these parameters are taken into account for the monitoring of the capacitors.

Software and electronic modules have been developed to compute online the lifetime of the electrolytic capacitors.

Finally, we present the results obtained by the prototype.

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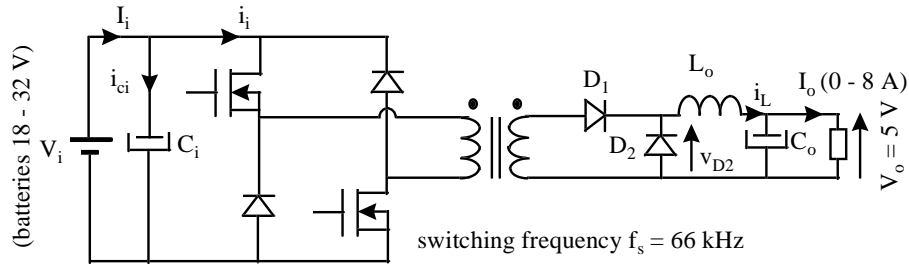


Fig. 1. Diagram of the converter SC1.

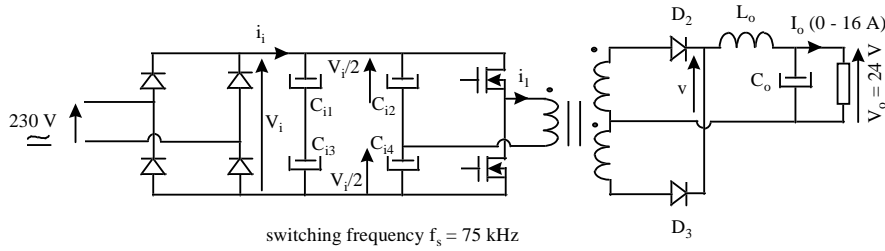


Fig. 2. Diagram of the converter SC2.

## 2 Presentation of the converters

The first static converter (SC1) studied is an industrial DC/DC “Forward” half-bridge asymmetrical switching mode power supply (40 W) as shown in Figure 1.

- The output filtering capacitors symbolized  $C_o$  are 2 aluminum electrolytic capacitors rated 2 200  $\mu\text{F}$ , 10 V, 105  $^{\circ}\text{C}$ , (MARCON CE USM 1A 222) in parallel.
- The input filtering capacitors symbolized  $C_i$  are 3 capacitors rated 1 500  $\mu\text{F}$ , 35 V, 105  $^{\circ}\text{C}$ , (NIPPON CHEMI-CON SXE 35VB-1500 18X20) in parallel with 2 capacitors rated 3 300  $\mu\text{F}$ , 35 V, 105  $^{\circ}\text{C}$ , (NIPPON CHEMI-CON SXE 35VB-3300 18X40). For converter compactness reason, two types of capacitors are used.

The second converter (SC2) is an industrial AC/DC “Forward” half-bridge symmetrical switching mode power supply (384 W) as shown in Figure 2.

- The output filtering capacitors symbolized  $C_o$  are 2 aluminum electrolytic capacitors rated 1 500  $\mu\text{F}$ , 35 V, 105  $^{\circ}\text{C}$ , (NIPPON CHEMI-CON SXE 35VB-1500 18X20) in parallel.
- The input filtering capacitors symbolized  $C_i$  are 4 aluminum electrolytic capacitors rated 680  $\mu\text{F}$ , 200 V, 105  $^{\circ}\text{C}$ , (NIPPON CHEMI-CON KMH 200VNSN-680 25.4X40).

In the converters SC1 and SC2, the electrolytic capacitors are used to filter and to store the electrical energy. For these converters, industrial users require that the capacitors must hold the same power level during at least 20 milliseconds, when the input voltage drops.

At ambient temperature equal to 25  $^{\circ}\text{C}$ , the electrolytic capacitors are responsible in SC1 and SC2 for more than 50% of breakdowns accounted to the power components.

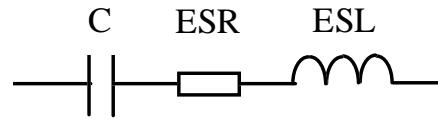


Fig. 3. Simplified equivalent circuit of an electrolytic capacitor.

## 3 Determination of the main parameters of the aged capacitors

### 3.1 Equations and equivalent circuits

An electrolytic capacitor can be schematized by the equivalent circuit in Figure 3, where:

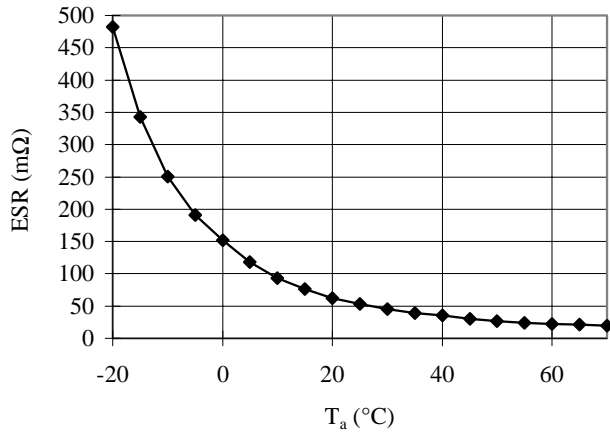
- $C$ : Capacitance (frequency dependent);
- $ESR$ : Equivalent series resistance representing all ohmic losses in the capacitor (frequency dependent);
- $ESL$ : Equivalent series inductance. Its value near some  $nH$  is frequency independent.

To study the aging of these components, we take for example the capacitors rated 2 200  $\mu\text{F}$ , 10 V, 105  $^{\circ}\text{C}$ , used to filter the output voltage of the converter SC1.

The different parameters characterizing the capacitors are measured with the help of a LCR meter in a frequency range of [20 Hz–1 MHz].

The measurement equipment shows that the capacitor is equivalent to a resistance  $R_s$  in series with a capacitance  $C_s$  until the frequency  $f_r$  ( $\approx 100$  kHz) is reached:

$$f_r = 1 / (2\pi\sqrt{ESLC}). \quad (1)$$



**Fig. 4.** *ESR versus ambient temperature for sound capacitors measured at 66 kHz.*

By considering the simplified equivalent circuit of a capacitor and by identifying its impedance to the measured impedance we get:

$$C_s = \frac{C}{1 - ESLC\omega^2} \quad (2)$$

$$R_s = ESR. \quad (3)$$

### 3.2 Influence of the ambient temperature

The increase of the ambient temperature  $T_a$  leads to a rise of  $C_s$  and a decrease of  $R_s = ESR$ . The influence of  $T_a$  on  $ESR$ , measured at the switching frequency of SC1 *i.e.* 66 kHz, is shown in Figure 4.

To measure  $ESR$ , the LCR meter injects a low current ripple through the capacitor. The temperature of the capacitor  $T_c$  can then be assimilated to the environmental temperature  $T_a$  because the self heating can be neglected.

### 3.3 Influence of the current ripple across the capacitors

Actually, during operation of the converter SC1, the current ripple can not be neglected. The case temperature  $T_c$  is thus equal to the sum of  $T_a$  and a temperature difference  $\Delta T$  due to Joule losses in the capacitor:

$$T_c = T_a + \Delta T. \quad (4)$$

The difference  $\Delta T$  depends on  $ESR$ , on the current across the capacitor and on the thermal resistance between the case and the ambient, as shown by the relation (5) [7–9]:

$$\Delta T = \frac{ESRI^2}{HS} = \frac{P}{HS} \quad (5)$$

with:  $I$ : RMS value of the current ripple;  $H$ : heat transfer per unit surface area ( $\text{W}/\text{K}\cdot\text{m}^2$ ).  $H$  depends on the diameter of the package, the diameter of the roll and on the cooling conditions [7,8];  $S$ : surface area of the capacitor.

