

# **TANTALUM CAPACITORS TESTS IN TEC-EPC LAB**

## **TESTS ON PARALLEL CONFIGURATION**

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## **C H A N G E L O G**

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# 1 INTRODUCTION

Due to their limited dimensions and weight compared to other capacitor types of equivalent performance, Solid Tantalum capacitors are widely used by many manufacturers in power supplies and in other applications where considerable surge and RMS currents are applied.

The previous ESA standard about de-rating rules for EEE components (RD #1, dated 1992) forbade the use of Tantalum Capacitors in power supply filters, and the reason of the prohibition was the (past) low reliability of such components in low impedance applications, where high surge and/or RMS currents were expected.

Component design and manufacturing updates along the years improved the quality of the tantalum capacitors, such that the original indications of circuit impedance from manufacturers have been reduced from several Ohm/Volt to fractions of Ohm/Volt. Lately the requirements of minimum circuit impedance for the use of such capacitors were even removed (provided that the relevant voltage, current and temperature ratings are respected).

For space applications, where long-term reliability is an utmost need, the concept of components application de-rating is applied to increase their reliability.

The documents AD #1 and #2 are currently applicable to all ESA projects, and give specific rules to be complied in the use of solid tantalum capacitors.

Despite the application of the de-rating rules set up by RD #1, in the recent past there have been cases of unexplained failures in space equipments, and gave some concern and brought ESA to issue a specific alert on tantalum capacitors applications (AD #3)

The exact cause of the failures has not been confirmed.

An investigation into possible causes has been performed at ESTEC resulting in the corrective/preventative actions defined in the relevant Alert.

The list of actions in AD #3 is not exhaustive however and is subject to addition pending further investigation.

# 2 SCOPE AND OBJECTIVES

The first scope of the present test investigation is to verify the long-term reliability of solid tantalum capacitors when they are connected in parallel configuration (so as to form a capacitor bank).

In fact, and as it is further explained in the '6.2.1: Issues of the parallel configuration' chapter, there are reasons to believe that failures due to tantalum capacitors weaknesses are more likely to occur when capacitors are put in parallel with no specific means to limit the current flowing through each one of them.

The second scope of this document is to clarify this problem by presenting some solutions to insure that the capacitors are correctly used.

The overall objectives of this test campaign were:

- To clarify the limits of utilization, in particular regarding the maximum allowable RMS current.
- To check capacitors robustness with respect to their de-rated limits.
- To check if the present ECSS de-rating rules do define a safe envelope of application.

A number of capacitor banks have been life –tested in different current regime conditions to simulate real-life applications within the boundaries established by the present ESA de-rating rules (AD #1 and AD #2)

This will help understanding whether the reliability of capacitors in practical applications is indeed sufficient to confirm their suitability for space applications, and whether the present de-rating rules do define a safe envelope of application.

### 3 APPLICABLE DOCUMENTS

The following documents are considered as applicable:

- |       |  |
|-------|--|
| AD #1 | ECSS-Q-60-11A, EEE Components, De-rating and end-of-life parameter drifts, 7-Sep-2004                  |
| AD #2 | TEC-Q/04-6649/QCT, EEE COMPONENT DERATING (ESA TAILORING OF ECSS-Q-60-11A), issue 1 rev 0, 14-Sep-2004 |
| AD #3 | EA-2004-MEP-06-A, ESA Alert on Use of Tantalum Capacitors on power supply filters, 29-Oct-2004         |

### 4 REFERENCE DOCUMENTS

The following documents are given as a reference:

- |       |   |
|-------|---|
| RD #1 | ESA PSS-01-301 Issue 2  |
| RD #2 | “An Exploration of Leakage Current” AVX Technical Information   |
| RD #3 | “Tantalum and Niobium Oxide Capacitors Equivalent Circuit Model Applicability to Simulation Software” J. Pelcak, 17 <sup>th</sup> European Passive Components Conference, October 2003, Stuttgart, Germany. |

### 5 LIST OF ACRONYMS

CB	Capacitor Bank
EEE	Electrical, Electronic & Electro-Mechanical
TC	Tantalum Capacitors
SCT	Surge Current Tested
STD	Standard
PCB	Printed Circuit Board
ESR	Equivalent Series Resistor
ESL	Equivalent Series Inductor
X	Capacitance
IR	Infrared
SP	Soldering Process
PT	Period of Test
WC	Worst Case

## 6 LIMITS OF UTILISATION

### 6.1 Individual capacitor use: Determination of the maximum RMS current for an individual TAJ D 22uF 35V.

In practical design cases, the designer needs to choose the capacitors to be used in the circuit according to the required electrical performances.

For low impedance, high RMS current applications, the designer needs the information of the capacitor rated voltage, rated RMS current, and impedance characteristics.

In the datasheet, or in the space procurement specification, the rated/de-rated RMS Current is not specified for the TC. The limitation is usually specified in terms of maximum rated allowable power dissipation per package. The following paragraph explains how to derive the maximum RMS current from the maximum power dissipation.

The guidelines of AVX for one single capacitor are the following:

The current waveform applied to the capacitor shall be decomposed in Fourier series. AVX provides the typical ESR values in function of frequency, and it is then possible to calculate the typical RMS power dissipation at each harmonic. Root-square sum of the individual harmonic contributions gives the typical RMS power dissipation for one capacitor. The next paragraph presents this method by using different ESR values (typical, maximum, or measured) of tantalum capacitors TAJ D 22uF 35V.

#### 6.1.1 METHOD OF THE MANUFACTURER WITH THE TYPICAL ESR

Assuming to apply a square current waveform (130KHz) with duty cycle=0.5, the RMS current at 25°C has to be lower than 1.12 A RMS to respect the rated power dissipation for that package (150mW) by using the typical ESR values in function of frequency at 25°C provided by AVX for a tantalum capacitor TAJ D 22uF 35V.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I <sup>2</sup>	Typical ESR [Ohms]	P [W]	Total P [W]
1.12	130000	1	130000	1.428887107	1.010375763	1.020859183	0.1264	1.29E-01	1.50E-01
		3	390000	0.476295702	0.336791921	0.113428798	0.09769	1.11E-02	
		5	650000	0.285777421	0.202075153	0.040834367	0.09279	3.79E-03	
		7	910000	0.20412673	0.144339395	0.020833861	0.09013	1.88E-03	
		9	1170000	0.158765234	0.112263974	0.0126032	0.0882	1.11E-03	
		11	1430000	0.129898828	0.091852342	0.008436853	0.08674	7.32E-04	
		13	1690000	0.109914393	0.077721213	0.006040587	0.08563	5.17E-04	
		15	1950000	0.09525914	0.067358384	0.004537152	0.08479	3.85E-04	
		17	2210000	0.084052183	0.059433868	0.003532385	0.08415	2.97E-04	
		19	2470000	0.075204585	0.053177672	0.002827865	0.08366	2.37E-04	
		21	2730000	0.068042243	0.048113132	0.002314873	0.08328	1.93E-04	
		23	2990000	0.062125526	0.043929381	0.001929791	0.08299	1.60E-04	
		25	3250000	0.057155484	0.040415031	0.001633375	0.08276	1.35E-04	
		27	3510000	0.052921745	0.037421325	0.001400356	0.08259	1.16E-04	
		29	3770000	0.049271969	0.034840544	0.001213863	0.08245	1.00E-04	
		31	4030000	0.046093132	0.032592767	0.001062288	0.08235	8.75E-05	
33	4290000	0.043299609	0.030617447	0.000937428	0.08227	7.71E-05			
35	4550000	0.040825346	0.028867879	0.000833354	0.08222	6.85E-05			
				sqrt of sumsq	1.115911994				

Fig.1: RMS current limit corresponding to the rated power dissipation for a TAJ D 22uF 35V with the typical ESR

But... the approach identified by AVX is NOT the worst case one, since the **TYPICAL** ESR=f(F) is used, and the power dissipated by the capacitor may be **HIGHER** than calculated !!!

### 6.1.2 MAXIMUM RMS CURRENT OBTAINED USING THE MAXIMUM ESR GIVEN BY THE MANUFACTURER

The maximum ESR (specified in the datasheet) can be used to determine the power dissipation with the same Fourier approach. The Rated Pd (150mW) is achieved for a the square wave current (130KHz) with 50% duty cycle equal to 0.41 A RMS with a considered ESR of 0.9Ω provided by AVX for a tantalum capacitor TAJ D 22uF 35V.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I <sup>2</sup>	Typical ESR [Ohms]	P [W]	Total P [W]
0.41	130000	1	130000	0.522748106	0.36963873	0.136632791	0.9	1.23E-01	1.50E-01
		3	390000	0.174249369	0.12321291	0.015181421	0.9	1.37E-02	
		5	650000	0.104549621	0.073927746	0.005465312	0.9	4.92E-03	
		7	910000	0.074678301	0.052805533	0.002788424	0.9	2.51E-03	
		9	1170000	0.058083123	0.04107097	0.001686825	0.9	1.52E-03	
		11	1430000	0.047522555	0.033603521	0.001129197	0.9	1.02E-03	
		13	1690000	0.040211393	0.028433748	0.000808478	0.9	7.28E-04	
		15	1950000	0.034849874	0.024642582	0.000607257	0.9	5.47E-04	
		17	2210000	0.030749889	0.021743455	0.000472778	0.9	4.26E-04	
		19	2470000	0.027513058	0.01945467	0.000378484	0.9	3.41E-04	
		21	2730000	0.024892767	0.017601844	0.000309825	0.9	2.79E-04	
		23	2990000	0.022728179	0.016071249	0.000258285	0.9	2.32E-04	
		25	3250000	0.020909924	0.014785549	0.000218612	0.9	1.97E-04	
		27	3510000	0.019361041	0.013690323	0.000187425	0.9	1.69E-04	
		29	3770000	0.018025797	0.012746163	0.000162465	0.9	1.46E-04	
		31	4030000	0.016862842	0.01192383	0.000142178	0.9	1.28E-04	
		33	4290000	0.015840852	0.011201174	0.000125466	0.9	1.13E-04	
35	4550000	0.01493566	0.010561107	0.000111537	0.9	1.00E-04			
sqrt of sumsq						0.408248404			

PI  
3.14159265

Fig.2: RMS current limit corresponding to the rated power dissipation for a TAJ D 22uF 35V with the maximum ESR

### 6.1.3 MAXIMUM RMS CURRENT OBTAINED BY MEASUREMENTS OF THE CAPACITOR IMPEDANCE

With the frequency analyser the impedance of the single capacitor is measured at 25°C. By using the real part of the measured impedance and assuming to apply a square current waveform (130KHz) with duty cycle=0.5, the RMS current at 25°C has to be lower than 0.93 A RMS to respect the rated power dissipation for that package (150mW).

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I <sup>2</sup>	Typical ESR [Ohms]	P [W]	Total P [W]
0.93	130000	1	130000	1.18781194	0.839909878	0.705448603	0.183	1.29E-01	1.50E-01
		3	390000	0.395937313	0.279969959	0.078383178	0.142	1.11E-02	
		5	650000	0.237562388	0.167981976	0.028217944	0.131	3.70E-03	
		7	910000	0.16968742	0.119987125	0.01439691	0.126	1.81E-03	
		9	1170000	0.131979104	0.09332332	0.008709242	0.124	1.08E-03	
		11	1430000	0.107982904	0.076355443	0.005830154	0.124	7.23E-04	
		13	1690000	0.091370149	0.064608452	0.004174252	0.124	5.18E-04	
		15	1950000	0.079187463	0.055993992	0.003135327	0.124	3.89E-04	
		17	2210000	0.069871291	0.049406463	0.002440999	0.124	3.03E-04	
		19	2470000	0.062516418	0.044205783	0.001954151	0.125	2.44E-04	
		21	2730000	0.056562473	0.039995708	0.001599657	0.126	2.02E-04	
		23	2990000	0.051643997	0.036517821	0.001333551	0.127	1.69E-04	
		25	3250000	0.047512478	0.033596395	0.001128718	0.128	1.44E-04	
		27	3510000	0.043993035	0.031107773	0.000967694	0.129	1.25E-04	
		29	3770000	0.040959032	0.02896241	0.000838821	0.129	1.08E-04	
		31	4030000	0.038316514	0.027093867	0.000734078	0.13	9.54E-05	
		33	4290000	0.035994301	0.025451814	0.000647795	0.131	8.49E-05	
35	4550000	0.033937484	0.023997425	0.000575876	0.133	7.66E-05			
sqrt of sumsq						0.927640528			

PI  
3.14159265

Fig.3: RMS current limit corresponding to the rated power dissipation for a TAJ D 22uF 35V with the measured ESR

## 6.1.4 SUMMARY

To have an idea of the maximum allowable current for different tantalum capacitor types, the same three approaches were applied for single use of TAJ 10uF, TPS 10uF and 22uF 35V. The FIG.4 summarizes this study. The details of the calculations for the TAJ 10uF and the TPS are available in annexes 1, 2 and 3.

		RMS Current* per types of tantalum capacitors			
Type	ESR	TAJ		TPS	
		10uF, 35V, K, RHJ, case D	22uF, 35V, M, RNJ, case D	10uF, 35V, K, R0300, case D	22uF, 35V, M, R0200, case D
Typical from AVX @25degC		1A RMS	1.12A RMS	0.9 A RMS	1.19 A RMS
Max at 100Khz		0.39A RMS	0.41 A RMS	0.71 A RMS	0.87 A RMS
Measured at @25degC		0.74A RMS	0.93 A RMS	0.93 A RMS	0.91 A RMS

- Assuming to apply a **square current waveform** with duty cycle=0.5 at 130KHz
- Power Dissipation of 150mW (cases D)

Fig.4: RMS current of TAJ and TPS capacitors to respect the rated power dissipation

For the same value of capacitance and rated voltage, the TPS capacitors give better performances than the TAJ ones: the TPS allow higher RMS current due to the lower ESR and the reduced ESR spread characteristics (Fig.5).

	TAJ		TPS	
	10uF	22uF	10uF	22uF
<b>Maximum Esr at 100kHz</b>	1Ω	0.9Ω	0.3Ω	0.2Ω

Fig.5: maximum ESR at 100kHz given in the manufacturer datasheet.

To follow a safe engineering approach, in absence of the envelope ESR(f) the user shall make use of the ESR maximum value given in the datasheet. Note that this may lead to a poor utilization of the devices....

## 6.1.5 REMARK CONCERNING THE MEASURED IMPEDANCES

The measured impedances (part 8 of this document presents the method and the set-up used to measure the impedance) of the capacitor 22uF, 35V, TAJ, case D, appear rather different with respect to the typical ones given in the datasheet. Fig.6 shows the measured impedances of 10 capacitors (22uF) and the typical one given by the manufacturer. In consequence, the RMS current value calculated with the measured ESR=f(F) is rather different from the calculation with the typical ESR=f(F) given by the manufacturer. It is important to note that the manufacturer explained that their typical impedances are only given for information.

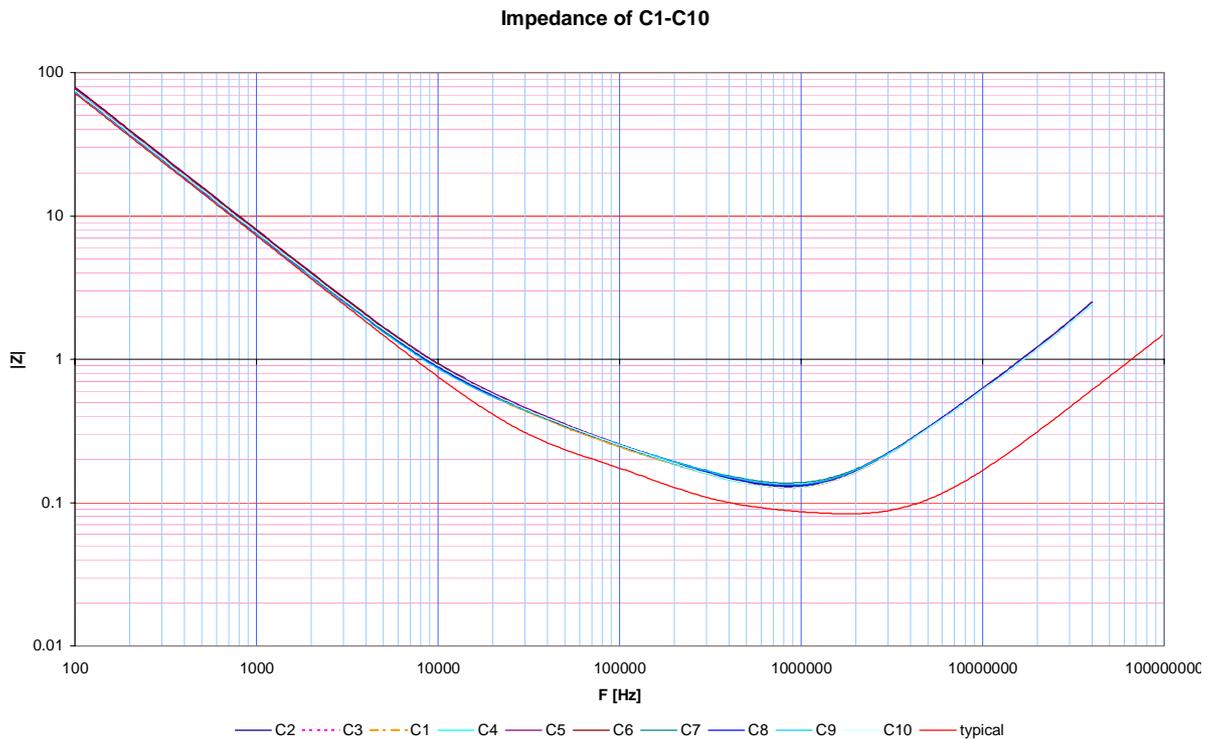


Fig.6: Impedances of TAJD, 22 $\mu$ F, 35V measured in the TEC-EP laboratory and the typical one given by the manufacturer

## 6.2 Capacitor used in parallel: Determination of the maximum RMS current of a capacitor bank

### 6.2.1 THE ISSUES OF THE PARALLEL CONFIGURATION

#### General Issue:

When capacitors are put in “straight” parallel configuration to form a capacitor bank, e.g. without resistors limiting each individual current, the current flowing into each one of them is determined not only by the circuit, but it is also highly dependent on the impedances spread of the individual capacitors.

To satisfy the power rating/de-rating, the maximum allowable RMS current into the capacitor bank cannot be the sum of the individual current capability: it shall be reduced as a decreasing function of the capacitors spread impedance.

Fig. 7 shows the phenomenon of an unequal repartition of currents in 10 capacitors connected in parallel. The uneven current repartition due to the capacitors impedance spread has for consequence a difference on the rms power dissipation of each capacitor.

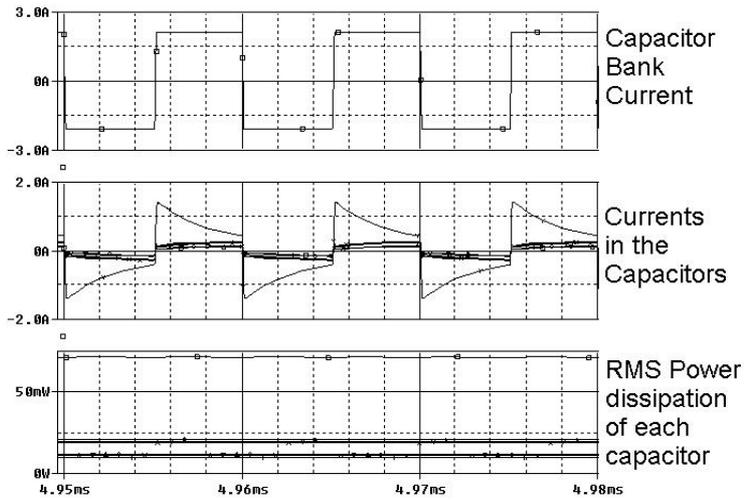


Fig.7: Unequal current repartition in a capacitor bank

The easiest way to be sure that the rated/de-rated power dissipation is never exceeded is to develop a model for each single capacitor and to vary the model elements by using a statistical analysis (Extreme Value Analysis - EVA -, Root Sum Square – RSS -, Monte Carlo, etc) to check whether the power dissipation criteria for all cases is met. The next paragraphs present several statistical analyses using 2 types of tantalum capacitor models.

### 6.2.2 RLC SERIES MODEL

A handy solution to model the tantalum capacitors is to use a simple RLC series model, identifying each element and its expected variation. A frequency analyser can give an approximation of the RLC equivalent circuit when a capacitor is characterized. Fig 8 presents the impedances of the equivalent circuit and a measured impedance of a TAJ D 22uF 35V.