### 3.4 Aging tests

In order to observe the evolution of  $ESR$  and  $C_s$  versus aging time and temperature, we applied to lots of 50 capacitors used in the converters SC1 and SC2, an accelerated thermal aging under their nominal voltages and temperature ( $T = 105^\circ\text{C}$ ).

In Figure 5, we represent the variation of  $ESR$  and  $C_s$  measured versus frequency for sound capacitors rated  $2200 \mu\text{F}$ ,  $10 \text{ V}$ ,  $105^\circ\text{C}$  and after an aging test of 3640 hours.

The loss of electrolyte inside the capacitor leads to a decrease of the capacitance  $C_s$  and an increase of the resistance  $ESR$  [3,8]. In addition, since the inductance  $ESL$  is independent on the aging, the resonance frequency rises (*cf.* Eqs. (1) and (2)).

The increase of  $ESR$  versus aging time is interesting because at the switching frequency of the converter,  $1/(C\cdot\omega)$  and  $ESL\cdot\omega$  can be neglected compared to  $ESR$ . Therefore, at this frequency, the capacitor impedance is almost equal to  $ESR$ . This evolution is also important since it determines the internal heating of the capacitor and then its lifetime [10,11].

The rise of  $ESR$  versus the aging is more important than the decrease of  $C_s$ . It represents a good indicator of fault of electrolytic capacitors, more especially as a theoretical law to predict  $ESR$  can be determined.

In Figure 6, we represent the experimental points of  $ESR$  measured at 66 kHz and  $T_a = 25^\circ\text{C}$ , for aged capacitors at  $T = 105^\circ\text{C}$ .

An interpolation between these measured points gives the variation of  $ESR$  versus time for the aging at  $T = 105^\circ\text{C}$ . For any other aging temperature  $T' \neq T$ , another evolution law can be determined. In fact, as shows Figure 6, for every point  $(t, ESR)$  corresponding to the curve at  $T = 105^\circ\text{C}$ , the time  $t'$  corresponding to the temperature  $T'$  can be calculated by the Arrhenius law [8]:

$$\frac{t'}{t} = \exp\left(E \frac{T - T'}{TT'}\right) \quad (6)$$

where  $E$  is the activation energy divided by Boltzmann's constant.  $E$  is estimated to 4700 [12].  $T$  and  $T'$  are the temperatures in Kelvin.

By considering  $1/ESR$ , a linear law [12,13] gives a theoretical prediction model of  $ESR$  versus time and temperature. It is given by the relation (7):

$$\frac{1}{ESR(t)} = \frac{1}{ESR(0)} \left[ 1 - kt \exp\left(-\frac{4700}{T}\right) \right] \quad (7)$$

where  $ESR(t)$  is the  $ESR$  value at time  $t \neq 0$ .  $ESR(0)$  is the  $ESR$  value at time  $t = 0$ .  $k$  is a constant depending on the construction and on the dimensions of the capacitor.  $t$  is the aging time.  $T$  is the aging temperature in Kelvin.

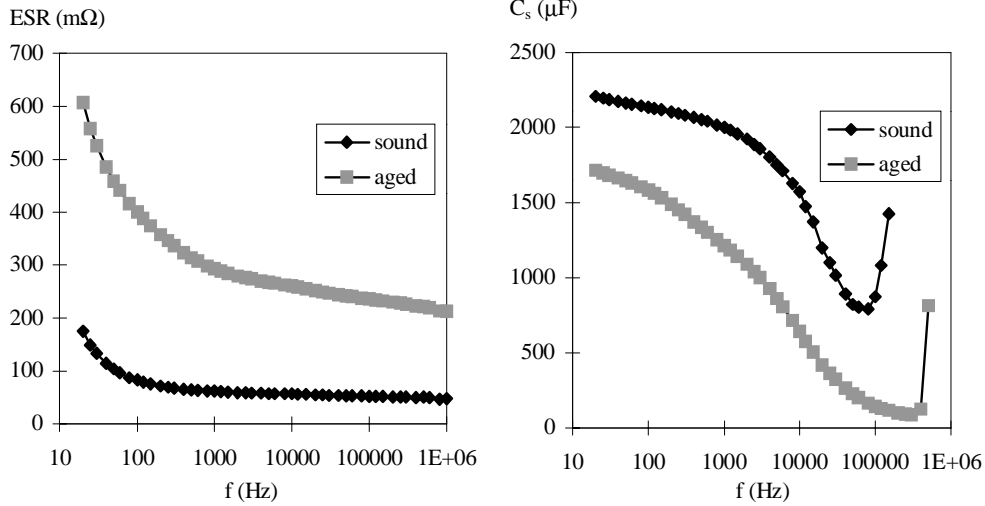


Fig. 5. Influence of the aging upon the characteristics of electrolytic capacitors.

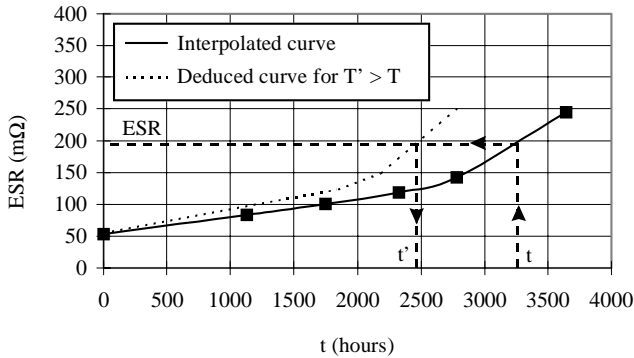


Fig. 6. Experimental model at 66 kHz fitting the aging law at  $T = 105\text{ }^{\circ}\text{C}$ .

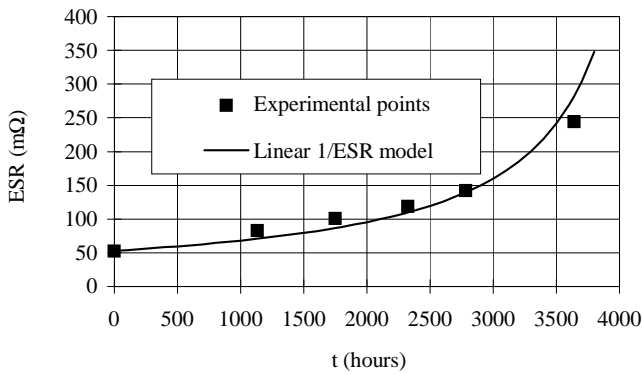


Fig. 7. Theoretical model at 66 kHz fitting the aging law at  $T = 105\text{ }^{\circ}\text{C}$ .

Figure 7 shows the theoretical law deduced from this model. The constant  $k$  is calculated by the least squares method to fit the experimental points ( $k = 58$ ). This model is a little pessimistic but provides a simple representation of the capacitor behavior.

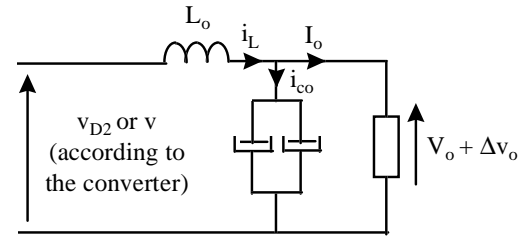


Fig. 8. Output circuit of the converters.

## 4 Electrical waveforms to monitor

### 4.1 Influence of electrolytic capacitors aging on the converters waveforms

#### 4.1.1 Output capacitors of SC1 and SC2: Filtering function

The only signal that is significantly modified when the capacitors are aged, is the output voltage ripple of the latter. The changes occurring to the ripple signal could be explained as follows for the two converters (the output schema is similar for both (*cf.* Fig. 8); where  $V_o$  is the DC output voltage and  $\Delta v_o$  is the AC component at the switching frequency of the converters.

During operation of the converters, the output filter capacitors wear out similarly because they are stressed by the same current ripple and the same ambient temperature (they are mounted near on the converter). At the switching frequencies of the converters, the total impedance of each capacitor is almost equal to its  $ESR$ , then the global resistance  $ESR_{eq}$  of the equivalent capacitor is equal to  $ESR/2$ . The output voltage ripple  $\Delta v_o$  is linked to the ripple current  $i_{co}$  through the capacitors by:

$$\Delta v_o \approx ESR_{eq} i_{co}. \quad (8)$$

The current  $i_{co}$  is almost equal to the current ripple  $\Delta i_L$  through the output smoothing inductor  $L_o$  because the

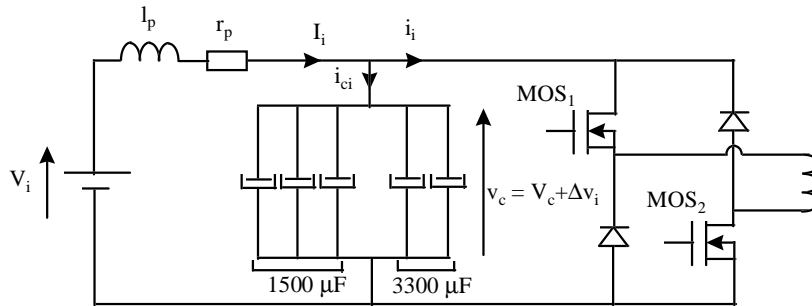


Fig. 9. Input circuit of the converter SC1.

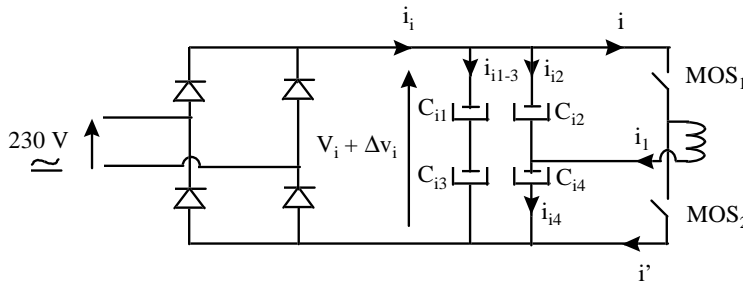


Fig. 10. Simplified input circuit of SC2.

load resistance ( $V_o/I_o$ ) is much higher than the capacitors resistance  $ESR_{eq}$ . This ripple depends only on the parameters of the converters but not on the capacitors worn state [14,15].

Therefore, for given input voltage and output current,  $\Delta v_o$  increases with the aging of the capacitors as  $ESR_{eq}$  rises.

#### 4.1.2 Input capacitors of SC1: Filtering function

Figure 9 illustrates the input circuit of SC1;  $r_p$  and  $l_p$  represent respectively the parasitic internal resistance and inductance of the batteries and the connecting wires.

At sound state,  $ESR$  of the capacitors rated  $3\,300\ \mu\text{F}$  is equal to  $22\ \text{m}\Omega$  and  $ESR$  of the capacitors rated  $1\,500\ \mu\text{F}$  is  $54\ \text{m}\Omega$ . The capacitors  $3\,300\ \mu\text{F}$  have then a more rapid aging than the capacitors  $1\,500\ \mu\text{F}$ . In fact, since  $1/(C\omega) \ll ESR$ , the Joule losses in the capacitors are given by:

$$P \approx \frac{(\Delta V_{i-eff})^2}{ESR} \quad (9)$$

where  $\Delta V_{i-eff}$  is the RMS value of the input voltage ripple  $\Delta v_i$ . The external surface area of the  $3\,300\ \mu\text{F}$  capacitors is  $6\,300\ \text{mm}^2$  and the surface area of the  $1\,500\ \mu\text{F}$  capacitors is  $4\,200\ \text{mm}^2$ . In addition, as the diameters of the  $3\,300\ \mu\text{F}$  and  $1\,500\ \mu\text{F}$  capacitors are identical and as the airflow conditions are approximately the same for the five capacitors (natural convection),  $H$  can be considered as a constant [9]. Then referring to equation (5) and equation (9) above, we conclude that the components rated  $3\,300\ \mu\text{F}$  are stressed by a temperature difference

$\Delta T$  almost 1.6 times higher than  $\Delta T$  for the capacitors  $1\,500\ \mu\text{F}$ .

Concerning the filtering function, the study is similar to the output waveforms. The input voltage ripple  $\Delta v_i$  is linked to the current ripple  $i_{ci}$  through the input capacitors by the relation:

$$\Delta v_i \approx ESR_{eq} i_{ci} \quad (10)$$

where  $ESR_{eq}$  is the equivalent resistance of the five filter input capacitors.

The consequence of the wearout of the input capacitors is that  $\Delta v_i$  increases *versus* the resistance  $ESR_{eq}$ , since the ripple current  $i_{ci}$  is independent on the worn state of the capacitors [14].

The input capacitors does not wear similarly but only on  $ESR_{eq}$  influences  $\Delta v_i$ . The filtering function is affected by the aging of the equivalent capacitor. Then the monitoring of  $ESR_{eq}$  value is sufficient to determine the worn state of the capacitors.

#### 4.1.3 Input capacitors of SC2: Filtering function

In Figure 10 is shown the equivalent input circuit of the converter SC2.

The capacitors  $C_{i1}$  and  $C_{i3}$  are used to filter the output voltage of the bridge rectifier whereas the capacitors  $C_{i2}$  and  $C_{i4}$  constitute the half bridge structure.

The input voltage can be divided into a low-frequency component  $V_i$  representing the rectified and filtered network source voltage and a high-frequency component  $\Delta v_i$  at a frequency equal to the double of the switching frequency of SC2 *i.e.*  $150\ \text{kHz}$  [14].