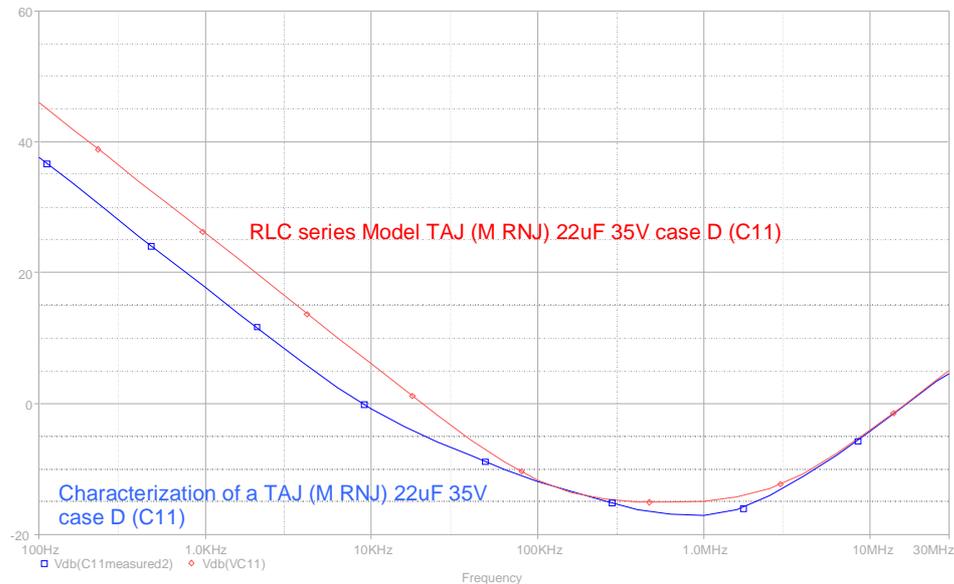


Fig. 8: Comparison between a RCL equivalent circuit and a TAJ D 22uF 35V characterized with the frequency analyser

The RLC model provides only an approximation of the real capacitor impedance.. The impedances are not exactly the same and it will have an impact on an analysis if this model is used.

### 6.2.3 MAXIMUM RMS CURRENT OBTAINED USING A WORST CASE ANALYSIS WITH THE RLC MODEL

To fix the amount of RMS current in the CB without exceeding the de-rated power dissipation, a statistical analysis was realised with Pspice (Monte Carlo Analysis with 1000 runs). Due to the lake of information concerning the possible variation of the impedances, an RLC equivalent circuit is used to replace each capacitor, with conservative margin. Fig 9 depicts the schematic of this simulation.

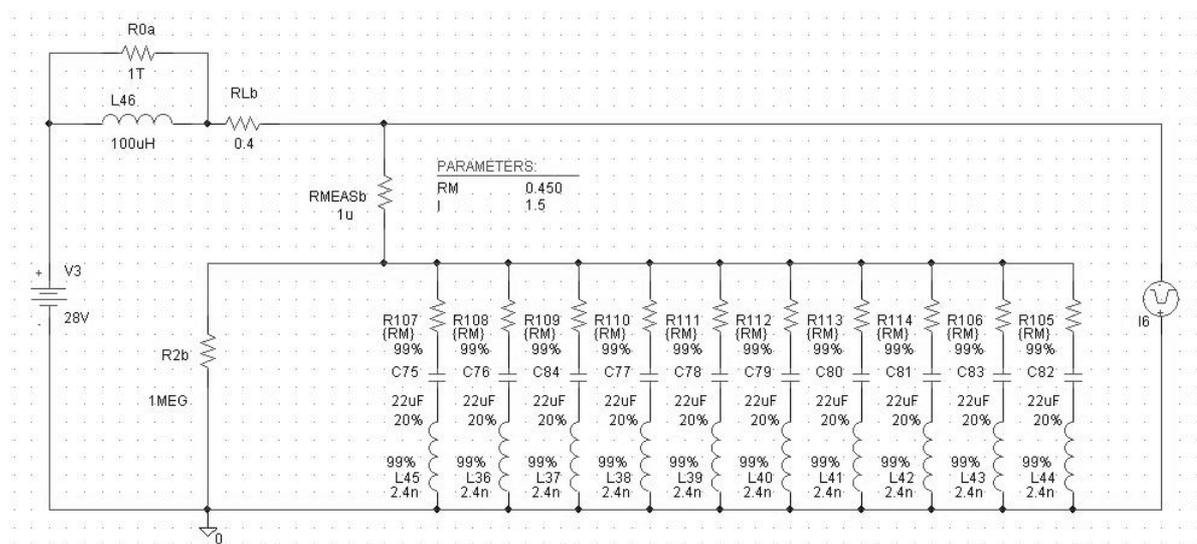


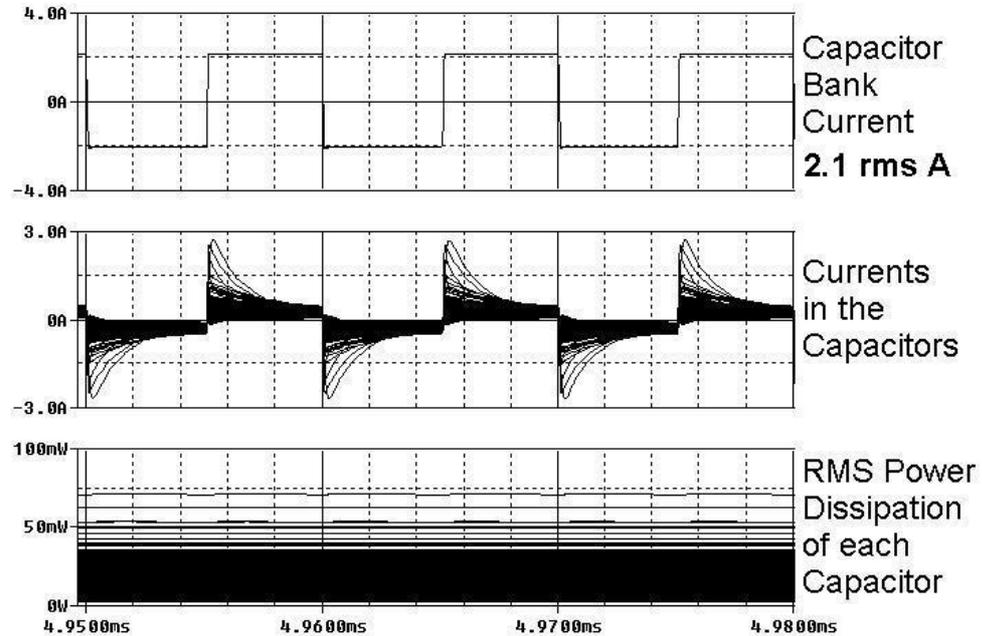
Fig. 9: schematic of the Monte Carlo analysis

The tolerances of the elements of the circuit were chosen in function of the available data in the datasheet. Conservative margin were taken. The table below presents the values and the tolerances of the RLC elements:

Elements	R	L	C
Initial value	ESRmax/2 where ESRmax is the max at 100kHz given by AVX <b>0.45Ω</b>	Typical parasitic inductor given by AVX <b>2.4nH</b>	Capacitance of the single capacitor <b>22uF</b>
Tolerance	<b>99%</b>	<b>99%</b>	Capacitor tolerance <b>20%</b>
Comments	To cover the range of values between 0 and ESRmax	To cover the range of values between 0 and 2 times the parasitic inductor	-
Range of value	<b>[0+, 0.9Ω]</b>	<b>[0+, 4.8nH]</b>	<b>22uF +/- 20%</b>

Fig. 10: values and the tolerances of the elements of the RLC model

The simulation gave the following result:



*Fig 11: results of the Monte Carlo Analysis*

By injecting **2.1A RMS** in the capacitor bank (square wave capacitor bank current, at a frequency of 100KHz and a duty cycle of 50%), the individual capacitor de-rated power dissipation is not exceeded.

As it has been shown in 6.2.2, the RLC equivalent circuit is not an accurate model. This RLC equivalent circuit method suffers from the limitations of the equivalent RLC model that does not accurately predict the typical impedance profile of the AVX TAJ tantalum capacitors. However in most of the cases the lack of data concerning the expected capacitor's impedance envelope in function of the frequency does not justify the use of more sophisticated models.

The next paragraph introduces a model developed in collaboration with the manufacturer AVX, and used for statistical analyses.

## 6.2.4 MANUFACTURER MODEL

AVX developed an accurate model to simulate the impedance of tantalum capacitors. This model is also temperature dependant. Figures 12 introduce the schematic of the AVX model for the TAJ, D, 22uF, 35V.

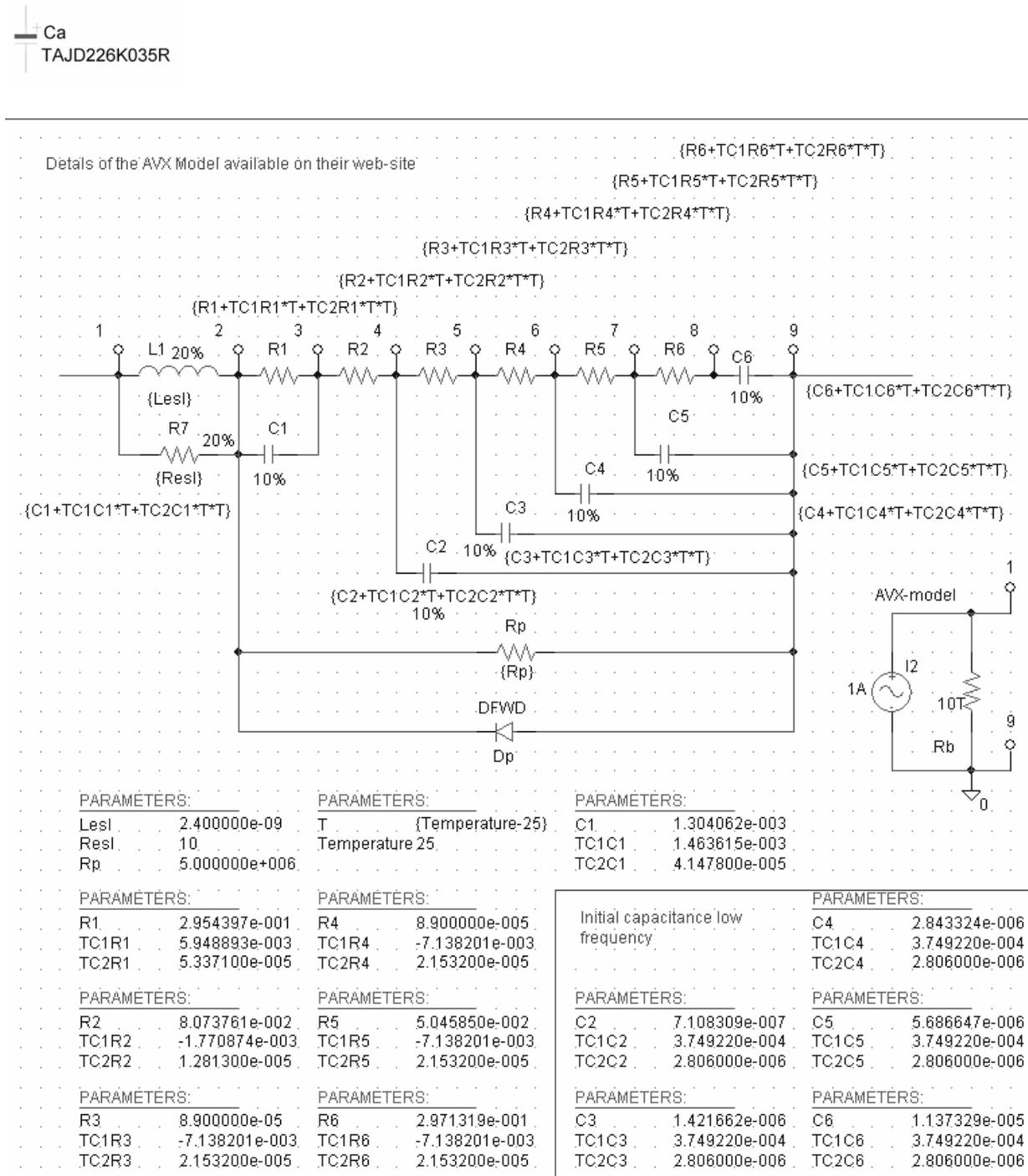


Fig 12a: Schematic of the AVX TC, TAJ, D, 22uF, 35V Model

```

.SUBCKT TAJD226K035R 1 9
*parasitic inductance
Lesl 1 2 2.400000e-009
Rels 1 2 10
*leakage current & reverse bias effects
Rp 2 9 5.000000e+006
Dp 9 2 DFWD
*RC-ladder model of frequency effects
R1 2 3 RMOD1 2.954397e-001
C1 2 3 CMOD1 1.304062e-003
R2 3 4 RMOD2 8.073761e-002
C2 4 9 CMOD2 7.108309e-007
R3 4 5 RMOD3 8.900000e-005
C3 5 9 CMOD3 1.421662e-006
R4 5 6 RMOD4 8.900000e-005
C4 6 9 CMOD4 2.843324e-006
R5 6 7 RMOD5 5.045850e-002
C5 7 9 CMOD5 5.686647e-006
R6 7 8 RMOD6 2.971319e-001
C6 8 9 CMOD6 1.137329e-005

.MODEL CMOD1 CAP (T_MEASURED=25 TC1=1.463615e-003 TC2=-
4.147800e-005)
.MODEL CMOD2 CAP (T_MEASURED=25 TC1=3.749220e-004
TC2=2.806000e-006)
.MODEL CMOD3 CAP (T_MEASURED=25 TC1=3.749220e-004
TC2=2.806000e-006)
.MODEL CMOD4 CAP (T_MEASURED=25 TC1=3.749220e-004
TC2=2.806000e-006)
.MODEL CMOD5 CAP (T_MEASURED=25 TC1=3.749220e-004
TC2=2.806000e-006)
.MODEL CMOD6 CAP (T_MEASURED=25 TC1=3.749220e-004
TC2=2.806000e-006)
.MODEL RMOD1 RES (T_MEASURED=25 TC1=5.948893e-003
TC2=5.337100e-005)
.MODEL RMOD2 RES (T_MEASURED=25 TC1=-1.770874e-003
TC2=1.281300e-005)
.MODEL RMOD3 RES (T_MEASURED=25 TC1=-7.138201e-003
TC2=2.153200e-005)
.MODEL RMOD4 RES (T_MEASURED=25 TC1=-7.138201e-003
TC2=2.153200e-005)
.MODEL RMOD5 RES (T_MEASURED=25 TC1=-7.138201e-003
TC2=2.153200e-005)
.MODEL RMOD6 RES (T_MEASURED=25 TC1=-7.138201e-003
TC2=2.153200e-005)
.MODEL DFWD D (RS=0.1 IS=1e-25 N=2.5 XTI=0 EG=0.1)
.ENDS

```

Fig 12b. Listing of the TC TAJ, D, 22uF, 35V Model.

The typical impedance from the AVX datasheet was compared to the response of the AVX model (Fig. 13).

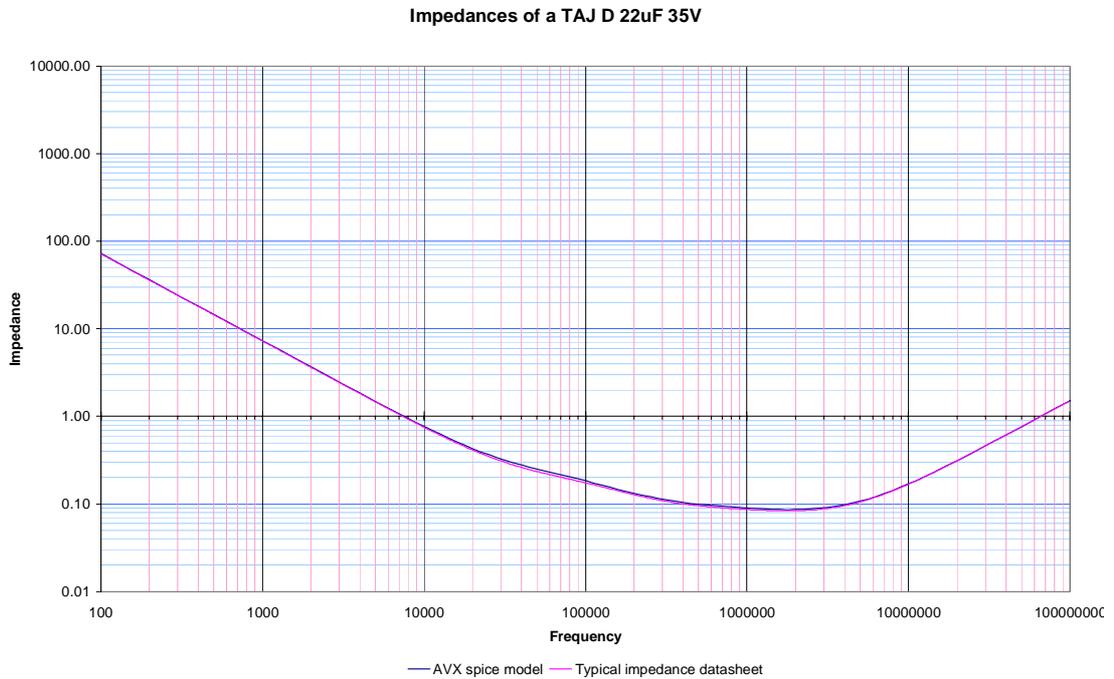


Fig. 13: Comparisons of the typical impedance and the response of the AVX model of a TAJ D 22uF 35V at 25degC.

The responses are exactly the same. This model is an accurate model and it comprises also the temperature influences on the impedances.

### 6.2.5 MODIFIED MANUFACTURER MODEL TO OBTAIN A STATISTICAL MODEL

The AVX model previously presented was used and completed with tolerances of some of its elements to obtain a statistical model. The statistical model respect the impedance expected variations provided by AVX as summarized in following table:

Laws	ESR at 100kHz	ESL	X at 100Hz
<b>Typical</b>	139mOhms	2.4nH	22uF
<b>Range of possible values of the model</b>	[80% of the typical ESR, ESR max*]	[50% of the typical ESL, 200% of the typical ESL]	Initial Tolerance +/-20%
<b>Values</b>	[111mOhms, 900mOhms]	[1.2nH, 4.8nH]	[17.6uF, 26.4uF]

\* ESRmax is the max at 100kHz given by AVX

Fig. 14: Expected variations of the tantalum capacitors TAJ 22uF 35V provided by AVX

Fig.15 presents the envelopes of the frequency characteristics given by the statistical model and the schematic of the statistical model.