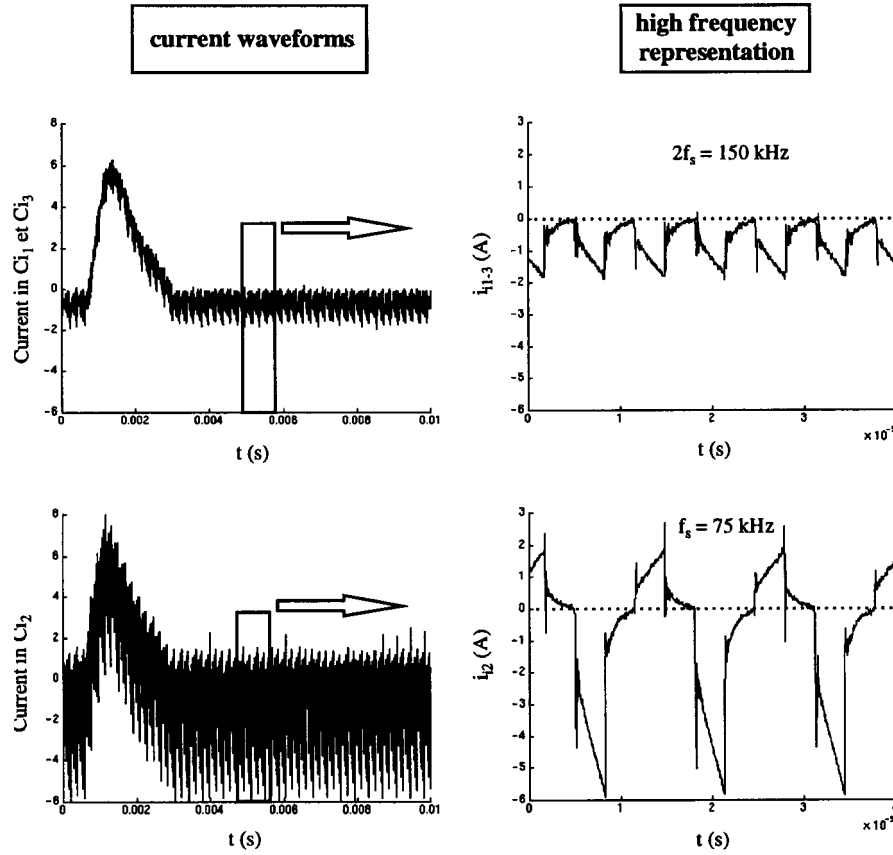


Fig. 12. Experimental current waveforms across the input capacitors.

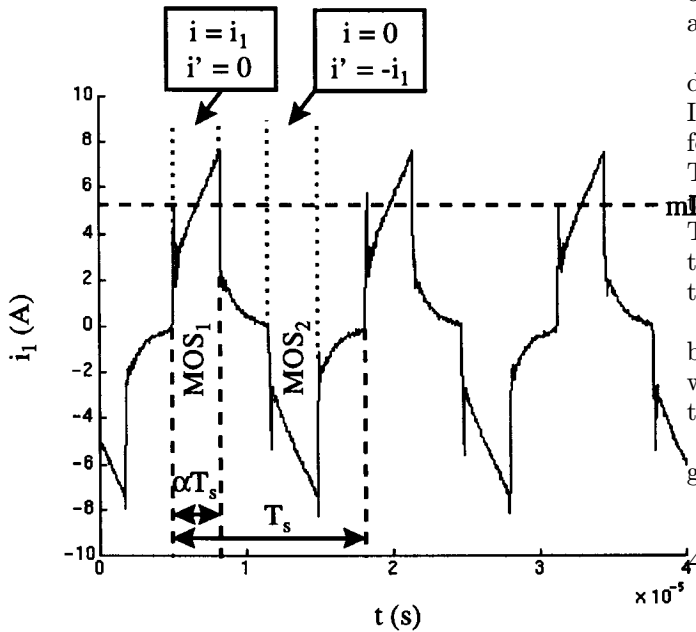


Fig. 11. Current  $i_1$  in the primary circuit of the transformer for  $I_o = 16$  A where  $\alpha$  is the duty ratio and  $T_s$  is the switching period.

In Figure 11, we represent the current  $i_1$  in the primary of the transformer measured experimentally for a running at  $I_o = 16$  A.

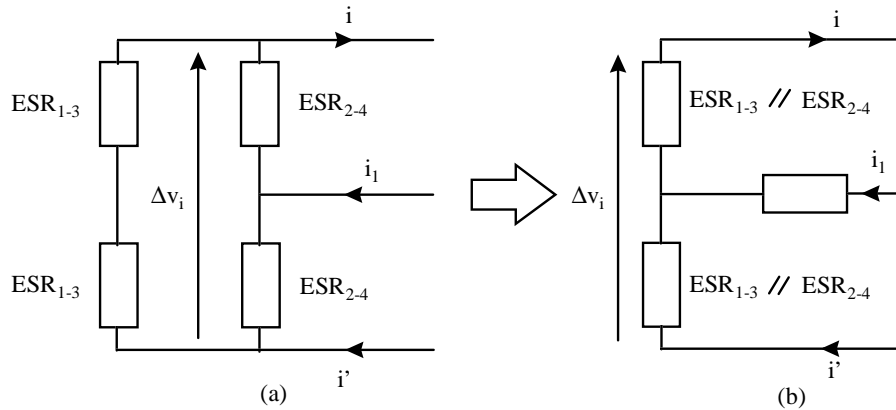
The input capacitors are stressed by currents with different *RMS* values. Their aging is then not similar. In Figure 12, we show the different input current waveforms for the converter SC2 using sound input capacitors. The current  $i_{i4}(t)$  through the capacitor  $C_{i4}$  is equal to the current  $i_{i2}$  through  $C_{i2}$  with a phase lagging of  $T_s/2$ . The *RMS* currents through  $C_{i2}$  and  $C_{i4}$  are greater than through  $C_{i1}$  and  $C_{i3}$ . Their aging is thus faster because the self heating is greater.

For high frequencies, the circuit of Figure 10 can be represented by the equivalent circuit of Figure 13a which can be transformed to Figure 13b by a Wye-Delta transformation (Fig. 13).

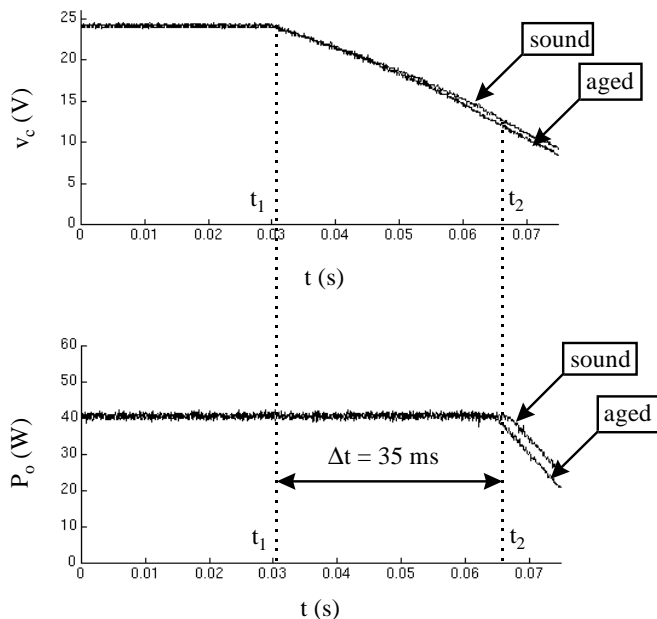
A simple expression of the input ripple voltage  $\Delta v_i$  is given by:

$$\Delta V_i(t) = \frac{ESR_{1-3} ESR_{2-4}}{ESR_{1-3} + ESR_{2-4}} \times (-i' - i) = -ESR_{eq}(i' + i). \quad (11)$$

When input capacitors wear, the input ripple voltage  $\Delta v_i$  increases proportionally to  $ESR_{eq}$ . The currents  $i$  and  $i'$  can be considered as independent of the worn state of the capacitors [14].



**Fig. 13.** Wye - Delta transformation of the input circuit of SC2.



**Fig. 14.** Output power transfer for a switching operation of input batteries.

#### 4.1.4 Input capacitors of SC1: Energy storage function

The input batteries of the converter SC1 deliver a DC voltage. The discharge of these batteries makes the DC voltage drops. Thus, they must be changed. The industrial requirements specify that when batteries are switched, the input capacitors must deliver electrical energy during at least 20 ms.

The purpose is to show the influence of the capacitors aging on the input voltage and on the output power transmitted to the load.

For sound input capacitors ( $ESR_{eq} = 17 \text{ m}\Omega$ ,  $C_{eq} = 10.5 \text{ mF}$  at  $25^\circ\text{C}$  and  $20 \text{ Hz}$ ) and worn capacitors ( $ESR_{eq} = 38.7 \text{ m}\Omega$ ,  $C_{eq} = 10 \text{ mF}$  at  $25^\circ\text{C}$  and  $20 \text{ Hz}$ ), Figure 14 illustrates the voltage  $v_c$  measured across the terminals of the capacitors and the output power  $P_o = V_o I_o$  during a switching operation of the input batteries.

Between the switching instant ( $t_1$ ) and the instant when the output power  $P_o$  drops ( $t_2$ ), the input

capacitors supply energy to the converter, the power  $P_o$  is maintained constant during a period  $\Delta t$  of about 35 ms which responds to the requirements.

Besides, we note that the voltage  $v_c$  and the power  $P_o$  are not much affected by the capacitors wearout. This can be argued by two reasons:

- At first, for low frequencies, the capacitance of an electrolytic capacitor is the preponderant element of its impedance: for the five input capacitors of SC1, the global capacitance  $C_{eq}$  decrease is equal to 5% while  $ESR_{eq}$  increases about 100%.
- Secondly, the equivalent resistance of the global circuit below the input capacitors (equal to  $V_i/I_i$ ) is much greater than  $ESR_{eq}$ .

#### 4.2 Transient state due to load variation

To monitor the state of filter electrolytic capacitors, some authors [3,4] take into account the whole ripple voltage across the capacitors. This method present a major disadvantage, it can not be applied to static converter working at variable load.

The aim of this paragraph is to show the influence of an output current variation on input and output voltage ripples  $\Delta v_i$  and  $\Delta v_o$  for the converters SC1 and SC2.

##### 4.2.1 Influence of a load variation on $\Delta v_o$

We have subjected the converters SC1 and SC2 to a load variation as shown in Figure 15 and measured experimentally the voltage ripple  $\Delta v_o$ .

We observe a transient increase of  $\Delta v_o$  when the output current changes.

##### 4.2.2 Theoretical interpretation of the results

Let us explain this transient phenomenon. The output circuit of the converters SC1 and SC2 is represented in Figure 16.

The voltage denoted by  $u$  represents  $v_{D2}$  in the case of SC1 and  $v$  in the case of SC2 (*cf.* Fig. 8).

The output circuit of the converters can be considered as a superposition of low and high frequency circuits.



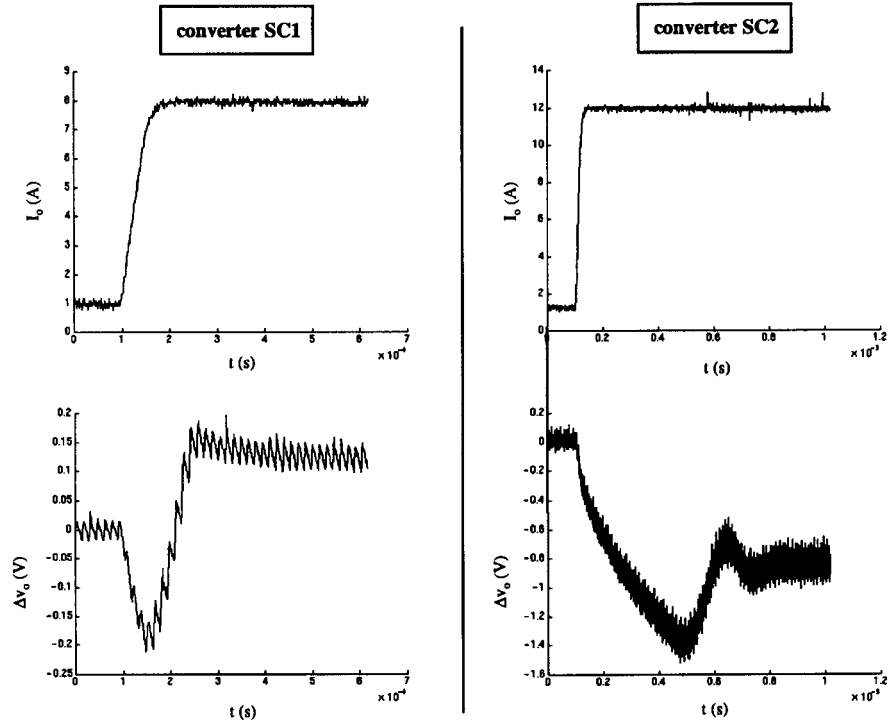


Fig. 15. Influence of a variable load on  $\Delta v_o$ .

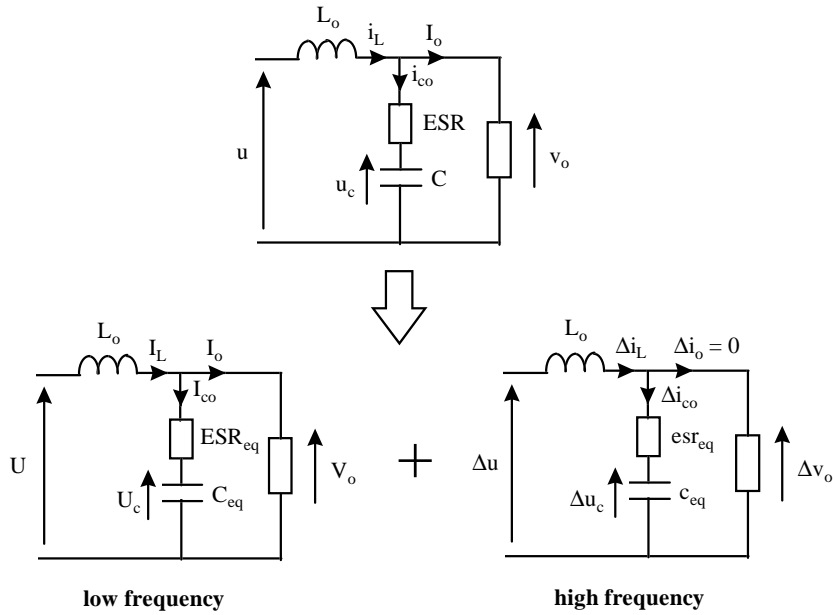


Fig. 16. Output circuit of SC1 and SC2.

All the input waveforms are then divided into low-frequency and high-frequency components:

$$\begin{aligned}
 u &= U + \Delta u \\
 v_o &= V_o + \Delta v_o \\
 i_{co} &= I_{co} + \Delta i_{co} \\
 i_L &= I_L + \Delta i_L \\
 u_c &= U_c + \Delta u_c.
 \end{aligned} \tag{12}$$

For the low frequencies, the input waveforms are given by:

$$U = ESR_{eq}I_{co} + U_c + L_o \frac{dI_L}{dt} \tag{13}$$

$$I_{co} = C_{eq} \frac{dU_c}{dt} \tag{14}$$

$$I_L = I_o + I_{co} \tag{15}$$

$$V_o = ESR_{eq}I_{co} + U_c. \tag{16}$$

At steady state operation, the input signals are expressed as follows:

$$\begin{aligned} I_{co} &= 0 \\ I_L &= I_o = \text{Constant} \\ U &= V_o = U_c. \end{aligned} \quad (17)$$

When the converter works at a transient operating mode, the current  $I_{co}$  through the output capacitors is no more equal to zero.