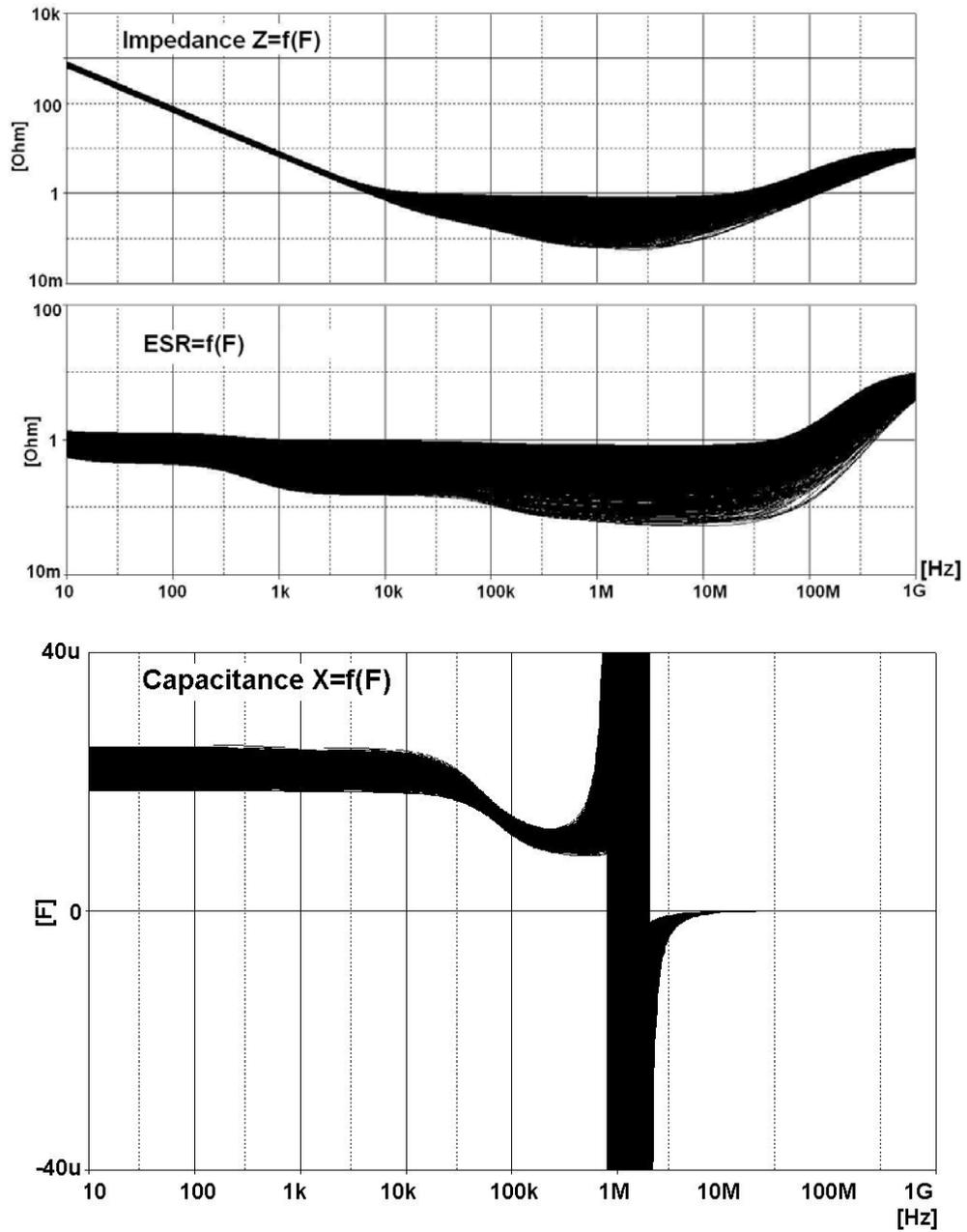


Fig.15a and b: Frequency characteristics of the new TAJ D 22uF 35V statistical model

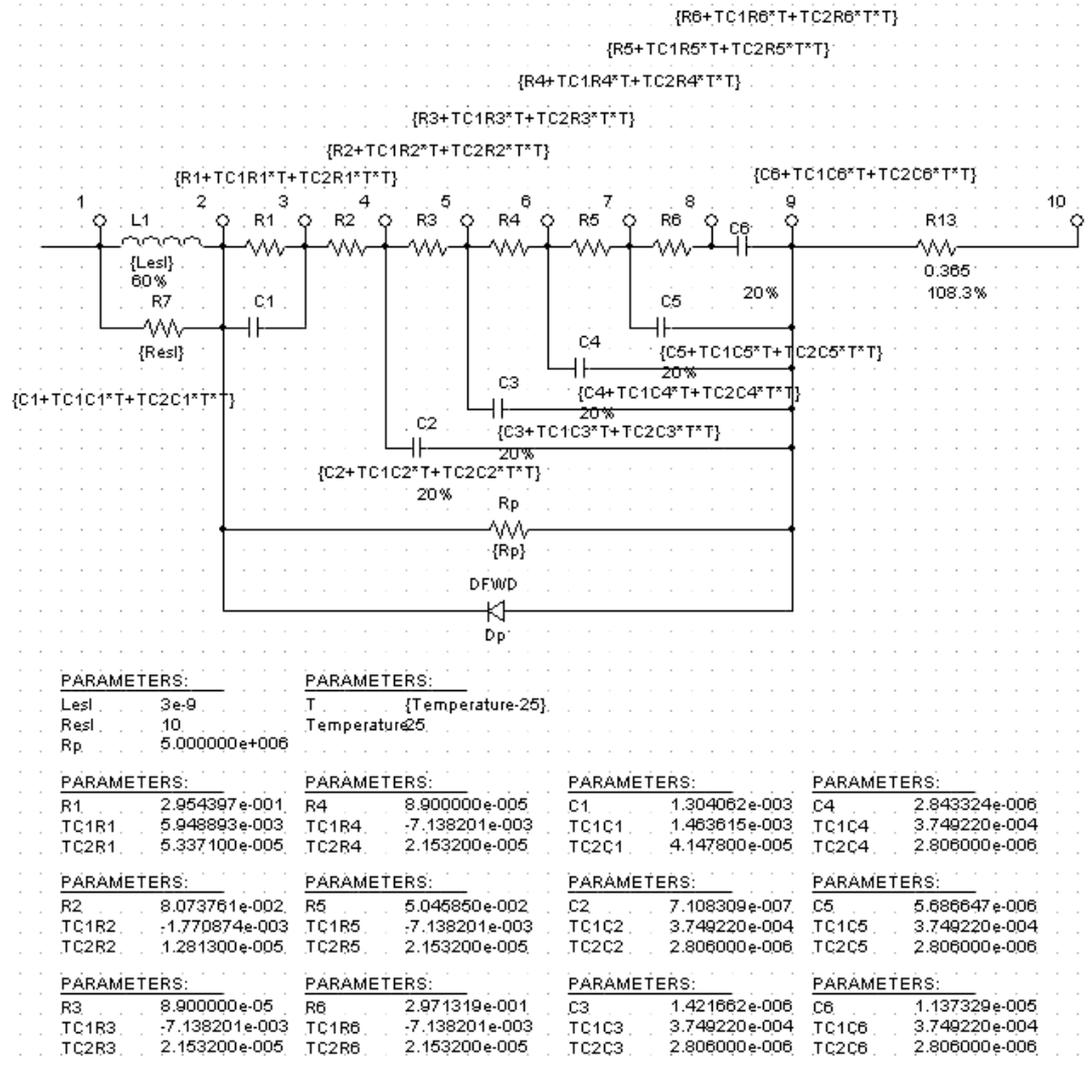


Fig.15c: The new TAJ D 22uF 35V statistical model

## 6.2.6 MAXIMUM RMS CURRENT OBTAINED USING A WORST CASE ANALYSIS WITH THE NEW MODELS

This model was then used for each capacitor in the bank. As for the Monte Carlo Analysis with the RLC models, the current injected in the capacitor bank (10 caps in parallel) was a square wave with a duty cycle=0.5 and a frequency of 100KHz. By iterations the maximum RMS current that can be injected in a capacitor bank, while respecting the individual power dissipation criteria for each capacitor was found (**2.2 Arms** for an individual capacitor de-rated power dissipation of 75mW). Fig.16 displays the results obtained with the Monte Carlo Analysis (1000 runs).

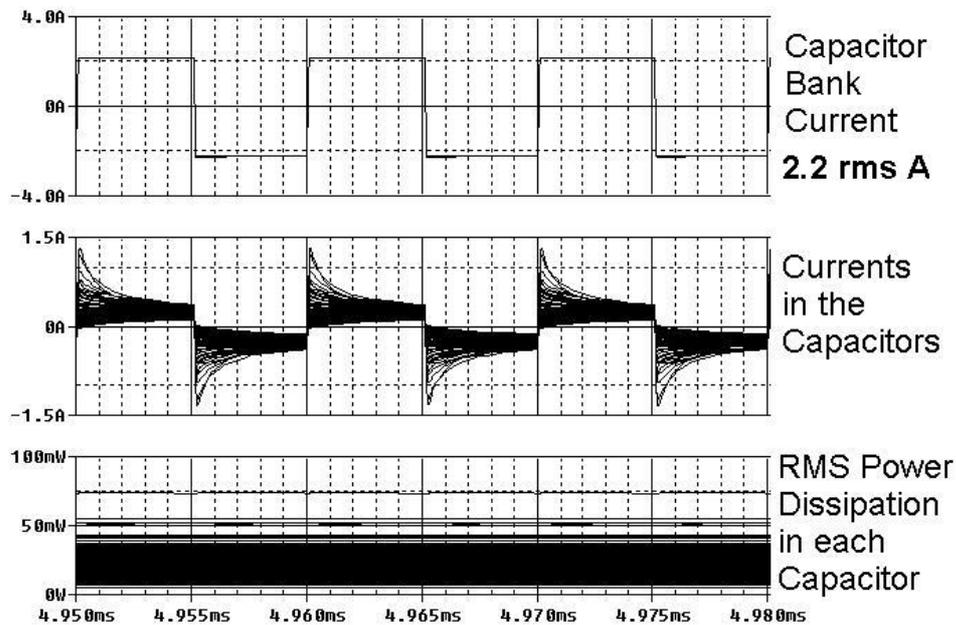


Fig.16: Result of the Monte Carlo simulation (1000 runs) with the modified AVX model.

## 6.2.7 CONCLUSIONS CONCERNING THE RESULTS OF THE MONTE CARLO ANALYSES

The Monte Carlo Analyses gave results relatively close for the 2 models used (RLC equivalent circuit model or modified AVX model). The simulation with the RLC models (with conservative margins) probably covers the worst case found with the simulation for the modified AVX model.

Assuming an applied square current waveform with duty cycle=0.5, the RMS current injected into a single capacitor type TAJ D 22uF 35V has to be lower than 0.8A RMS (at 25°C) to respect the de-rated power dissipation criteria for that package (75mW) given the typical ESR values in function of frequency at 25°C provided by AVX <sup>1</sup>.

One can note that the performances of 10 capacitors in parallel (TAJ D 22uF 35V) are not very interesting for power applications, where a high RMS current needs to be filtered. The large possible variations of ESR among the capacitors (fig.4) limit the current that can be injected into the bank to a factor only equal to 2.1/0.8=2.6 with respect to the maximum allowable current for a single capacitor (RLC model).

AVX advises for parallel configuration to use multi-anode tantalum capacitors (TPM), which have a lower ESR and a smaller range of ESR variations.

<sup>1</sup>. Method explained in the paragraph 6.1

## 7 CAPACITOR UNDER TESTS

There are many manufacturers of TC (Firadec, Kermet, AVX, etc.) with different series (TAJ, TPS for AVX, CTC21 for Firadec, etc.), different rated voltage (from 3.6V to 35V) and different value of capacitance (from a few uF to several hundreds of uF).

Due to their failure in different ESA programs, the present study focuses only on the TAJ types (35V) from the manufacturer AVX.

Capacitors ref.	Type	Quantity	Delivery week	Remarks
TAJD226M035RNJ	TAJD 22uF 35V	50	Week 50 (2004)	ESA SCT
TAJD106K035RHJ	TAJD 10uF 35V	50	Week 49 (2004)	ESA SCT

To ensure full traceability, each capacitor was labelled.

Capacitors ref.	Type	Labels
TAJD226M035RNJ	TAJD 22uF 35V ESA SCT	C1 to C50
TAJD106K035RHJ	TAJD 10uF 35V ESA SCT	B1 to B50

## 8 INITIAL SIGNATURES

The leakage current and the impedances of the capacitors represent their signature. During the tests the signatures of the capacitors are followed and their eventual evolutions analysed. At the beginning of the tests campaign, the individual signatures of all the capacitors were identified. The following part presents and analyses the results.

The detailed test set-ups and test conditions are specified in paragraph 11

## 8.1 Leakage current

The measurements of the 50 capacitors TAJs 22F and the 50 capacitors TAJs 10 $\mu$ F gave the following results:

TESTS OF TANTALUM CAPACITORS  
22 $\mu$ F 35V

Reference  
TAJD226M035RNJ-AVX-ESA

Individual Signature of the capacitors

Reference	Capacitor Bank	Temperature	Leakage Current	Test Time
C1	CB13	22	7.01E-08	04:31.6
C2	CB13	22.1	6.41E-08	04:32.1
C3	CB13	22.3	1.05E-07	04:34.6
C4	CB13	22.4	6.81E-08	04:32.2
C5	CB13	22.7	2.04E-07	04:32.2
C6	CB13	22.7	1.24E-07	04:32.3
C7	CB13	22.6	7.51E-08	04:32.5
C8	CB13	22.8	6.61E-08	04:31.7
C9	CB13	23	6.01E-08	04:32.7
C10	CB13	22.9	6.41E-08	04:31.3
C11	CB14	22.9	7.81E-08	04:31.1
C12	CB14	22.7	9.42E-08	04:32.2
C13	CB14	22.6	6.91E-08	04:32.5
C14	CB14	22.9	7.01E-08	04:32.0
C15	CB14	23	8.01E-08	04:32.2
C16	CB14	23.2	1.06E-07	03:32.6
C17	CB14	23.3	8.92E-08	04:30.8
C18	CB14	23.3	1.66E-07	04:30.2
C19	CB14	23.7	6.01E-08	04:31.5
C20	CB14	23.4	6.71E-08	04:32.1
C21	CB15	23.3	6.71E-08	04:31.2
C22	CB15	23.3	6.41E-08	04:31.3
C23	CB15	23.4	6.51E-08	04:32.2
C24	CB15	23.5	2.06E-07	04:31.9
C25	CB15	22.8	6.31E-08	04:31.1
C26	CB15	23	6.01E-08	04:31.6
C27	CB15	23	8.51E-08	04:30.3
C28	CB15	23.2	6.51E-08	04:32.8
C29	CB15	23.3	1.18E-07	04:32.1
C30	CB15	23	5.61E-08	04:31.2
C31	CB16	23	7.01E-08	04:31.3
C32	CB16	23.1	1.00E-07	04:31.8
C33	CB16	23.2	6.71E-08	04:32.2
C34	CB16	23.2	7.31E-08	04:32.2
C35	CB16	23.3	8.72E-08	04:31.3
C36	CB16	23.5	6.71E-08	04:32.0
C37	CB16	23.4	7.01E-08	04:32.0
C38	CB16	23.3	7.51E-08	04:31.0
C39	CB16	23.3	6.21E-08	04:32.0
C40	CB16	21.3	6.21E-08	04:31.5
C41	CB17	21.5	1.10E-07	04:31.8
C42	CB17	21.9	9.22E-08	04:32.2
C43	CB17	22	6.71E-08	04:32.3
C44	CB17	22.1	1.75E-07	04:31.1
C45	CB17	22.2	6.51E-08	04:32.1
C46	CB17	22.6	7.31E-08	04:32.9
C47	CB17	22.6	2.30E-07	04:30.9
C48	CB17	22.7	7.21E-08	04:33.0
C49	CB17	22.7	5.71E-08	04:31.3
C50	CB17	22.7	9.02E-08	04:30.7

TESTS OF TANTALUM CAPACITORS  
10uF 35V

Reference  
TAJD226M035RNJ-AVX-ESA

Individual Signature of the capacitors

Reference	Capacitor Bank	Temperature	Leakage Current	Test Time
B1	CB7	22	6.01E-08	04:29.2
B2	CB7	22	6.21E-08	04:31.5
B3	CB7	22	3.71E-08	04:31.9
B4	CB7	22	2.70E-08	04:35.5
B5	CB7	22	3.81E-08	04:31.4
B6	CB7	22	2.70E-08	04:36.4
B7	CB7	22	2.60E-08	04:31.3
B8	CB7	22	2.30E-08	04:32.8
B9	CB7	22	3.51E-08	04:33.1
B10	CB7	22	9.92E-08	04:30.3
B11	CB8	22	2.00E-08	04:34.2
B12	CB8	22	2.20E-08	04:32.2
B13	CB8	22	2.60E-08	04:31.0
B14	CB8	22	2.60E-08	04:33.3
B15	CB8	22	2.50E-08	04:33.8
B16	CB8	22	2.20E-08	04:33.5
B17	CB8	22	2.80E-08	04:30.6
B18	CB8	22	2.20E-08	04:31.2
B19	CB8	22	6.31E-08	04:31.6
B20	CB8	22	2.50E-08	04:33.1
B21	CB9	22	1.40E-07	04:30.8
B22	CB9	22	3.31E-08	04:32.1
B23	CB9	22	5.31E-08	04:33.3
B24	CB9	22	2.70E-08	04:30.9
B25	CB9	22	2.40E-08	04:31.7
B26	CB9	22	2.40E-08	04:31.2
B27	CB9	22	2.50E-08	04:31.3
B28	CB9	22	3.11E-08	04:32.1
B29	CB9	22	2.70E-08	04:32.5
B30	CB9	22	3.81E-08	04:30.7
B31	CB10	22	3.41E-08	04:32.0
B32	CB10	22	2.70E-08	04:29.6
B33	CB10	22	2.80E-08	04:31.1
B34	CB10	22	2.91E-08	04:30.9
B35	CB10	22	7.01E-08	04:32.8
B36	CB10	22	2.70E-08	04:32.2
B37	CB10	22	2.40E-08	04:31.4
B38	CB10	22	3.41E-08	04:30.6
B39	CB10	22	6.21E-08	04:30.8
B40	CB10	22	3.01E-08	04:30.7
B41	CB11	22	2.30E-08	04:30.9
B42	CB11	22	2.30E-08	04:32.0
B43	CB11	22	2.10E-08	04:33.1
B44	CB11	22	2.30E-08	04:29.8
B45	CB11	22	2.00E-08	04:35.4
B46	CB11	22	2.00E-08	04:31.3
B47	CB11	22	2.60E-08	04:32.1
B48	CB11	22	3.61E-08	04:31.8
B49	CB11	22	1.80E-08	04:30.0
B50	CB11	22	2.10E-08	04:33.3

### Analysis of the results

A statistical analysis was performed on the individual leakage currents.

Leakage Current	Mean	Sigma	Min	Max	Datasheet Max
50 TC TAJ D 22uF 35V (surge current tested)	88.8nA	40.7nA	60nA	230nA	7.7uA
50 TC TAJ D 10uF 35 V (surge current tested)	35nA	12.88nA	20nA	140nA	3.5uA

Confidence level of the statistical variables: 95%

The leakage current of the 2 series (10uF and 22uF) of capacitors is much lower than the maximum one given in the manufacturer datasheet. There is a ratio of 33 for the TAJ 22uF between the datasheet maximum leakage current and the maximum measured leakage current. This ratio is equal to 25 for the TAJ 10uF.

## 8.2 Initial Frequency characterization

### 8.2.1 TAJ 22UF 35V SURGE CURRENT TESTED (REF: TAJ D 226 M 035 RNJ SCT)

#### 8.2.1.1 Initial individual Impedances

The test method and set-up to measure the impedances is defined in the paragraph 11 of the present document.

The initial individual impedance measurements of the TAJ 22uF gave the following results:

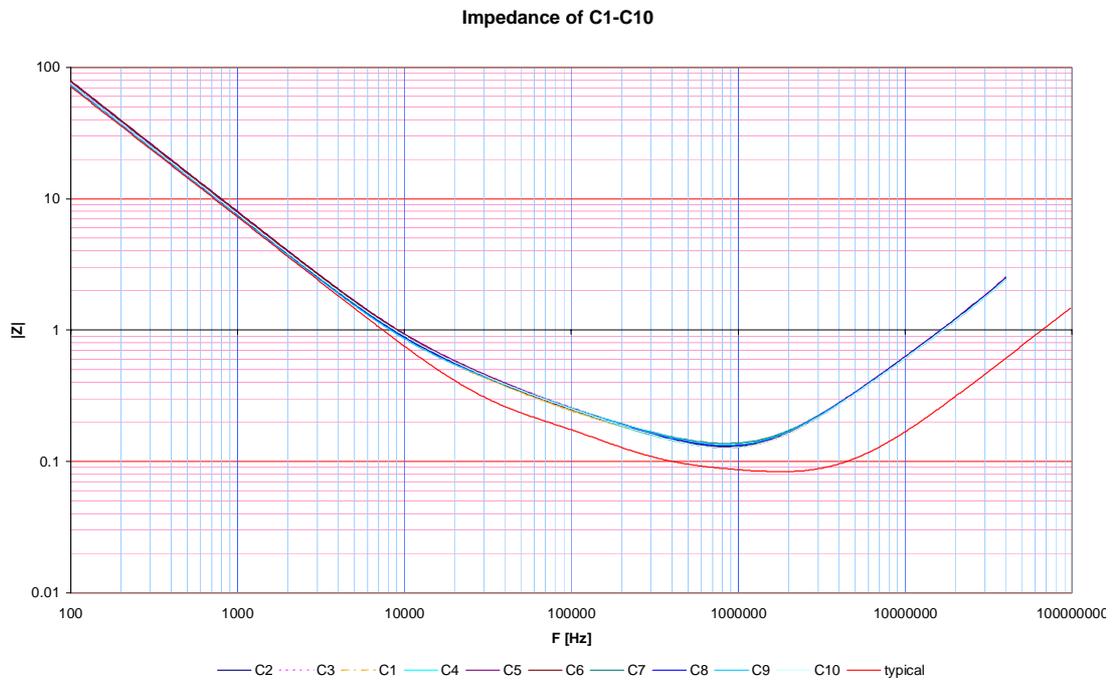


Fig 17: Impedances of 10 capacitors TAJD 22uF 35V (C1-C10)

The plots of the impedances of the capacitors C11 to C50 are available in annex 1.

#### **Analysis of the results:**

As shown by the figures 7 and in annex 1 of the impedance in function of the frequency, the individual impedances do not present significant differences between each other. It was as expected, since the capacitors come from the same lot.

However a non-negligible difference remains between the measurements results and the typical impedance given by the manufacturer. It is important to highlight that in the impedances characterization, the accuracy and the stability of the frequency analyzer is checked by the measure of a stable PM90 capacitor before and after the tantalum capacitor impedances measurements.

#### *8.2.1.2 ESR=f(F) and Capacitance X=f(F)*

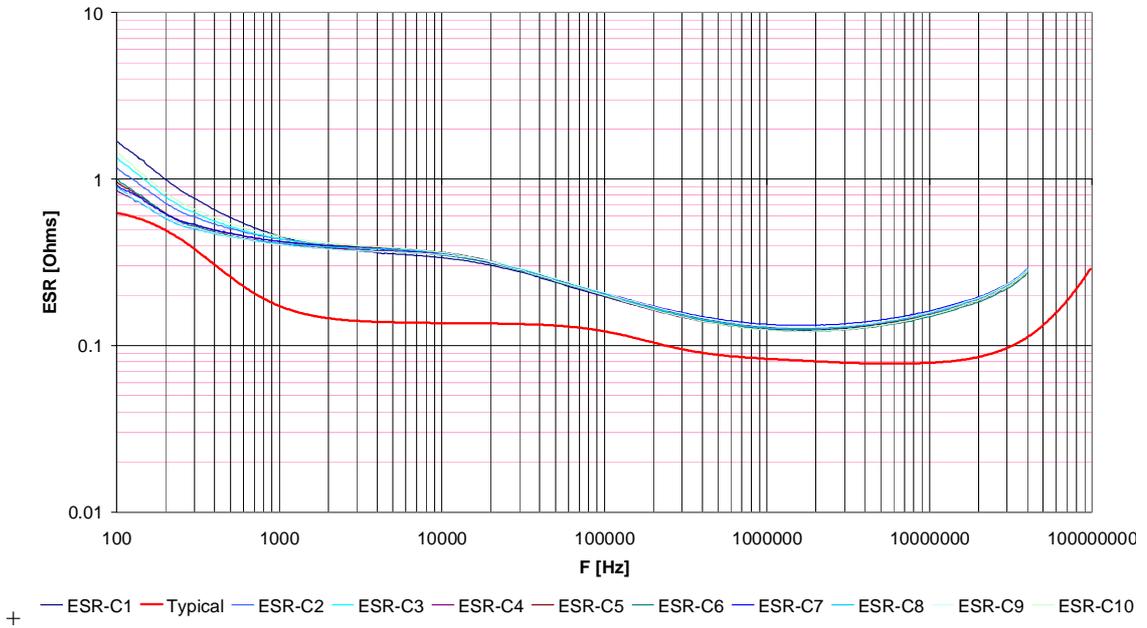
With the measurement of the impedance (module and phase), it is possible to plot the ESR and the capacitance in function of the frequency of the capacitors. The impedance can be decomposed in two parts:

$$Z(F) = ESR(F) + \frac{1}{j \cdot X(F) \cdot \omega}$$

Where, F is the frequency [Hz], X the capacitance of the capacitor [F], and  $\omega$  the pulsation [rad/s].

The next paragraph presents the frequency –dependent capacitance and ESR of the capacitors C1-C10, as well as a statistical analysis.

**ESR=f(F) C1-C10**



**X=f(F) C1-C10**

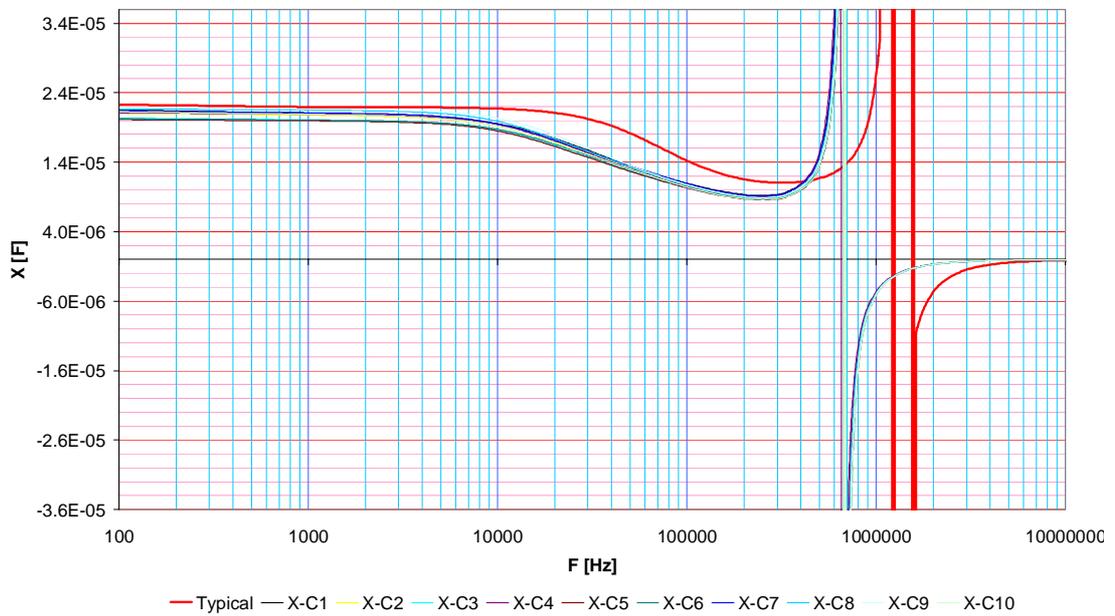


FIG 18A AND 13B: ESR (F) AND CAPACITANCE X(F) OF 10 CAPACITORS TAJD 22UF 35V (C1-C10)

**Analysis of the results:**

In the datasheet the ESR is measured at 100KHz and the capacitance at 120Hz. The table below summarises the ESRs and capacitances of the capacitors TAJ D 22uF 35V at these frequencies and at ambient temperature.

Capacitor	X at 120Hz [uF]	ESR at 100KHz [Ohms]
C1	21.49	0.197
C2	21.02	0.204
C3	20.33	0.201
C4	21.09	0.198
C5	20.11	0.204
C6	20.22	0.199
C7	21.32	0.206
C8	21.64	0.203
C9	21.85	0.207
C10	21.20	0.200
C11	21.03	0.207
C12	20.56	0.200
C13	21.79	0.200
C14	21.12	0.201
C15	21.75	0.207
C16	21.52	0.204
C17	21.53	0.202
C18	21.89	0.204
C19	21.30	0.193
C20	21.78	0.205
C21	21.31	0.190
C22	20.32	0.202
C23	21.76	0.200
C24	21.49	0.206
C25	21.32	0.198

Capacitor	X at 120Hz [uF]	ESR at 100KHz [Ohms]
C26	21.23	0.202
C27	20.23	0.199
C28	21.03	0.206
C29	21.69	0.210
C30	21.43	0.199
C31	21.32	0.209
C32	21.66	0.205
C33	21.96	0.201
C34	21.53	0.196
C35	20.52	0.196
C36	21.71	0.198
C37	21.39	0.199
C38	21.80	0.203
C39	20.35	0.200
C40	20.82	0.205
C41	21.79	0.201
C42	21.58	0.206
C43	21.09	0.199
C44	21.75	0.204
C45	21.78	0.205
C46	22.01	0.204
C47	21.08	0.189
C48	20.60	0.196
C49	21.46	0.199
C50	21.95	0.203

Capacitance	
Mean	21.29
Standard Error	0.074377
Median	21.41
Mode	21.32
Standard Deviation	0.525924
Sample Variance	0.276596
Kurtosis	-0.357143
Skewness	-0.79803
Range	1.9
Minimum	20.11
Maximum	22.01
Sum	1064.5
Count	50
Largest(1)	22.01
Smallest(1)	20.11
Confidence Level(95.0%)	0.149466

ESR	
Mean	0.20144
Standard Error	0.0006235
Median	0.2015
Mode	0.204
Standard Deviation	0.0044085
Sample Variance	1.944E-05
Kurtosis	0.7139474
Skewness	-0.637983
Range	0.021
Minimum	0.189
Maximum	0.21
Sum	10.072
Count	50
Largest(1)	0.21
Smallest(1)	0.189
Confidence Level(95.0%)	0.0012529

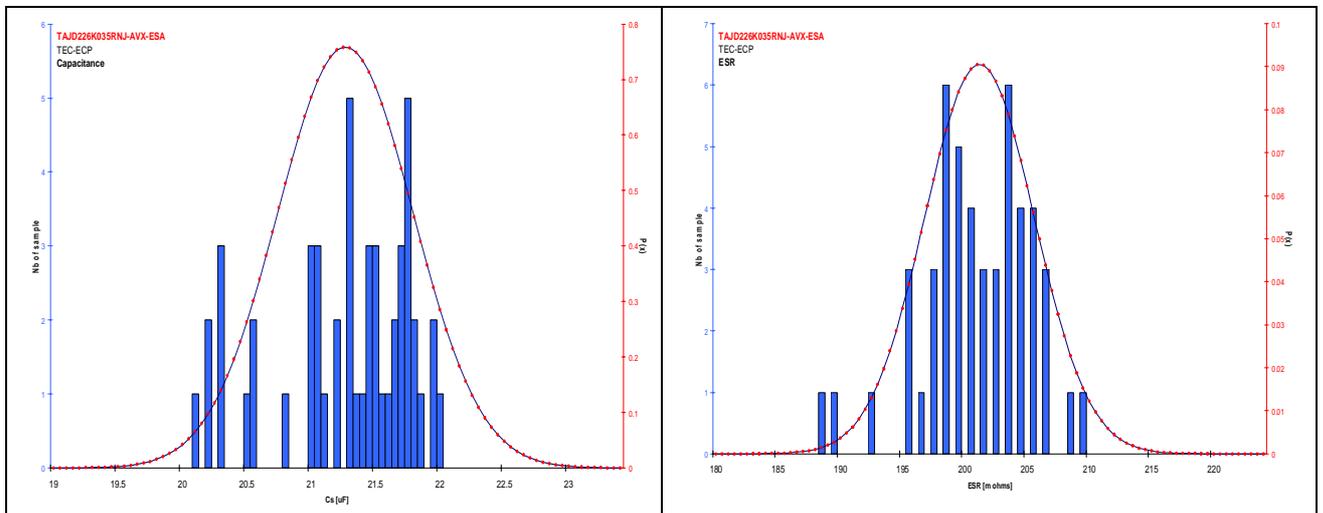


Fig 19: Capacitances and ESRs statistical analysis of the 50 capacitors (C1-C50) TAJD 22uF 35V

The initial tolerance of the capacitors is +/-20%. All the capacitance values are in this range. The low number of measurements (50) explains the fact that the repartition of the capacitances measured is not represented by a Gaussian and also why the histogram is not centered exactly on the value 22uF.

The typical value of the ESR of the TAJ D 22uF 35V at 100KHz and 25degC is 138.7mΩ (from the datasheet software SpitanII, available on the web-site of AVX). This typical value is much lower than the measured values. The typical ESR performances of the given in the datasheet are better than the ESRs performances of the measured capacitors.

The mean of the overall ESRs measurements is 201mΩ and the values are comprised in the range +/-6% of the mean. This narrow range of values is probably due to the fact that the capacitors come from the same lot.

The maximum ESR is specified at 900m Ω in the manufacturer datasheet (at100Khz). The measured values are much lower than this value. The manufacturer takes margin probably for eventual differences of ESR among different lots.

## 8.2.2 TAJ 10UF 35V SURGE CURRENT TESTED (REF: TAJ D 106 K 035 RHJ SCT)

### 8.2.2.1 Initial individual Impedances

The initial single impedances of the TAJ10uF give the following results:

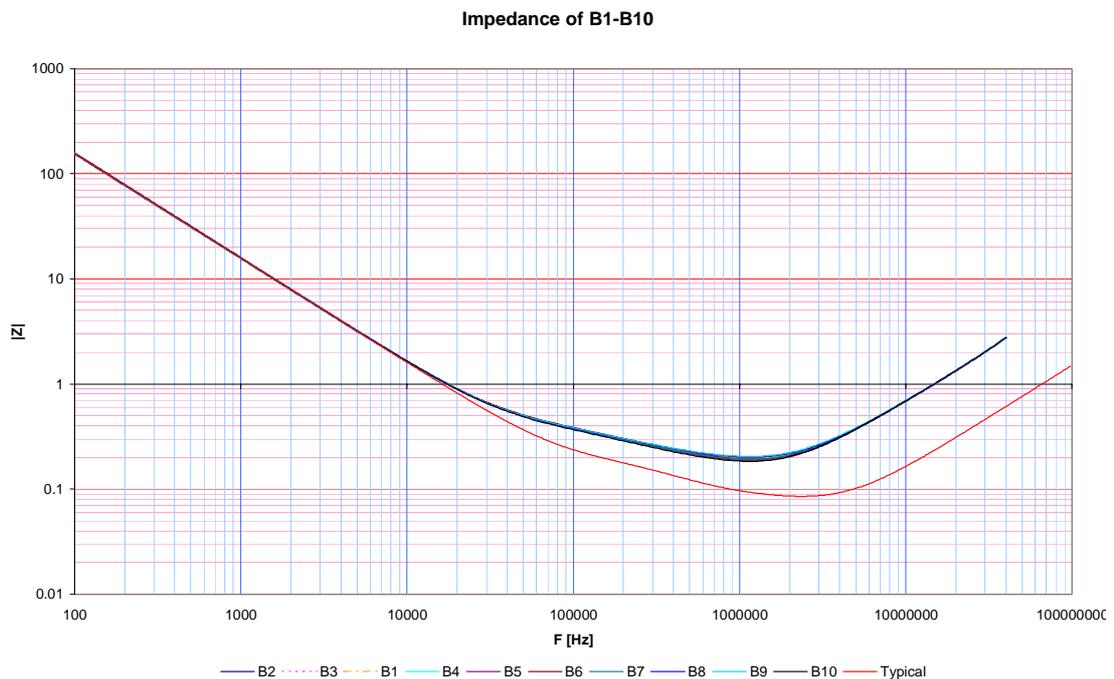


Fig 20: Impedances of 10 capacitors (B1-B10) TAJD10uF 35V

**Analysis of the results:**

As for the capacitors TAJ D 22uF, the TAJ D 10uF present impedances very close between them (same lot), but different in comparison with the typical one given by the manufacturer. From these measurements, the ESRs and the capacitances of the capacitors were plotted.

**8.2.2.2 ESR=f(F) and Capacitance X=f(F)**

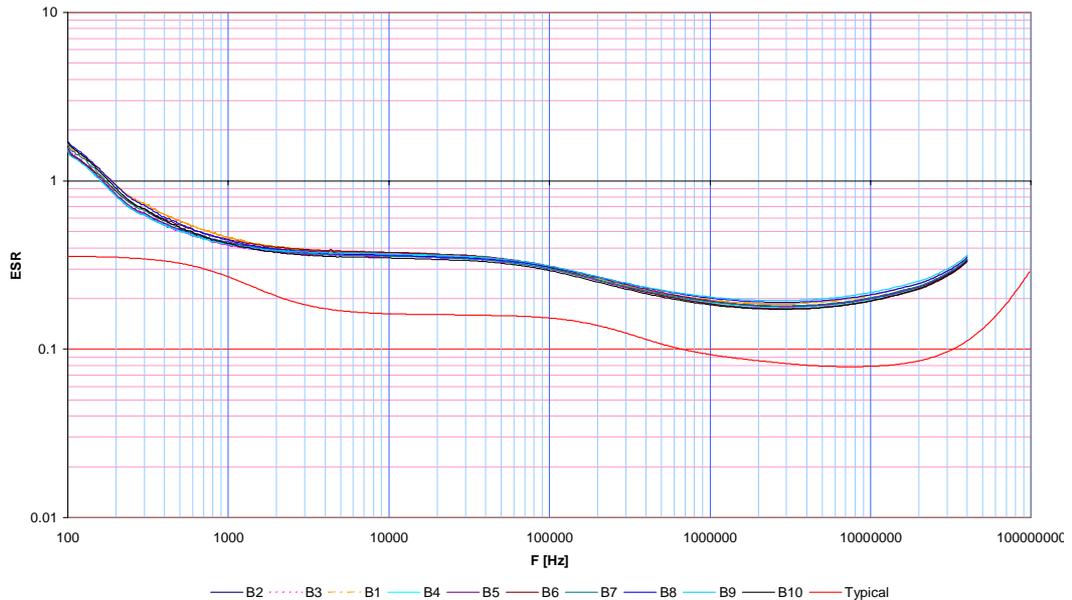
With the measurement of the impedance (module and phase), it is possible to plot the ESR and the capacitance in function of the frequency of the capacitors. The impedance can be decomposed in two parts:

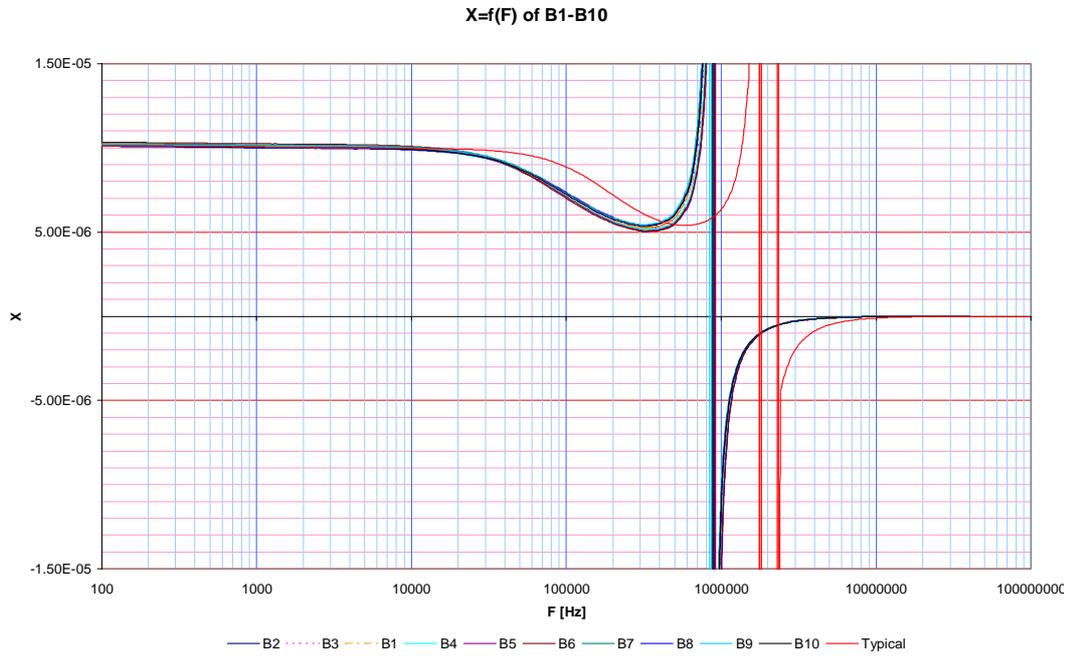
$$Z(F) = ESR(F) + j \cdot \frac{1}{X(F) \cdot \omega}$$

where F is the frequency [Hz], X the capacitance of the capacitor [F], and  $\omega$  the pulsation [rad/s].

The next paragraph presents for the capacitors B1-B10, their capacitances and ESRs in function of the frequency as well as a statistical analysis.

**ESR=f(F) of B1-B10**





*Fig 21a and b: ESRs and Capacitances of 10 capacitors (B1-B10) TAJD 10uF 35V*

The plots of ESRs=f(F) and X=f(F) of the capacitor B11 to B50 are available in annex 2.

**Analysis of the results:**

In the datasheet the ESR is measured at 100KHz and the capacitance at 120Hz. The table below summarises the ESRs and capacitances of the capacitors TAJ D 10uF 35V at these frequencies and at ambient temperature and pressure.