The parameters of the capacitors ( $ESR_{eq}$ ,  $C_{eq}$ ) are calculated at low-frequency. This frequency ( $f_{eq}$ ) is determined according to the load variation waveform [14].

We suppose that  $f_{eq}$  is always less than 1/10 of the switching frequency of the converter to make possible the separation between low and high-frequency components.

By denoting  $m$  the transformation ratio between the primary and the secondary of the transformer,  $\alpha$  the duty ratio of the converter, the average value  $\langle u \rangle$  of the voltage  $u$  is function of  $V_o$  and  $V_i$ :

$$\langle u \rangle = \alpha m V_i \quad (18)$$

$$\langle u \rangle = V_o. \quad (19)$$

In transient mode, the relation (19) is no more right, because the current  $I_o$  is variable, the current in the inductor  $L_o$  is not constant. To simplify the study, we can suppose  $\langle u \rangle$  still equals  $\alpha m V_i$  because  $\alpha$  and  $V_i$  remain unchanged. As  $\langle u \rangle = U$  (high-frequency component  $\Delta u$  has a mean value equal to zero), we consider that  $U$  remains constant (equal to 5 V in the case of SC1 and 24 V in the case of SC2). Equations (13), (14) and (15) give:

$$U = U_c + ESR_{eq} C_{eq} \frac{dU_c}{dt} + L_o \frac{d}{dt} \left( I_o + C_{eq} \frac{dU_c}{dt} \right) \quad (20)$$

then:

$$U_c + ESR_{eq} C_{eq} \frac{dU_c}{dt} + L_o C_{eq} \frac{d^2 U_c}{dt^2} = U - L_o \frac{dI_o}{dt}. \quad (21)$$

Referring to the equations (14) and (16), the output voltage  $V_o$  can be written as:

$$V_o = U_c + ESR_{eq} C_{eq} \frac{dU_c}{dt}. \quad (22)$$

If we denote by  $V_{excit}$  the voltage  $U - L_o \frac{dI_o}{dt}$ , we have:

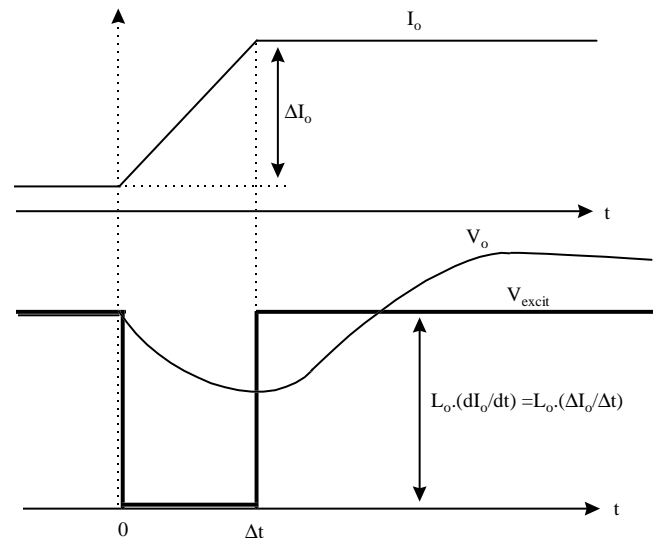
$$\frac{V_o(p)}{V_{excit}(p)} = \frac{\omega_o^2 + 2z\omega_o p}{p^2 + 2z\omega_o p + \omega_o^2} \quad (23)$$

where  $p$ : Laplace operator

$$\begin{aligned} z &= \frac{ESR_{eq}}{2} \sqrt{\frac{C_{eq}}{L_o}} \\ \omega_o &= \frac{1}{\sqrt{L_o C_{eq}}}. \end{aligned}$$

We represent in Figure 17 the output voltage  $V_o$  response to the excitation voltage  $V_{excit}$ , for a variable current  $I_o$ .

In Figure 17 the transient phenomenon at low-frequency of the output voltage can be seen quite similar to the measured one (Fig. 15).



**Fig. 17.** Theoretical interpretation of the transient of the  $V_o$  voltage.

#### 4.2.3 Parameters to monitor

In order to avoid errors in the lecture of the state of the filtering capacitors, the increase of the transient values of  $\Delta v_o$  should not be a synonym of  $ESR$  rise.

To overcome such problem, we chose as indicator of fault of the capacitors, the fundamental component  $\Delta v_{of}$  of the voltage ripple  $\Delta v_o$ .

The choice of the average rectified signal of  $\Delta v_o$  as fault indicator, suggested by some authors [3,4], gives the same results as  $\Delta v_{of}$  in steady state operation only, but does not avoid the transient values of  $\Delta v_o$  and may generate wrong predicted service life of the capacitors.

To facilitate the processing of the different waveforms [1,14], the signal considered to monitor the  $ESR$  value, is the average rectified signal of  $\Delta v_{of}$ .

We represent in Figure 18, the fundamental signal  $\Delta v_{of}$  (Curve 1a for SC1 and Curve 2a for SC2), the average rectified signal of  $\Delta v_{of}$  (Curve 1b for SC1 and Curve 2b for SC2) and the average rectified value of the original signal  $\Delta v_o$  (Curve 1c for SC1 and Curve 2c for SC2) for a load variation sequence. We notice that the surge value of  $\Delta v_o$  is completely detected by the Curves 1c and 2c while the Curves 1b and 2b show a negligible increase of the image of  $\Delta v_o$  considered. Because of the high transient values affecting the Curves 1c and 2c, they can not be used as indicators of fault of the capacitors. The Curves 1b and 2b show a little increase at the moment of the load change and give a faithful image of the capacitors worn state.

#### 4.2.4 Influence of the aging on $\Delta v_o$ at variable load

We have shown the influence of the aging of filtering capacitors on converters waveforms in steady state operation, we observe now their influence in variable load operation.

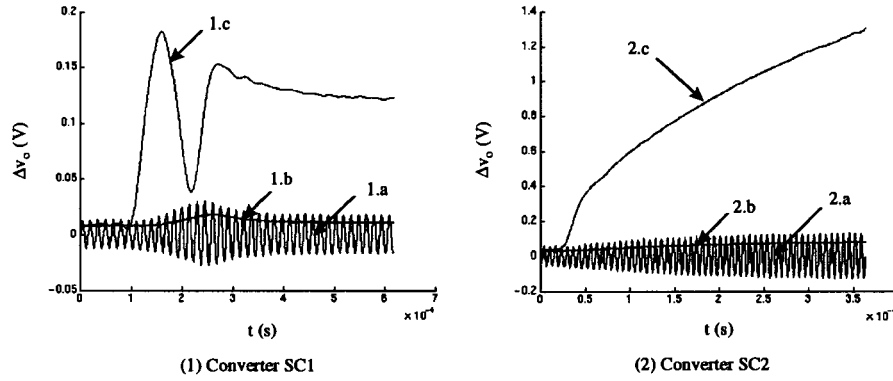


Fig. 18. Processing of  $\Delta v_o$ .