Capacitor	X at 120Hz [uF]	ESR at 100KHz [mOhms]
B1	10.23	309.912
B2	10.14	307.268
B3	10.09	296.907
B4	10.08	297.648
B5	10.14	304.038
B6	10.32	295.581
B7	10.26	289.325
B8	10.08	296.101
B9	10.17	296.644
B10	10.11	276.301
B11	10.26	304.748
B12	10.36	306.279
B13	10.24	308.302
B14	10.26	301.567
B15	10.35	302.760
B16	10.31	310.237
B17	10.25	314.755
B18	10.08	312.380
B19	10.26	312.180
B20	10.21	303.233
B21	10.23	298.789
B22	10.30	309.772
B23	10.32	308.230
B24	10.31	303.926
B25	10.11	296.977

Capacitor	X at 120Hz [uF]	ESR at 100KHz [mOhms]
B26	10.26	306.023
B27	10.18	305.587
B28	10.17	313.004
B29	10.27	300.191
B30	10.25	311.162
B31	10.20	318.453
B32	10.33	315.335
B33	10.27	309.710
B34	10.09	329.226
B35	10.09	312.620
B36	10.08	311.869
B37	10.23	301.210
B38	10.22	312.473
B39	10.35	297.891
B40	10.25	299.030
B41	10.31	309.117
B42	10.10	314.216
B43	10.32	304.063
B44	10.14	308.771
B45	10.24	298.845
B46	10.07	309.740
B47	10.18	291.961
B48	10.08	321.120
B49	10.17	316.443
B50	10.19	306.234

Capacitance	
Mean	10.21
Standard Error	0.01238
Median	10.23281
Mode	#N/A
Standard Deviation	0.08754
Sample Variance	0.007663
Kurtosis	-1.18029
Skewness	-0.137861
Range	0.285684
Minimum	10.07104
Maximum	10.35673
Sum	510.5002
Count	50
Largest(1)	10.35673
Smallest(1)	10.07104
Confidence Level(95.0%)	0.024879

ESR	
Mean	305.76315
Standard Error	1.253705
Median	306.25648
Mode	#N/A
Standard Deviation	8.8650331
Sample Variance	78.588812
Kurtosis	1.8502115
Skewness	-0.449533
Range	52.925186
Minimum	276.30094
Maximum	329.22612
Sum	15288.157
Count	50
Largest(1)	329.22612
Smallest(1)	276.30094
Confidence Level(95.0%)	2.519413

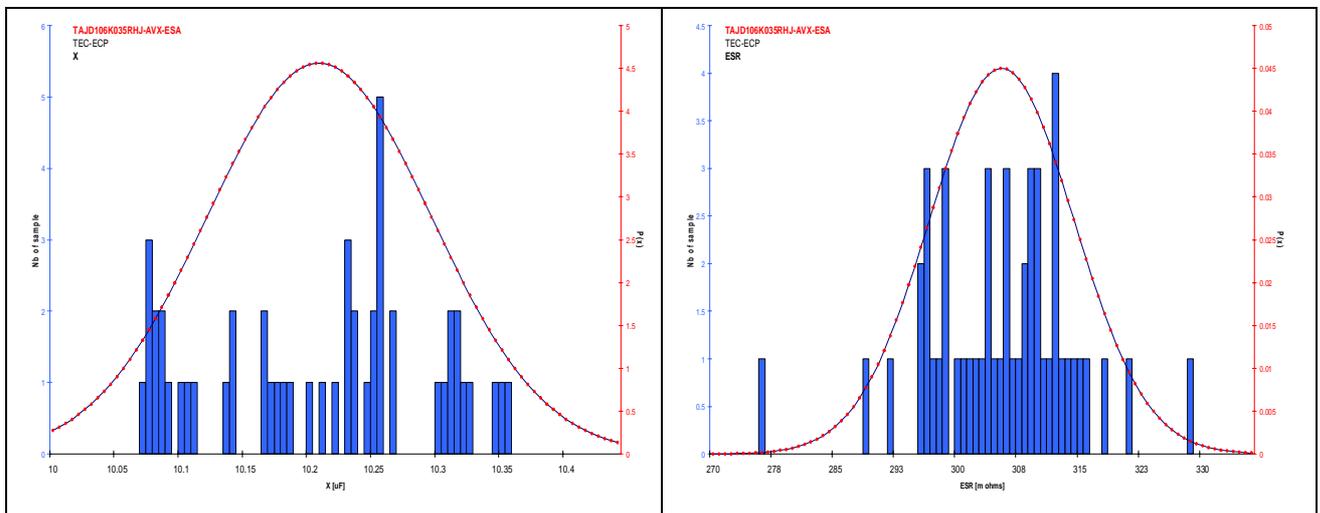


Fig 22: Capacitances and Esrs statistical analysis of the 50 capacitors (B1-B50) TAJD 10uF 35V

The initial tolerance of the capacitors is +/-10%. All the capacitances measured do belong to this range. As for the 22uF capacitors, the low number of measurements (50) explains the fact that the repartitions of the capacitances and ESRs measurements are not represented by a Gaussian and also why the histograms are not centered on the typical value.

The typical value of the ESR of the TAJ D 10uF 35V at 100KHz and 25degC is 168.3mΩ (from the datasheet software SpitanII, available on the web-site of AVX). This value is much lower than the measured values. The frequency impedance performances of the typical impedance given in the datasheet are better than the performances of the measured capacitors.

The mean of the overall ESRs measurements is 305.8mΩ and the values are comprised in the range +/-10% around this mean. This narrow range of values is probably due to the fact that the capacitors come from the same lot.

The maximum ESR is specified at 1Ω (100 KHz) in the manufacturer datasheet. The measured values are much lower than this value. The manufacturer takes a margin probably for eventual differences of ESR among different lots.

## 9 CAPACITOR SOLDERING

A total of 10 capacitor banks were soldered. Each capacitor bank consists of 10 capacitors in parallel (same type and value).

Capacitors ref.	Type	Caps. Labels	CB Labels
TAJD106K035RHJ	TAJD 10uF 35V ESA SCT	B1 to B10	CB7
		B11 to B20	CB8
		B21 to B30	CB9
		B31 to B40	CB10
		B41 to B50	CB11

Capacitors ref.	Type	Caps. Labels	CB Labels
TAJD226M035RNJ	TAJD 22uF 35V ESA SCT	C1 to C10	CB13
		C11 to C20	CB14
		C21 to C30	CB15
		C31 to C40	CB16
		C41 to C50	CB17

### 9.1 Soldering conditions

#### 9.1.1 AVX GUIDELINES

The guidelines of the manufacturer AVX for IR reflow are the following:

- The slope of the component land temperature profile has to be lower than 2degC/sec.
- The peak of temperature has to be lower than 220degC (see figure 23).
- The period of time when the component land temperature is higher than the solder melting temperature (186degC) has to be shorter than 45 seconds.

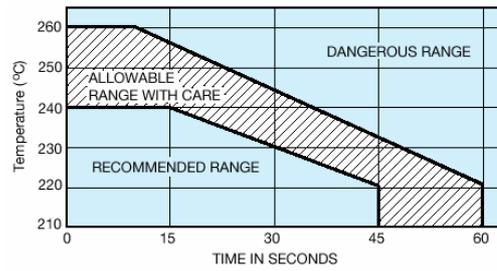
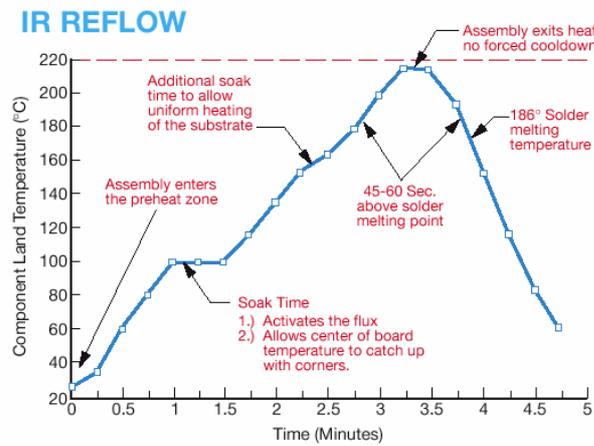


Fig 23. Allowable range of peak temp. /time combination for IR reflow

AVX summarizes these three precautions with the following graph (Fig. 24).



Recommended Ramp Rate Less than 2°C/sec.

Fig. 24: Ideal temperature profile for IR reflow.

### 9.1.2 ESA ALERT

After failures of TC, ESA emitted recommendations concerning the soldering process in the ESA-Alert. The extract of this alert is the following:

The maximum soldering temperature is limited to 10°C less than that recommended by the manufacturer, and the relevant soldering time is equal to or less than the minimum recommended by the manufacturer. Due to capacitor dielectrics being very sensitive to thermal damage during component attachment, in particular the higher voltage dielectrics (35 Volt +), it is essential that the appropriate profile be applied as recommended by the capacitor manufacturer. It should be noted that older date codes may require different profiles to those currently advertised, this should be checked with the manufacturer.

In other words, the maximum peak of component land temperature has to be lower than 210degC. The slopes and the period time when the temperature is higher than 186degC remain the same.

### 9.1.3 TEMPERATURE PROFILES OF THE TESTED CAPACITOR BANKS

The capacitors were soldered by NETRONIC (Bogardeind 164, 5664 EN Geldrop, The Netherlands). This company works sometimes for ESTEC (sections SCI-AP and SCI-AI). With the help of Bengt Johlander and Johannes Heida from these two sections, it was decided to ask Netronic to solder the capacitors.

During the soldering process it appeared that it is difficult to follow the temperature profile (Fig. 24) of AVX. Another capacitor bank (CB12) with commercial capacitors (22uF, not surge current tested) was used to measure the component land temperature. Fig. 25 presents the measured profile. This temperature profile shows that the capacitors were soldered safely within the applicable limits. The peak of temperature is 200degC, the increased slope is lower than 2deg/sec and the period when the temperature is higher than 186 (solder melting point) is close to 45 seconds.

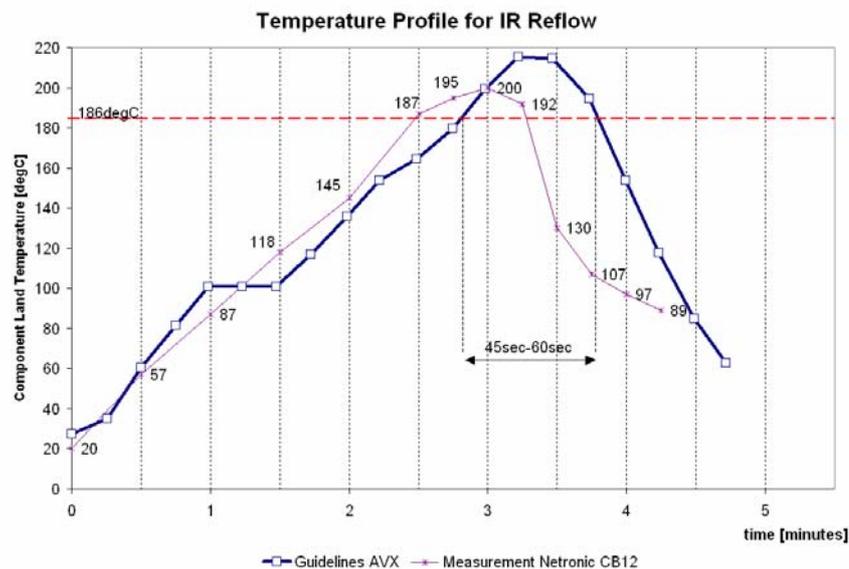
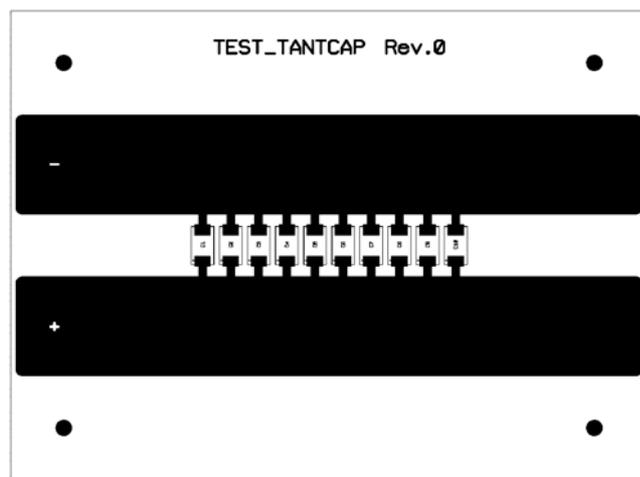
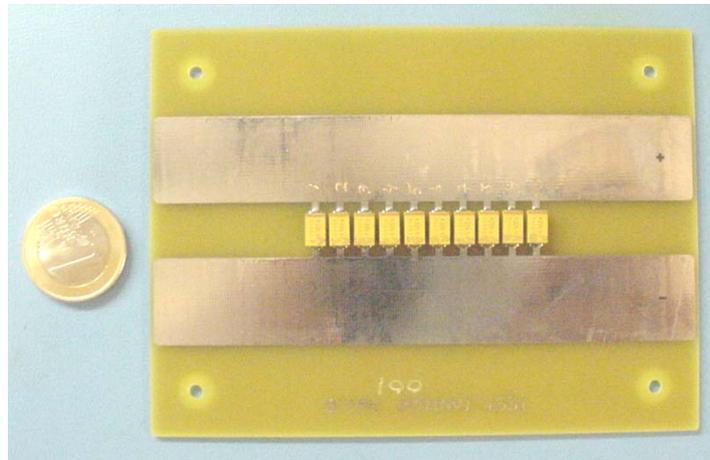


Fig. 25: Soldering conditions (guidelines, recommendations and measurements)

Carole Villette, and Gianni Corocher from the Materials Mechanics and Processes Section (TEC-QMM) have inspected the capacitors after the soldering process according to ESA PSS 738.

Due to the temperature profile (low peak temperature) many solder joints show discontinuities, voids and/or porosity, which will not be acceptable for flight equipment according to the standard. This might have a consequence on the electrical connections between the capacitors and the PCB if they are mechanically stressed and/or with thermal

cycles. However for this study, it was decided that the capacitor banks were fit for the relevant tests (no thermal or mechanical stress was foreseen), and in fact the capacitors stayed well connected to the PCBs until the end of the test campaign.



*Fig. 26a and b: Capacitor bank after soldering process and printed circuit of the PCB*

## 9.2 *Check of the capacitor bank signatures after the soldering process*

Each capacitor was characterized individually before the soldering process (part 8). To be sure that the soldering process didn't affect the signatures of the capacitors, the capacitor banks were characterized after the soldering process.

### 9.2.1 LEAKAGE CURRENTS AFTER THE SOLDERING

#### Leakage current results:

Capacitor banks (CB13 to CB17) of TAJD 22uF 35V (C1 to C50)

		Sum of single Caps Leakage Current CB	CB Leakage Current	Ratio
C1-C10	CB13	9.02E-07	9.27E-07	1.03
C11-C20	CB14	8.81E-07	9.37E-07	1.06
C21-C30	CB15	8.50E-07	8.59E-07	1.01
C31-C40	CB16	7.34E-07	7.41E-07	1.01
C41-C50	CB17	1.03E-06	1.07E-06	1.04

Capacitor banks (CB7 to CB11) of TAJD 10uF 35V (B1 to B50)

		Sum of single Caps Leakage Current CB	CB Leakage Current	Ratio
C1-C10	CB7	4.34765E-07	4.09756E-07	0.94247679
C11-C20	CB8	2.79492E-07	2.92683E-07	1.047196433
C21-C30	CB9	4.22744E-07	5.07317E-07	1.200057334
C31-C40	CB10	3.65644E-07	3.80488E-07	1.040597661
C41-C50	CB11	2.31407E-07	2.43902E-07	1.05399641

#### Leakage current analysis:

Except for the capacitor bank CB9, the leakage current before and after the soldering process is the same. However the leakage current of the capacitor bank CB9 is much lower than the maximum given by the datasheet (35uA for the 10 capacitors in parallel).

The soldering process did not affect the leakage current of the capacitors.

### 9.2.2 FREQUENCY CHARACTERIZATIONS AFTER THE SOLDERING

#### Capacitor bank CB13 of TAJD 22uF 35V (C1 to C50)

To see if the soldering process has an effect on the impedances before and after the soldering process, the capacitor banks were characterized and compared to the calculated total impedance with the 10 individual capacitors impedances measured before the soldering process. The measurements and calculations gave the following results.

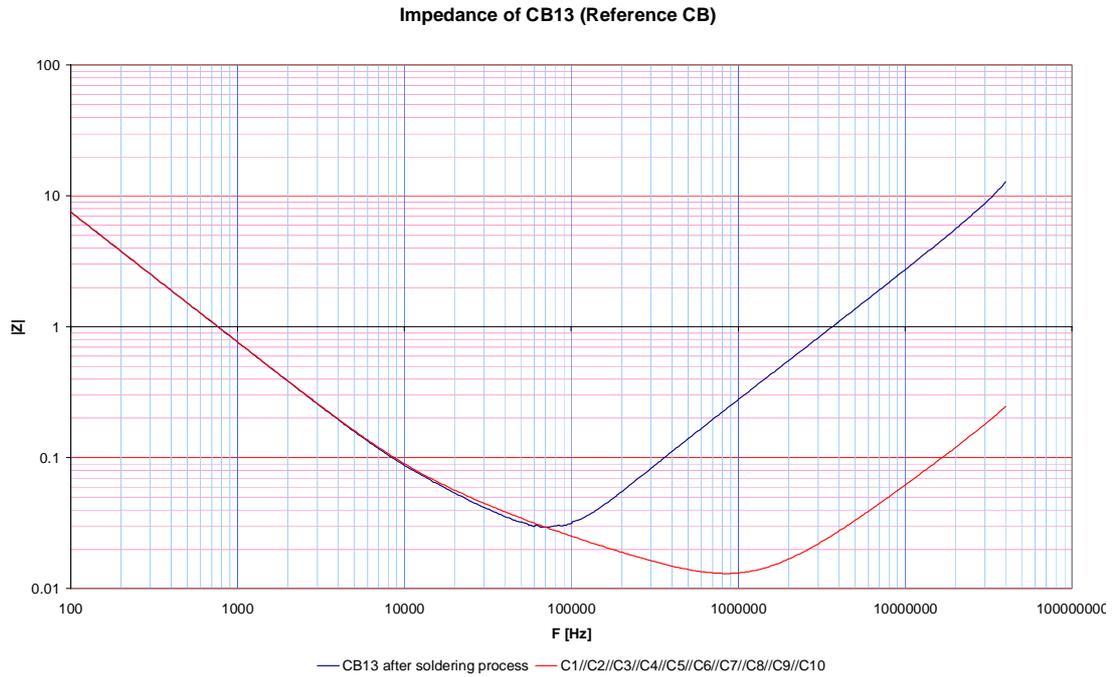


Fig. 27: Comparisons of the impedances of CB13 before and after the soldering process for the TAJD 22uF 35V

**Capacitor banks CB7 of TAJD 10uF 35V (B1 to B50)**

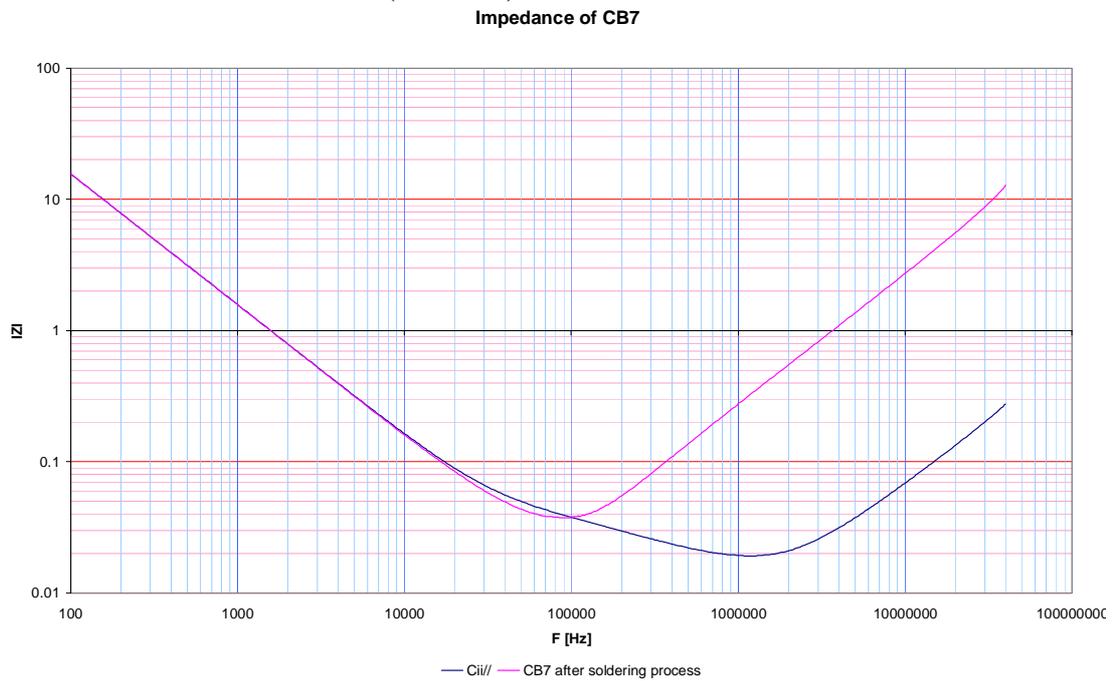


Fig. 28: Comparisons of the impedances of CB7 before and after the soldering process for the TAJD 10uF 35V (B1...B10)

The graphs of the comparison of the capacitor banks CB7 to CB11 and CB14 to CB17 are available in annex 7.

### **Analysis of the frequency measurements:**

The capacitances (at low frequency) of all the capacitor banks are exactly equal to the sum of the individual capacitances of the single capacitors before the soldering process.

In high frequency the slopes of the impedances have changed a little bit. In other words the series inductance has increased. Moreover the amplitude of the impedance at the frequency resonance is higher due to the parasitic resistors added. The consequence of these parasitic elements introduction (resistor and inductor) is also visible: the frequency resonance of the capacitor bank is lower than the resonance of the expected resonance with the calculated impedance of the individual measured impedances in parallel.

## **10 POWER TESTS CONDITIONS**

### ***10.1 General conditions***

The tests performed concern only the TAJD 22uF 35V (CB13 to CB17).

- All tests were performed in ambient pressure conditions.
- The life test of the capacitor banks were performed at a controlled temperature ( $85^{\circ}\text{C} \pm 3^{\circ}\text{C}$ ) by placing (gluing) the relevant PCB containing the 10 capacitors in parallel on the temperature-controlled plates described in this chapter.
- The frequency of operation of the converter to generate the RMS current through the capacitor bank was  $131 \text{ KHz} \pm 5\%$ .
- The capacitor banks were stressed at the de-rated voltage.
- Each capacitor bank was tested for overall leakage current and impedance at the beginning of the test campaign (after the soldering process) and at approximately fixed intervals during the life testing (every 100 hours). The detailed test set up and test conditions are specified in paragraph 11.

### ***10.2 Capacitor banks conditions***

#### **10.2.1 CB 13: REFERENCE**

CB 13 is the reference capacitor bank. This capacitor bank was not tested, but its signature was measured when the other capacitor banks were characterized at approximately fixed intervals during the life testing (every 100 hours).

#### **10.2.2 CB 14: CONTINUOUS REGIME 1**

CB 14 is the capacitor bank subjected to continuous RMS current regime 1, and within the applicable current de-rating conditions defined in AD #1, AD #2 and at the end of this chapter (“10.3 definition of rms current in regime 1”).

#### **10.2.3 CB 15: CONTINUOUS REGIME AT 2.5ARMS**

The Worst Case methods described in paragraph II take into account all the possible variations between capacitors using the manufacturer data. At 2.1 - 2.2 A rms, the user is sure that the de-rated power dissipation limit will not be reached (75mW). To validate the safe utilization domain (rms current between 0 and 2.1-2.2A rms found with the worst-case analyses) CB15 was subjected to continuous RMS current at approximately 2.5A rms.

### 10.2.4 CB 16: INTERMITTENT REGIME AT 2.5ARMS

The specific test condition for CB 16 is representative of an application with frequent start-stop cycles (for example output capacitor banks of power supplies connected to digital equipments).

The Worst Case methods described in paragraph II take into account all the possible variations among capacitors using the manufacturer data. At 2.1 - 2.2 A rms, the user is sure that the de-rated power dissipation limit will not be reached (75mW). To validate the safe utilisation domain (rms current between 0 and 2.1-2.2A rms found with the worst-case analyses), CB16 was subjected to intermittent RMS current from 0% to 100% of 2.5 A rms with period of stress of 5 minutes.(the capacitor bank was electrically stressed only for half of the period i.e. for 2minutes and 30 seconds).

### 10.2.5 CB 17: INCREASED REGIME

Due to the unknown operating rms current corresponding to the de-rated power dissipation limit, the capacitor bank CB17 was tested at different stress regimes. CB17 was initially stressed below its de-rated power dissipation limit starting at 2.5 A RMS and progressively the current was increased in steps (of 1 RMS A) after each periodical signature testing (every 100 hours).

## 10.3 Regime 1 conditions

Two analyses were performed to find the maximum allowable RMS current corresponding to the de-rated power dissipation criteria (75mW) for the particular capacitor bank CB14, taking into account of the individual capacitor impedances measured before the soldering process.

### 10.3.1 FIRST ANALYSIS: RLC EQUIVALENT CIRCUIT

From the measurements of the capacitors impedances, the capacitors RLC equivalent circuits were identified. A simulation was performed with the identified RLC circuits.

Fig .28 and 29 depict respectively the circuit used for this simulation and the simulation results.

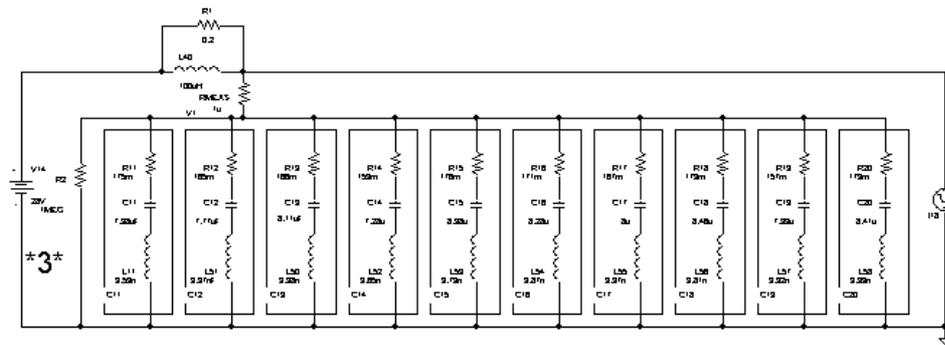


Fig. 29: Simulation with the CB14 (C11 to C20) in transient with the equivalent RCL circuit measured before the soldering process.

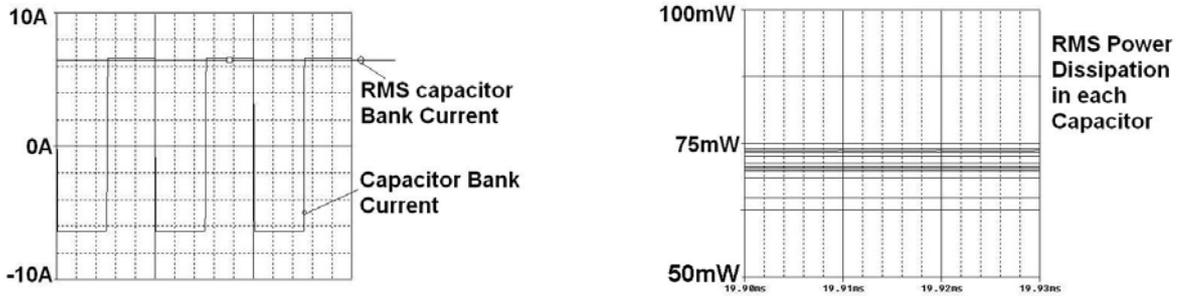


Fig.30a and b: simulation with the RLC equivalent circuits of the capacitors of CB14, identified before the soldering process.

Taking into account of the set-up used to produce the current across the capacitor bank, also a more realistic current waveform (trapezoidal, see Figure 30) was simulated to check the relevant impact on the individual power dissipation



Capacitor bank CB14 current

Individual RMS Power Dissipations

Fig.31a and b: simulation with the RLC equivalent circuits of the capacitors of CB14, identified before the soldering process.

In both cases the limit of the de-rated power dissipation of CB14 was reached at least in one of the capacitors with a total maximum RMS current of 6.5A RMS.

### 10.3.2 SECOND ANALYSIS: CURRENT VECTORS SUM

From the measurements of the capacitors impedances of CB14 before soldering, the method of the current vectors sum was applied to find the limit in rms current corresponding to the de-rated power dissipation:

By assuming that the individual capacitor currents have the same type of waveforms (square wave, with a duty cycle of 50%), but with different amplitudes, it is possible to calculate, the amount of RMS current that can be injected in each single capacitor to respect the de-rated power dissipation (75mW) criteria with the measured ESR of each single capacitor.

For instance, for the capacitor C11 of CB14, the following table gives the results:

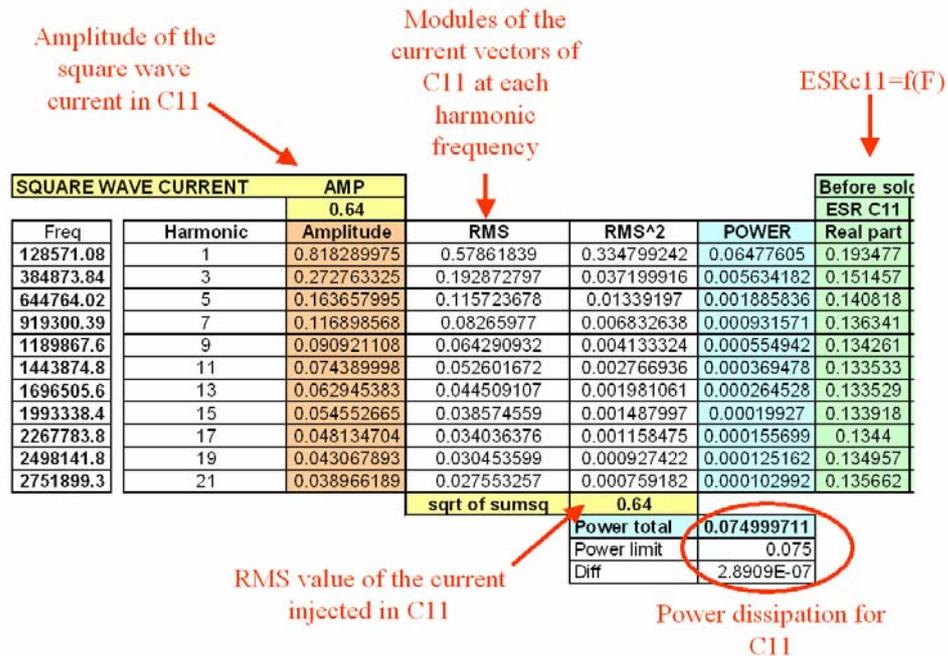


Fig.32a: Details of the power dissipation calculation in one capacitor

The amplitude of the square wave current in this capacitor is 0.64A to reach the de-rated power dissipation (75mW). At each harmonic frequency, the rms values of the harmonic current in the capacitor C11 were identified. These values give the modules of the capacitor C11 current vectors at each harmonic frequency. Note, that the phases of the capacitor C11 current vectors are linked to their impedances.

Then the RMS current of the capacitor bank is calculated by summing the individual rms current vectors at each harmonic frequency. Square root of the sum square of the harmonic sums gives the overall RMS current than can be injected in the capacitor bank.

For the capacitor bank 14, it gave the following table:

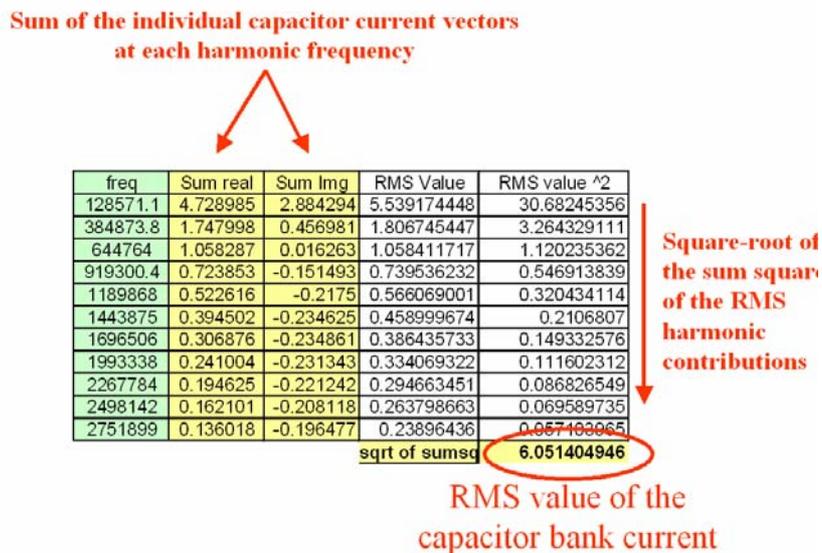


Fig.32b: Details of the power dissipation calculation in the capacitor bank CB14 with the vectors sum method

For this capacitor bank, with this second approach, the total CB14 rms current was evaluated at 6ARMS to fulfill the de-rated power dissipation criteria in each single capacitor. The advantage of this method was to use the real measured ESRs and not an approximate equivalent circuit. This method also presents a drawback concerning the waveforms of the current in the single capacitor: they are always assumed to be square wave with a duty cycle of 50%. This assumption is not rigorous. Besides, the impedances of the capacitors may change during the life testing and consequently the ESRs too.

### 10.3.3 CONCLUSION: DEFINITION OF THE REGIME 1 RMS CURRENT

In the regime one, the level of the rms capacitor bank current was evaluated to reach the de-rating power dissipation limit. Two calculations were performed. The first one was using the individual  $ESR=f(F)$  of each capacitor, and the second one, by using the RLC model of each individual capacitor, identified for both before the soldering process.

For CB14, the de-rated power dissipation limits correspond to a maximum capacitor bank current in the area of 6 - 6.5 A RMS. To be sure that this capacitor bank was stressed at the operating point of the de-rated power dissipation, the CB14 was stressed at 7A rms.

## 11 INSTRUMENTS AND MEASUREMENT METHODS

### 11.1 Impedances measurement

The impedances were measured with an Impedance Gain-Phase analyser HP4194A from 100Hz to 40MHz at ambient  $T^\circ$  and pressure (Fig. 33). The perturbation injected in the capacitors was 0.5V RMS with a DC bias of 2.2 volts.



Fig. 33: Frequency Analyser

Before and after each characterization, the test set up was validated by the characterization of a “stable” PM90SR 10uF, esr of 10m $\Omega$  at ambient temperature). This simple test allows checking the stability of the frequency analyser and the quality of the measurements. Fig. 34 shows how the equipment gives a good appreciation of this stable capacitor.

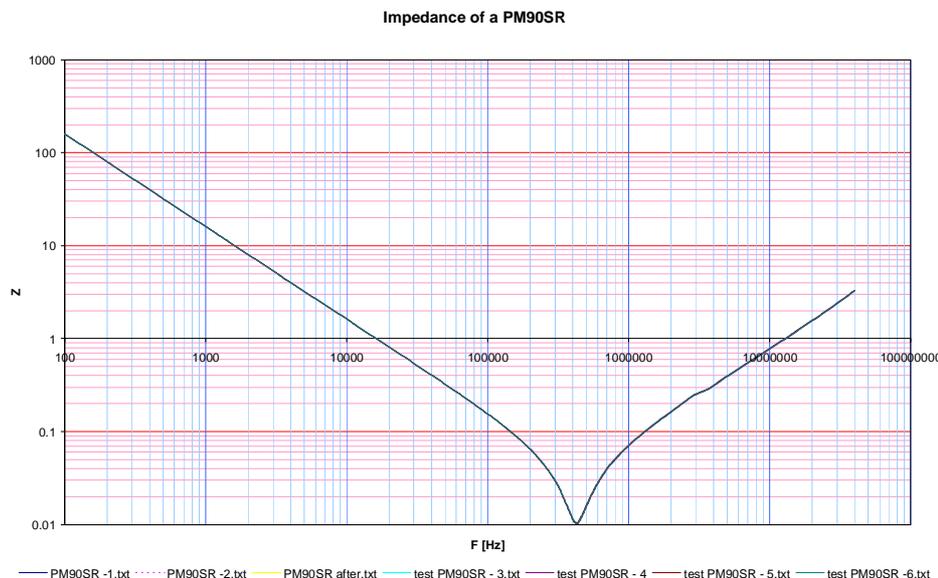


Fig. 34: Verification of the measurements with a stable capacitor PM90SR

The impedance characterizations of the PM90 SR were always very close each other. The equivalent circuit RLC in series of the PM90SR was also identified.

Example of RLC equivalent circuit of a PM90SR 10uF given by the frequency analyser:

$R=10.0964\text{m}\Omega$ ,  $L=13.7734\text{nH}$ ,  $C=9.99071\mu\text{F}$ .

## 11.2 Leakage currents measurement

The leakage current depends on three factors: time, temperature and voltage applied to the capacitors. For more detail concerning the leakage current of tantalum capacitors, please refer to RD#2.

The measurements of the leakage current were realised after 4minutes and 30 seconds, at ambient temperature and pressure, and with a dc voltage of 35V (+/-2%).

A resistor is placed in series with the capacitor to limit the charging current and to read the leakage current via the voltage drop of this resistor.

For the single capacitors, a resistor of 100k $\Omega$  is placed in series with the TC. The leakage current is very small and 100k $\Omega$  are needed to perform a sufficiently accurate measurement of the current.

The leakage current of the single TC was measured with the same principle of clip connector than for the impedances with frequency analyser.

Assuming that the capacitance of the CB is about 10 times the capacitance of one single TC (10 caps are in parallel on one CB), a resistor of 10k $\Omega$  is placed in series with the CB for the CB leakage current measurements to conserve the same time constant of charge of the tantalum capacitor bank than during the measure of the leakage current of the single tantalum capacitor. This series resistor allows limiting the charge and to have a good accuracy of the current reading.

A steady source of power, such as a regulated power supply is used. Fig 35 presents the schematic of the circuit used to measure the leakage current.

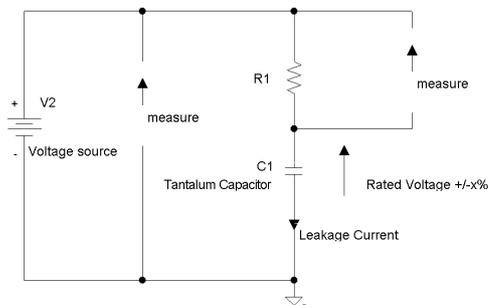
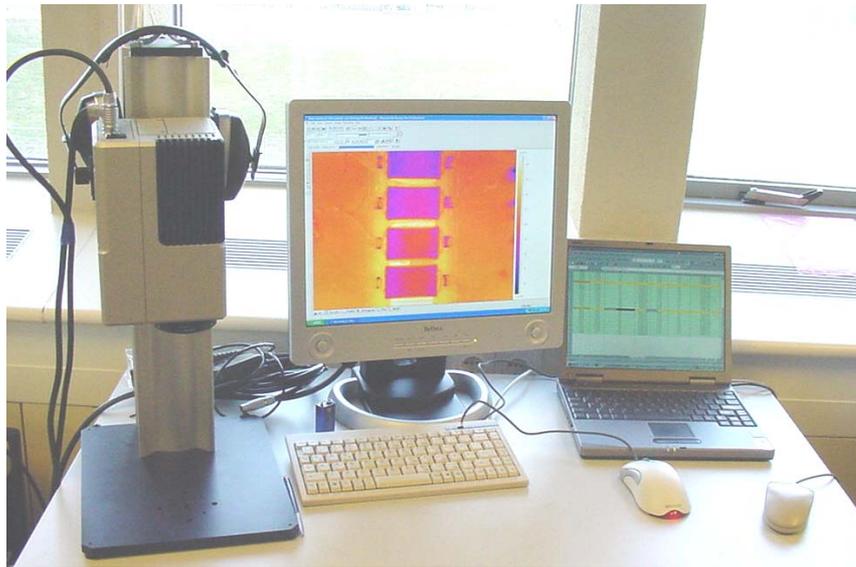


Fig. 35: Circuit for the leakage measurement

The voltage source used to supply the capacitor was 2 power supplies in series (Delta Elektronika ES-030-5 (30V-5A)). During the measurement, a Philips multimeter PM2525 with a thermocouple was used to measure the ambient temperature. Two multimeters measured the voltage of the power supply (Philips PM2525) and the leakage current via the voltage drop of the series resistor (Fluke 45 Dual Display Multimeter).