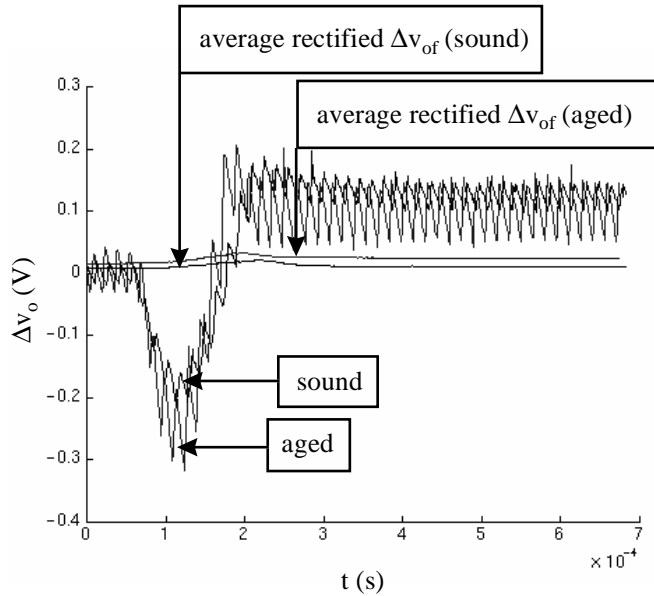


Fig. 19. Transient of  $\Delta v_o$  for sound and aged capacitors.

For example, Figure 19 illustrates the voltage ripple  $\Delta v_o$  of SC1, for the load variation of Figure 15, with sound capacitors ( $ESR_{eq} = 27 \text{ m}\Omega$  at  $25^\circ\text{C}$  and  $66 \text{ kHz}$ ) and worn capacitors ( $ESR_{eq} = 71 \text{ m}\Omega$  at  $25^\circ\text{C}$  and  $66 \text{ kHz}$ ).

We observe that the aging of the capacitors affects  $\Delta v_o$  in steady state operation and at variable load operation by inducing higher transient values of  $\Delta v_o$ . The average rectified signal of  $\Delta v_{of}$  shows a negligible increase and provides better image worn state of the capacitors.

#### 4.2.5 Influence of the load variation on $\Delta v_i$

We studied the input voltage ripple for a load variation sequence. For the two converters SC1 and SC2, we have detected transient values of  $\Delta v_i$  due to the variation of  $\Delta v_o$  (cf. Fig. 20).

For the converter SC2, the low-frequency component of the input voltage is also affected by the load change.

Similarly as for the output voltage, Figure 20 confirms the necessity to consider the fundamental component  $\Delta v_{if}$

of the ripple voltage  $\Delta v_i$ . In fact, this signal shows a negligible increase under a load change and gives a satisfying image of the worn state of the input filter capacitors.

## 5 Prediction method of the capacitors Fault

We demonstrated in Section 3 that the electrolytic capacitors wearout depends on aging time and temperature applied to the components. Their electrical characteristics drift and especially the equivalent series resistance  $ESR$  increases.

For the industrial users of switched power supplies, the definition of the capacitors useful working life is fixed by the voltage ripple admitted. For the converters SC1 and SC2, the limit voltage ripples  $\Delta v_{if}$  and  $\Delta v_{of}$  define the limit value of  $ESR$  and then the useful life of the capacitor [16].

The aim of the study is to utilize the voltage ripple to determine the  $ESR$  value of filter electrolytic capacitors at any time  $t$ , for given temperature  $T_a$ , current  $I_o$  and voltage  $V_i$ . A prediction model of  $ESR$  is used then to predict the time remaining to failure.

For the input and the output circuits of the converters, the average rectified value ( $\delta V_f$ ) of the fundamental voltage ripple ( $\Delta v$ ), is function of the resistance  $ESR_{eq}$  but also on the output current  $I_o$  and the input voltage  $V_i$ . We get then:

$$\delta V_f = f(I_o, V_i, ESR_{eq}). \quad (24)$$

As shown previously (cf. Sects. 4.1.1, 4.1.2, and 4.1.3),  $ESR_{eq}$  is function of the  $ESR$  values  $ESR_1$  and  $ESR_2$  of each filter capacitor and can be written as:

$$ESR_{eq} = f(ESR_1, ESR_2). \quad (25)$$

For sound capacitors, we determine experimentally the function  $\delta V_f = f(ESR_{eq})$  for  $I_o$  and  $V_i$  given.

The resistance  $ESR_1$  and  $ESR_2$  are function of the case temperatures  $T_{c1}$  and  $T_{c2}$  of each capacitor (cf. Fig. 4).  $ESR_1$  and  $ESR_2$  can be written as follows:

$$ESR_1 = f(T_{c1}) \quad (26)$$

$$ESR_2 = f(T_{c2}) \quad (27)$$

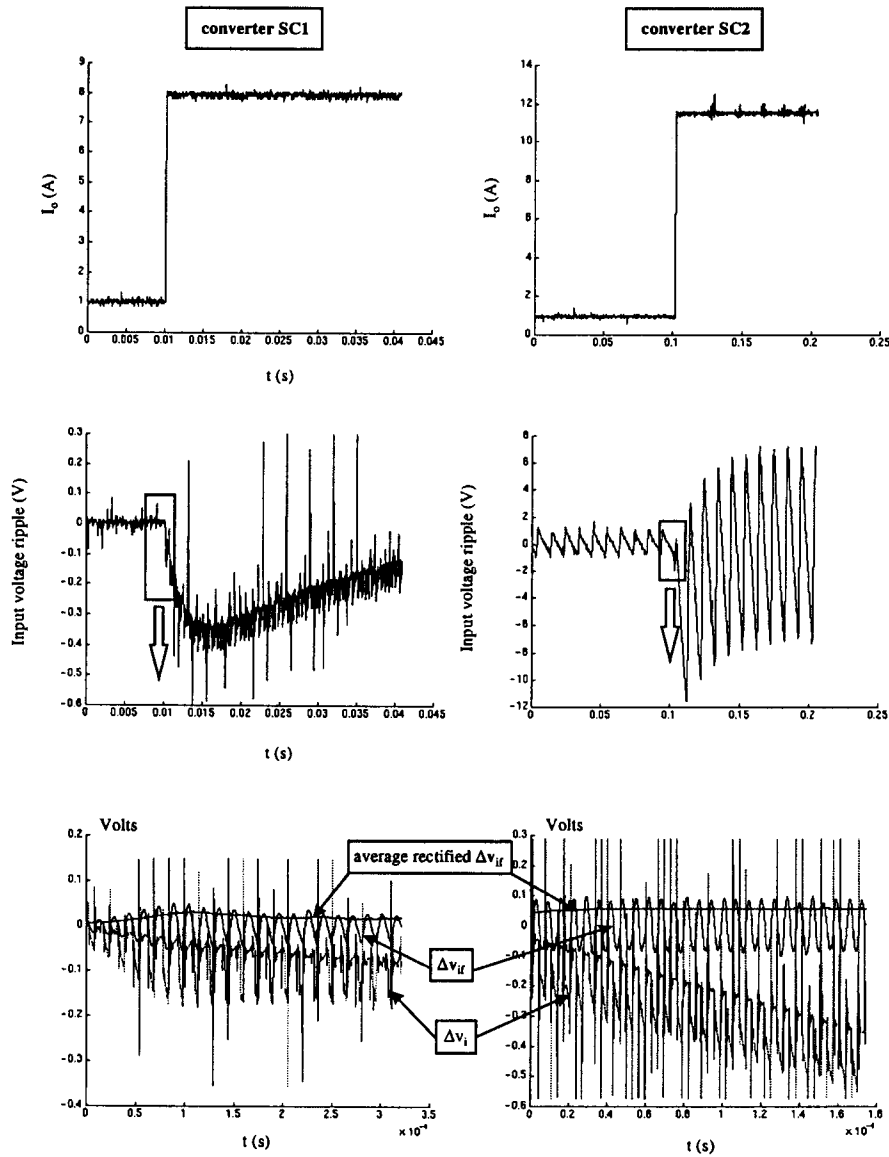


Fig. 20. Processing of  $\Delta v_i$ .