## 11.3 Temperature Measurement

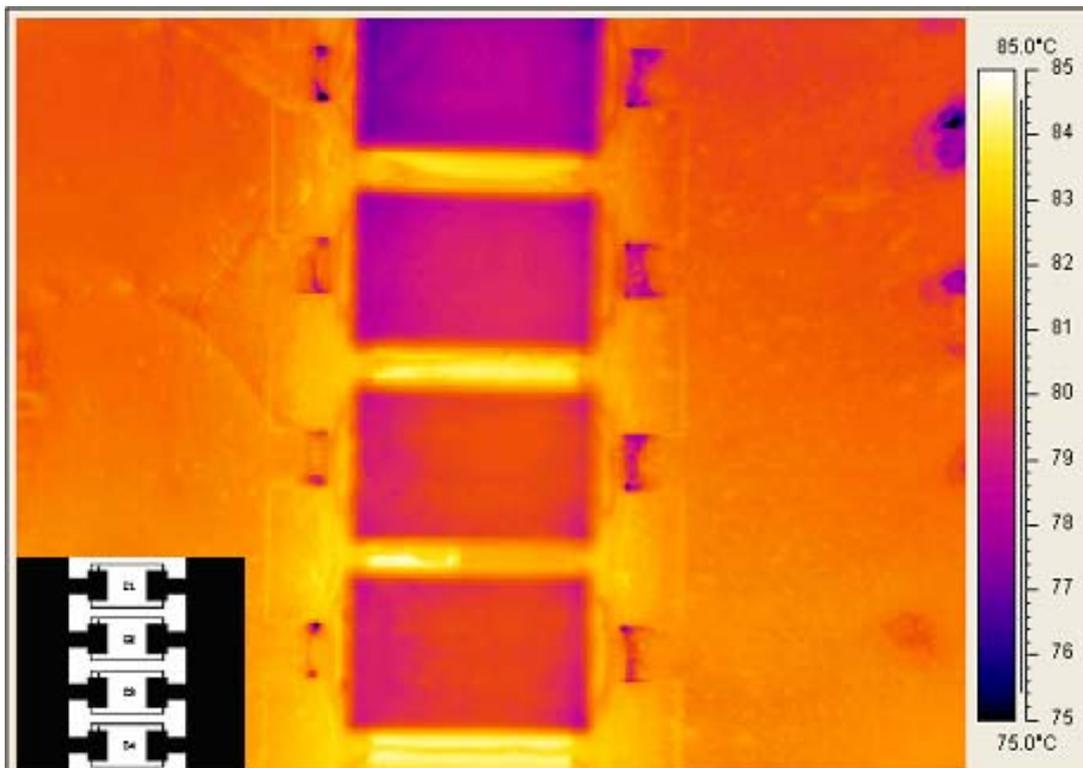
The thermal camera of the TEC-QCT has been used to take picture of the temperature capacitors (Flir Thermcamera SC3000). This device is exceptionally used in the TEC-EP laboratory (Fig. 36).



*Fig. 36: Thermal Camera*

A thermal picture of a capacitor bank painted in black was taken to find the best place to measure the temperature with thermocouples during the tests (Fluke 54II and Keithley 871).

Fig. 37 reports the picture taken.



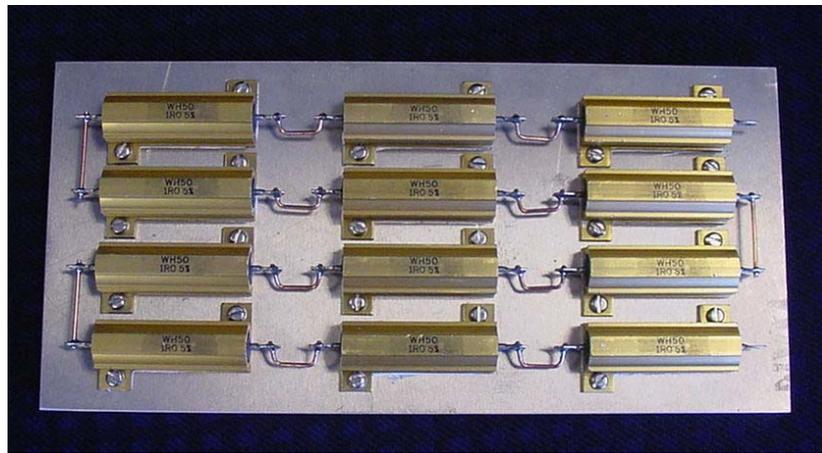
*Fig. 37: Thermal Pictures of the TC on CB*

The warmest areas are located between the capacitors. It is important to note that the distances between each capacitor respect the recommended placements given by the manufacturer.. After the measurement it was decided to use thermocouples and to place them between two capacitors to measure their body temperature.

## 12 FACILITIES FOR THE POWER TESTS

### 12.1 *Temperature controlled plates*

Temperature controlled plate were developed to guarantee a capacitors temperature of 85degC. The capacitor banks have been glued on one face of the aluminium plate. On the other side, 12 resistors of 1 $\Omega$  are connected in series and can dissipate several ten of watts. The drawings of the plates are shown on annex 8.



*Fig.38: Resistors face of the aluminum plate*

The temperature of the plate is controlled via a control card, detailed in annex 8.

### 12.2 *Converters for electrical stress*

The topology of the converters used to stress electrically the capacitor banks is a step-down converter (single inductor buck topology). Fig. 39 illustrates the topology with the theoretical waveforms of current at different points of the circuit.

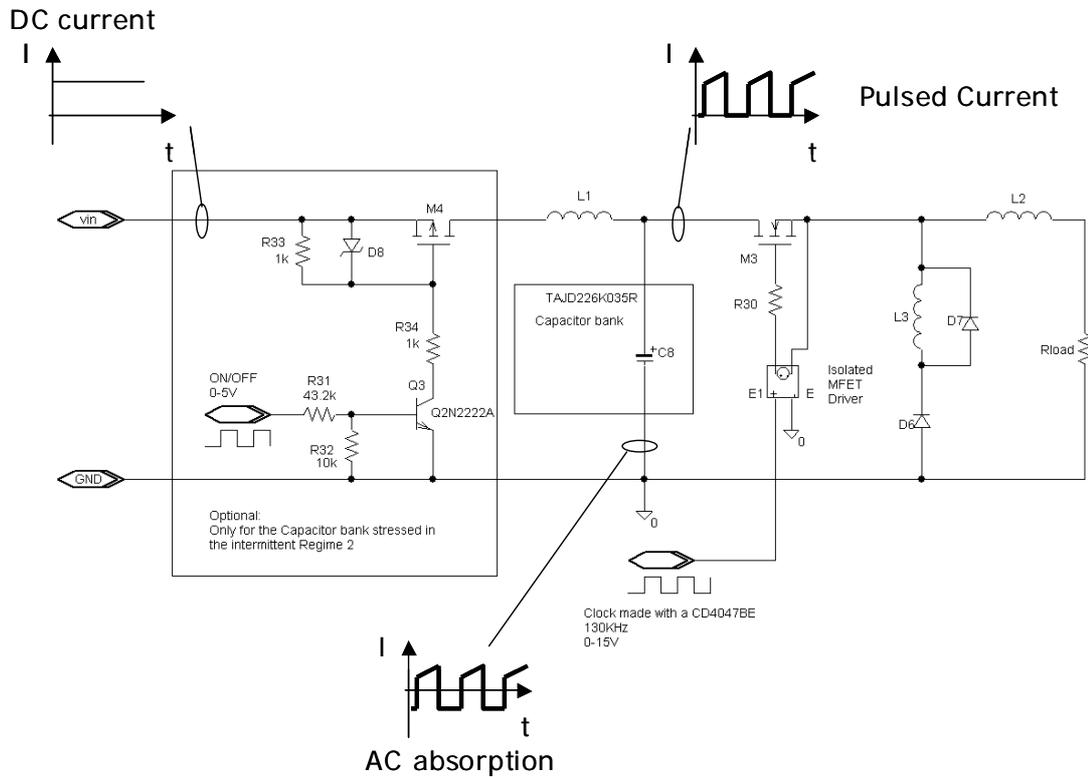


Fig. 39: buck converter to stress electrically the capacitor bank

The current injected in the capacitor bank is almost square wave. The slopes when the current is positive are due to the presence of the inductors. The capacitor bank and the inductor L1 form an input filter, which allows the power supply to deliver a constant current. The capacitor bank absorbs the AC part of the MFET M3 current. The elements in the square area are optional and only used for the capacitor bank CB16, stressed by intermittent current application.

Fig. 43 illustrates the typical waveform of current injected in the capacitor bank.

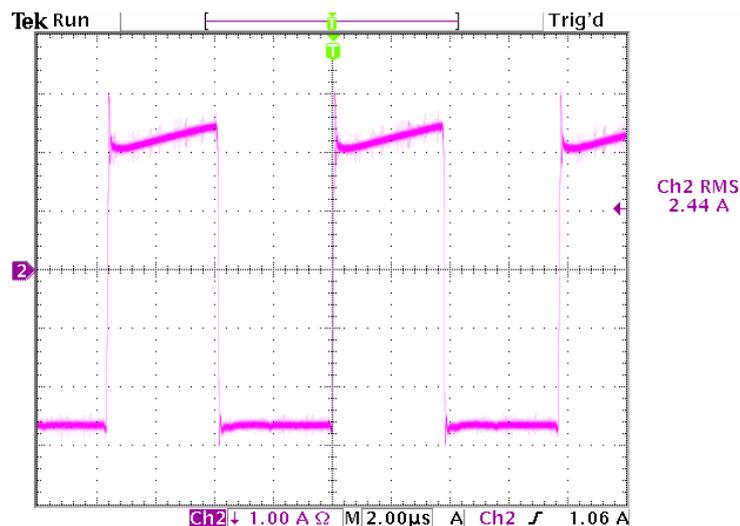


Fig. 40: Example of current injected in the capacitor banks

## 12.3 Test set-ups

### 12.3.1 SET-UP FOR THE IMPEDANCES CHARACTERIZATION

Fig. 38a and b present the set-up used to identify the signatures of the capacitors.



Fig. 41a and b: Frequency Analyser and its clip connector

For the single characterization a clip connector was used to avoid hand soldering (which might affect the capacitor electrical performances).

### 12.3.2 SET-UPS FOR THE POWER TESTS

Figures 45, 46, 47 show the complete stress set-up for the capacitor banks. The PCBs are mounted on the heating plates, close to the power converters.

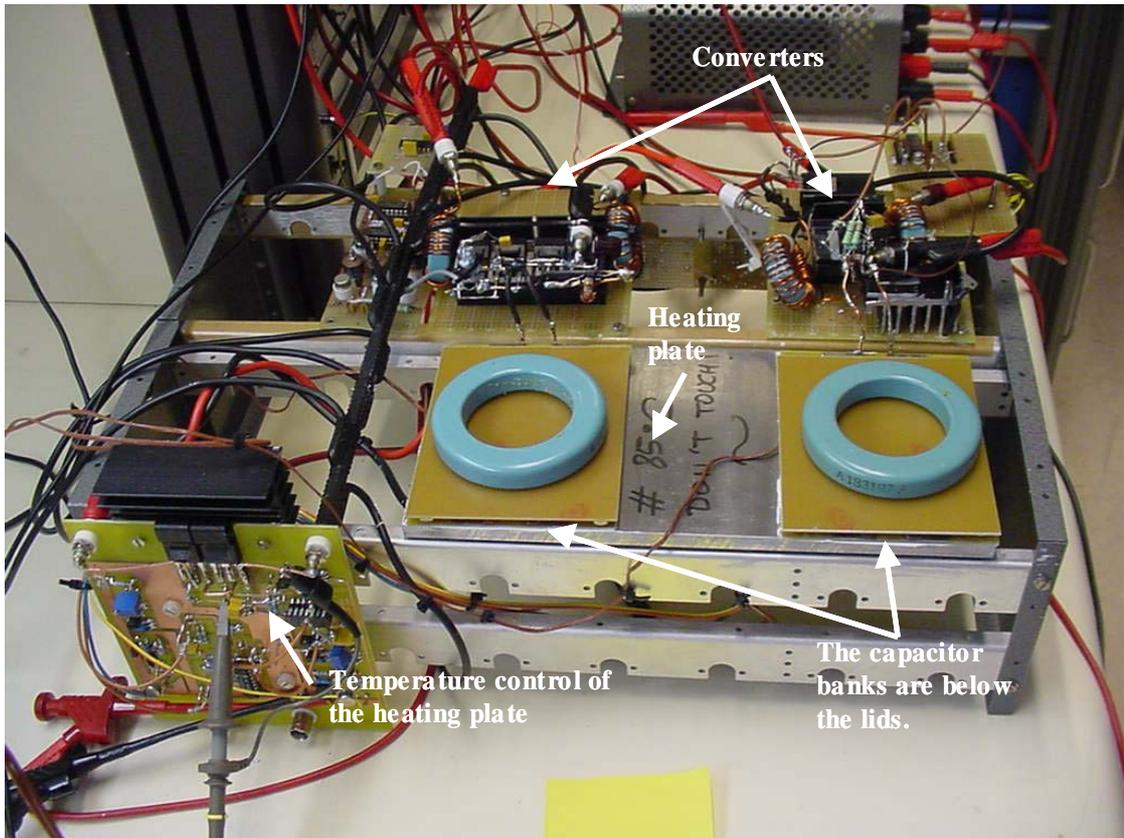


Fig. 42: Set-up for the CB 15 and 16

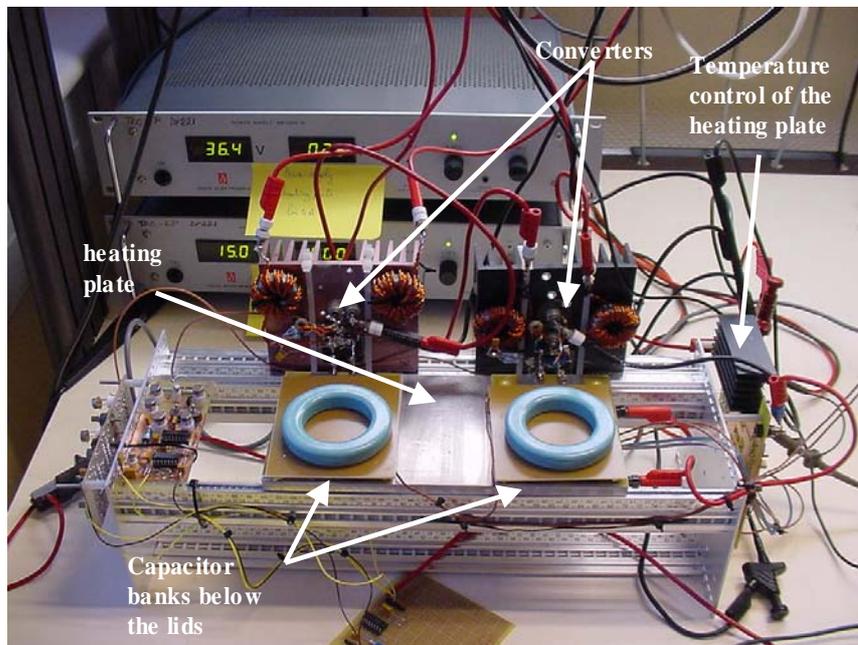


Fig. 43: Set-up for the CB 14 and 17

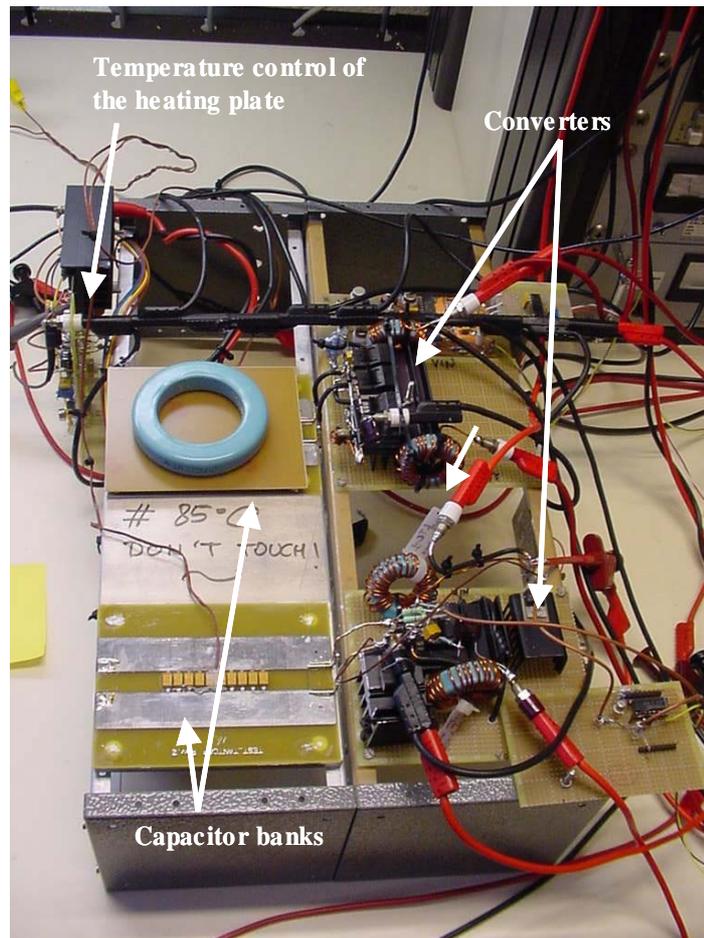
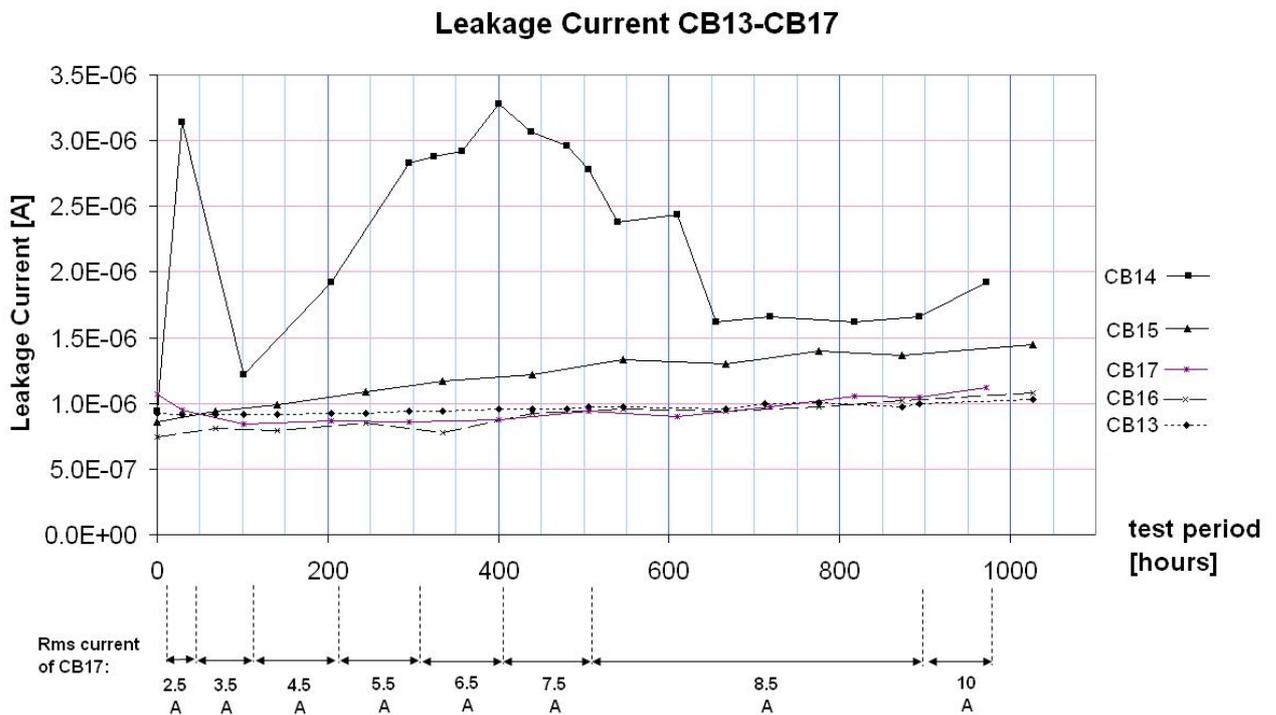


Fig. 44: Set-up for the CB 15 and 16

## 13 CAPACITOR BANKS LIFE TESTS

During the test period, no failure occurred. All the capacitor banks were tested for about 1000 hours.