Referring to equations (4) and (5), for a given resistance  $ESR$ , the case temperature  $T_c$  is a function of the ambient temperature  $T_a$  and of the RMS value of the ripple current through the capacitor. This latter depends on  $I_o$  and  $V_i$ , then:

$$T_{c1} = f(I_o, V_i, T_a) \quad (28)$$

$$T_{c2} = f(I_o, V_i, T_a). \quad (29)$$

Equations (25) to (29) give:

$$ESR_{eq} = f(I_o, V_i, T_a). \quad (30)$$

The relation (24) becomes:

$$\delta V_f = f(I_o, V_i, T_a). \quad (31)$$

For sound capacitors, knowing the values of  $\delta V_f$ ,  $I_o$  and  $V_i$ , the relation (31) gives the ambient temperature  $T_a$ . The

temperatures  $T_{c1}$  and  $T_{c2}$  are then calculated from the equations (28) and (29). The  $ESR_1$  and  $ESR_2$  values are deduced from the equations (26) and (27). The function  $\delta V_f = f(ESR_{eq})$  is thus experimentally determined. The method established is summarized in Figure 21.

When capacitors wear under aging conditions, the function  $\delta V_f = f(ESR_{eq})$  is unchanged because it does not depend on the worn state of the capacitors but only on the ripple current *i.e.*  $I_o$  and  $V_i$  (*cf.* Eqs. (8), (10) and (11)).

The knowledge of  $\delta V_f$ ,  $I_o$  and  $V_i$  is sufficient at any time of the capacitors life, to compute the value of  $ESR_{eq}$  as illustrated in Figure 21.

Hence, the predictive maintenance method needs two essential parts:

- The measurement at  $t = 0$ , for the converter using sound electrolytic filter capacitors of the signals  $\delta V_f$ ,

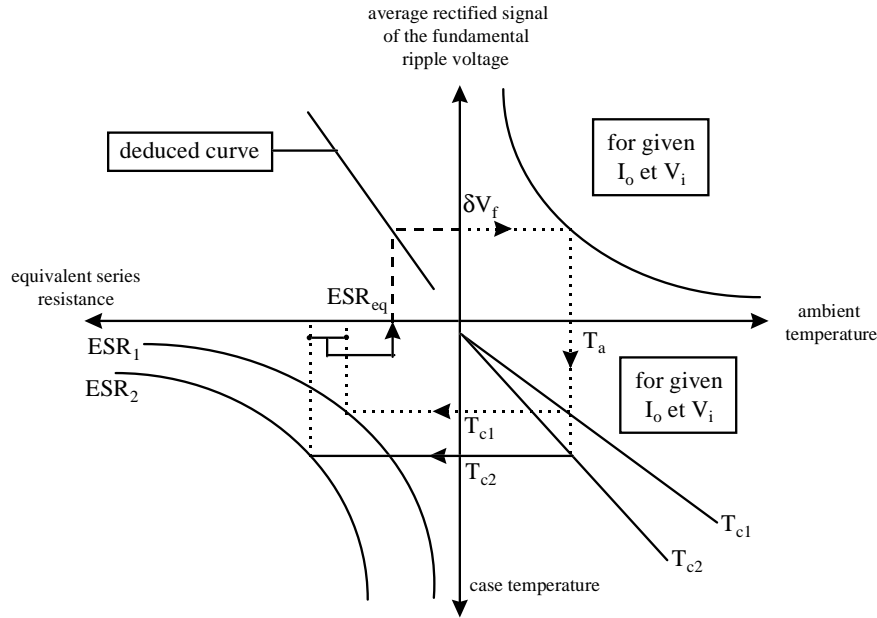


Fig. 21. Monitoring method of the filter electrolytic capacitors.

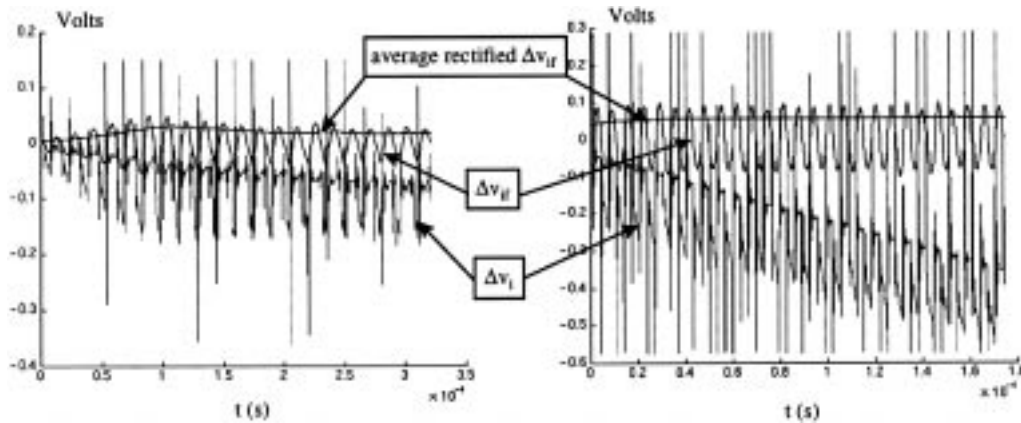


Fig. 22. Results obtained with sound and worn capacitors for  $I_o = 8$  A,  $V_i = 24$  V and  $T_a = 25$  °C.

$T_{c1}$ ,  $T_{c2}$ ,  $I_o$ ,  $V_i$  and  $T_a$  and the storage of the functions  $\delta V_f$ ,  $T_{c1}$  and  $T_{c2}$  versus  $I_o$ ,  $V_i$  and  $T_a$  (cf. relations (28), (29) and (31)).

- The measurement at  $t \neq 0$ , during operation of the converter, of the signals:
  - $\delta V_f$ ,  $I_o$ ,  $V_i$  in order to deduce the value of  $ESR_{eq}$  at that time.
  - The temperature  $T_a$  that gives the case temperature of each capacitor and then  $ESR_{eq}$  for sound capacitors [14].

A prediction model of  $ESR_{eq}$  versus time and temperature is finally used to compute the time remaining to failure (cf. Eq. (7)).

## 6 Results

Figure 22 shows the results obtained by the fault prediction method of capacitors, applied to the output circuit

of the converter SC1, using sound components (Fig. 22a) and aged components (Fig. 22b). We can see how an aged capacitor reduces to 2.5 years the time before failure of the converter.

## 7 Conclusion

Accelerated aging tests carried out on electrolytic capacitors showed that the equivalent series resistance  $ESR$  is the best indicator of fault of these components.  $ESR$  increases according to a well known law versus aging time and temperature.

We also observed the influence of the aging of the capacitors on the voltage filtering and proved that in steady state operation, the voltage ripple increases almost proportionally to  $ESR$ .

At variable load state, we found that high transient values occurred on the voltage ripple which can lead to

faulty alarms by giving wrong predicted values of the resistance  $ESR$ . To avoid such errors, we suggest the monitoring of the fundamental component of the voltage ripples.

We noted too that the storage function of electrical energy is almost unaffected by the aging of capacitors.

Since the voltage ripple depends on  $ESR$  and also on the output current, the input voltage and the ambient temperature, all these parameters are taken into account in the fault prediction method.

The results obtained by this method were confirmed by industrial users.

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