### 13.1 Evolution of the Capacitor banks leakage current during the life tests



Capacitor Bank CB13 (reference, not stressed)  
 Capacitor Bank CB14 (continuous regime, 7 RMSA)  
 Capacitor Bank CB15 (continuous regime, 2.5 RMSA)  
 Capacitor Bank CB16 (intermittent regime, 2.5 RMS A)  
 Capacitor Bank CB17 (increase regime from regime, 2.5 RMS A to 10 RMS A)

#### Analysis of the results

The leakage currents were always lower than the maximum expected (sum of individual max).

Nevertheless the leakage current of CB14 – subject to the highest RMS current at the beginning of the test campaign – shows rather large variations.

## 13.2 Evolution of the Capacitor banks impedances during the life tests

### 13.2.1 CAPACITOR BANK CB13 (REFERENCE, NOT STRESSED)

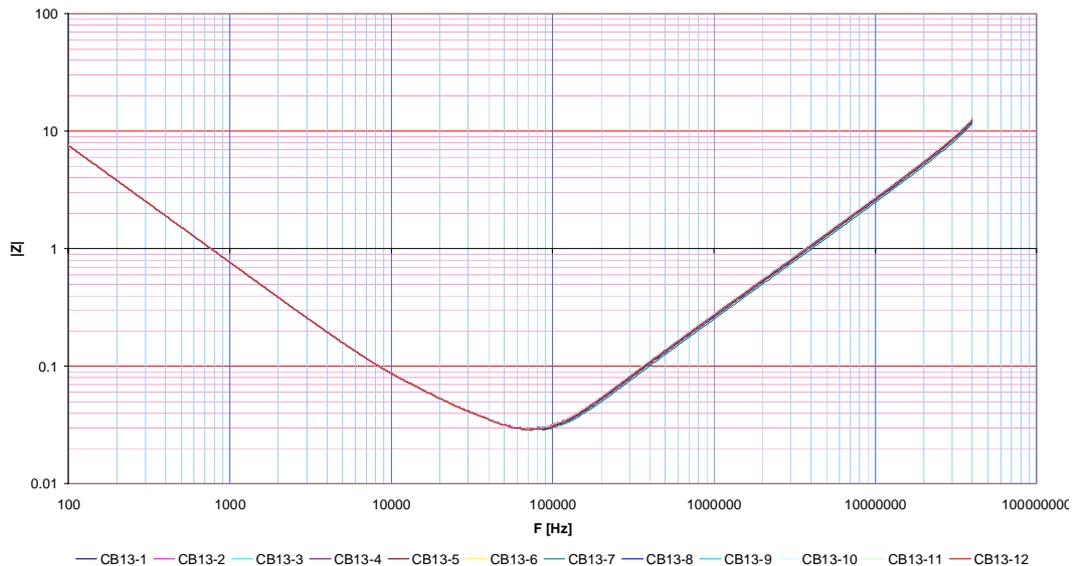


Fig. 46: Impedance of CB13 during the life testing of CB14-CB15-CB16-CB17

CB13 was characterized:	Name
After the soldering process.	CB13-1
When CB14&CB17 were characterized after 30 hours of test, And CB15&CB16 after 68 hours of test.	CB13-2
When CB14&CB17 were characterized after 102 hours of test, And CB15&CB16 after 141 hours of test.	CB13-3
When CB14&CB17 were characterized after 204 hours of test, And CB15&CB16 after 244 hours of test.	CB13-4
When CB14&CB17 were characterized after 296 hours of test, And CB15&CB16 after 335 hours of test.	CB13-5
When CB14&CB17 were characterized after 401 hours of test, And CB15&CB16 after 440 hours of test.	CB13-6
When CB14 was characterized after 480 hours of test.	CB13-7
When CB14&CB17 were characterized after 506 hours of test, CB15&CB16 after 546 hours of test.	CB13-8
When CB14 was characterized after 540 hours of test.	CB13-9
When CB14&CB17 were characterized after 610 hours of test, CB15&CB16 after 667 hours of test.	CB13-10
When CB14 was characterized after 655 hours of test.	CB13-11
When CB14&CB17 were characterized after 718 hours of test, CB15&CB16 after 776 hours of test.	CB13-12
When CB14&CB17 were characterized after 816 hours of test, CB15&CB16 after 774 hours of test.	CB13-13
When CB14&CB17 were characterized after 893 hours of test	CB13-14
When CB14&CB17 were characterized after 972 hours of test, CB15&CB16 after 1027 hours of test.	CB13-15

#### Analysis of the results:

The impedance of the reference capacitor bank (CB13) remains the same during all the tests.

## 13.2.2 CAPACITOR BANK CB14 (CONTINUOUS REGIME 7 A RMS)

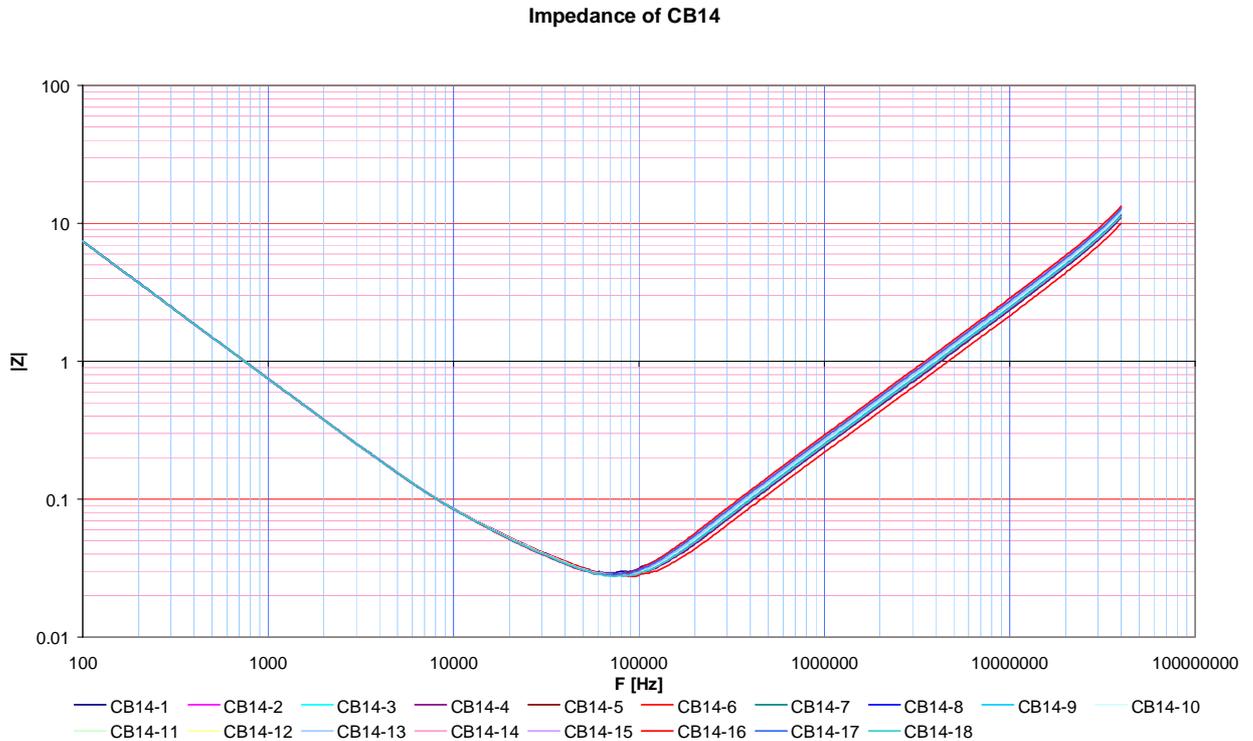


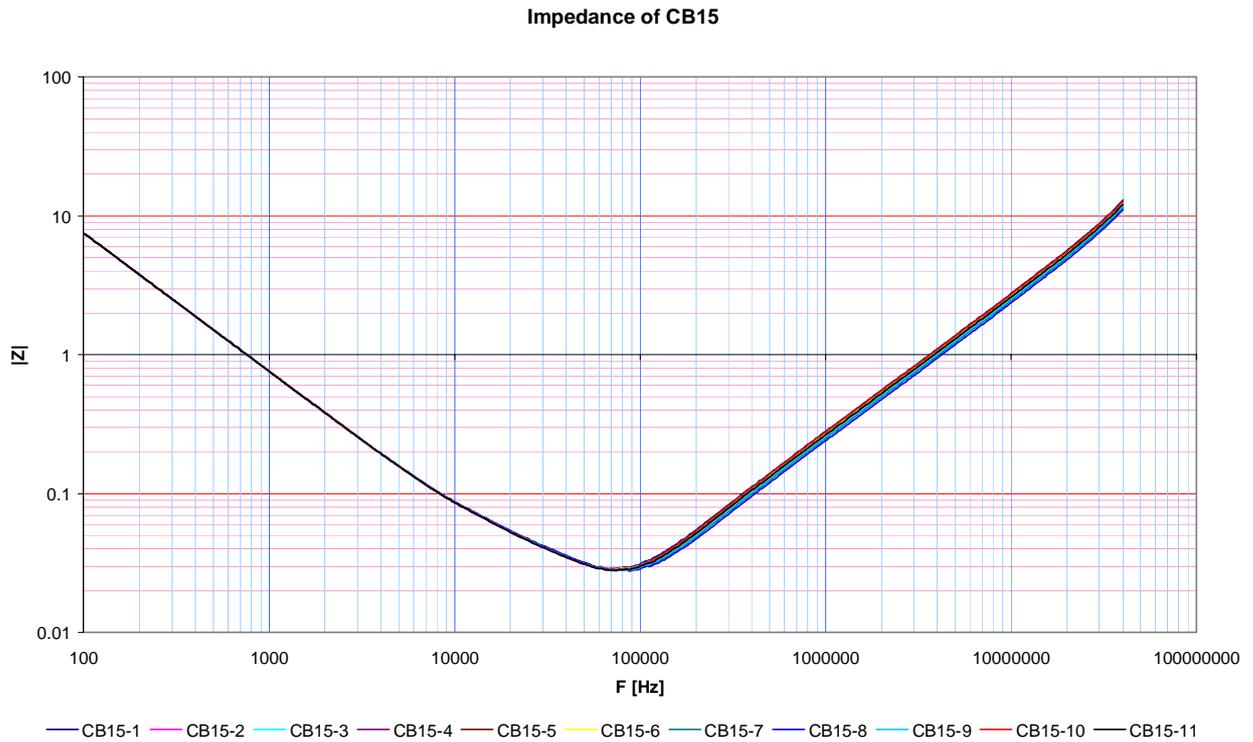
Fig. 47: Impedance during the life testing of CB14

<b>CB14 was characterized:</b>	<b>Name</b>
After the soldering process.	CB14-1
After 30 hours of test.	CB14-2
After 102 hours of test.	CB14-3
After 204 hours of test.	CB14-4
After 296 hours of test.	CB14-5
After 325 hours of test.	CB14-6
After 357 hours of test.	CB14-7
After 401 hours of test.	CB14-8
After 438 hours of test.	CB14-9
After 480 hours of test.	CB14-10
After 506 hours of test.	CB14-11
After 540 hours of test.	CB14-12
After 610 hours of test.	CB14-13
After 655 hours of test.	CB14-14
After 718 hours of test.	CB14-15
After 816 hours of test.	CB14-16
After 893 hours of test.	CB14-17
After 972 hours of test.	CB14-18

### Analysis of the results:

The capacitance of the capacitor banks remains the same (low frequency part). It seems that the ESL of the capacitor banks changed (high frequency part). This variation may be essentially due to differences in the position of the capacitor bank, when it is connected to the frequency analyzer.

### 13.2.3 CAPACITOR BANK CB15 (CONTINUOUS REGIME 2.5A RMS)



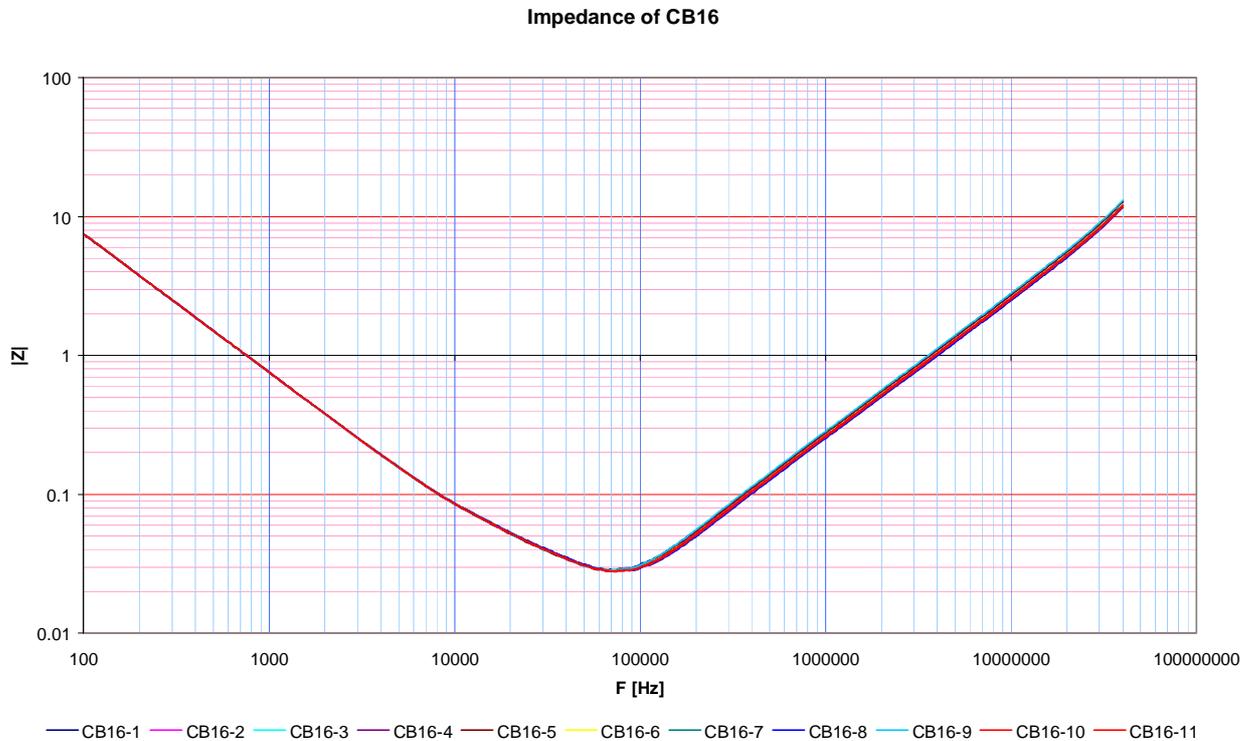
*Fig.48: Impedance during the life testing of CB15*

<b>CB15 was characterized:</b>	<b>Name</b>
After the soldering process.	CB15-1
After 68 hours of test.	CB15-2
After 141 hours of test.	CB15-3
After 244 hours of test.	CB15-4
After 335 hours of test.	CB15-5
After 440 hours of test.	CB15-6
After 546 hours of test.	CB15-7
After 667 hours of test.	CB15-8
After 776 hours of test.	CB15-9
After 873 hours of test.	CB15-10
After 1027 hours of test.	CB15-11

**Analysis of the results:**

The capacitance of the capacitor banks remains the same (low frequency part). It seems that the ESL of the capacitor banks changed (high frequency part). This variation may be essentially due to differences in the of the capacitor bank, when it is connected to the frequency analyzer.

### 13.2.4 CAPACITOR BANK CB16 (INTERMITTENT REGIME 0-2.5 A RMS)



*Fig. 49: Impedance during the life testing of CB16*

<b>CB16 was characterized:</b>	<b>Name</b>
After the soldering process.	CB16-1
After 68 hours of test.	CB16-2
After 141 hours of test.	CB16-3
After 244 hours of test.	CB16-4
After 335 hours of test.	CB16-5
After 440 hours of test.	CB16-6
After 546 hours of test.	CB16-7
After 667 hours of test.	CB16-8
After 776 hours of test.	CB16-9
After 874 hours of test.	CB16-10
After 1027 hours of test.	CB16-11

**Analysis of the results:**

The capacitance of the capacitor banks remains the same (low frequency part). It seems that the ESL of the capacitor banks changed (high frequency part). This variation may be essentially due to differences in the position of the capacitor bank, when it is connected to the frequency analyzer.

**Analysis of the results:**

The impedance of this capacitor bank remains the same during all the tests.

### 13.2.5 CAPACITOR BANK CB17 (INCREASE REGIME FROM 2.5 ARMS TO 10 ARMS)

Impedance of CB17

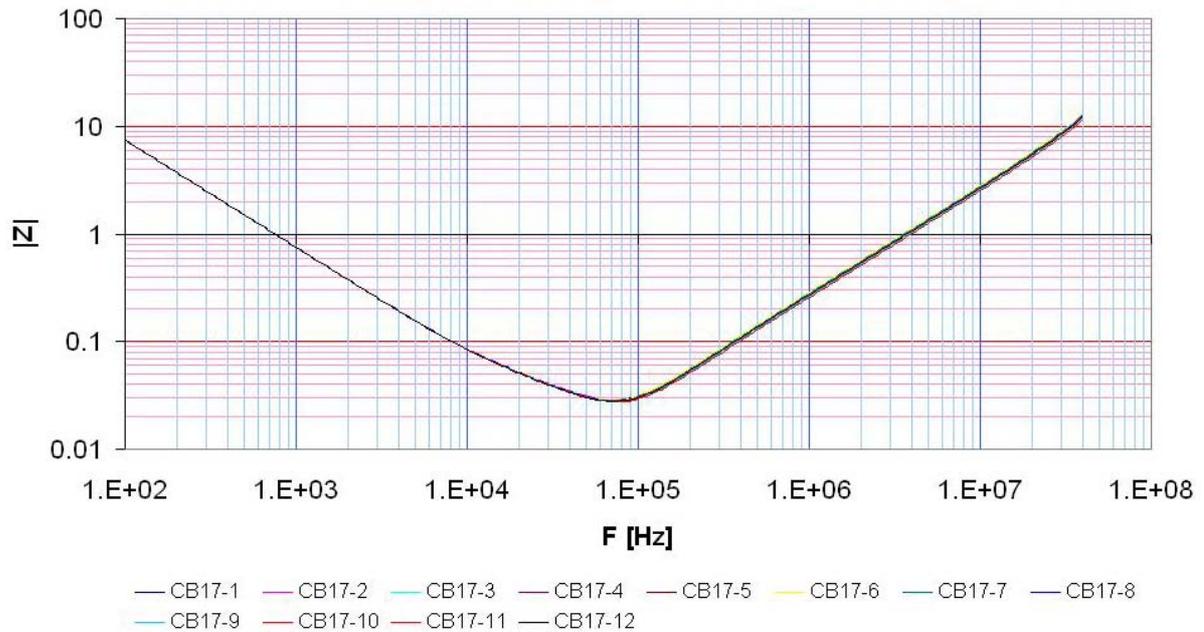


Fig. 50: Impedance during the life testing of CB17

CB17 was characterized:	Name	CB17 was characterized:	Name
After the soldering process.	CB17-1	After 204 hours of test: 30 hours at 2.5Arms. + 72 hours at 3.5Arms. + 102 hours at 4.5Arms.	CB17-4
After 30 hours of test at 2.5Arms.	CB17-2	After 296 hours of test: 30 hours at 2.5Arms. + 72 hours at 3.5Arms. + 102 hours at 4.5Arms. + 92 hours at 5.5Arms.	CB17-5
After 102 hours of test: 30 hours at 2.5Arms. + 72 hours at 3.5Arms.	CB17-3	After 401 hours of test: 30 hours at 2.5Arms. + 72 hours at 3.5Arms. + 102 hours at 4.5Arms. + 92 hours at 5.5Arms. + 105 hours at 6.5Arms.	CB17-6

<p>After 506 hours of test:  30 hours at 2.5Arms.  + 72 hours at 3.5Arms.  + 102 hours at 4.5Arms.  + 92 hours at 5.5Arms.  + 105 hours at 6.5Arms.  + 105 hours at 7.5Arms.</p>	CB17-7	<p>After 718 hours of test:  30 hours at 2.5Arms.  + 72 hours at 3.5Arms.  + 102 hours at 4.5Arms.  + 92 hours at 5.5Arms.  + 105 hours at 6.5Arms.  + 105 hours at 7.5Arms.  + 104 hours at 8.5Arms.  + 108 hours at 8.5Arms  + 97 hours at 8.5Arms</p>	CB17-10
<p>After 610 hours of test:  30 hours at 2.5Arms.  + 72 hours at 3.5Arms.  + 102 hours at 4.5Arms.  + 92 hours at 5.5Arms.  + 105 hours at 6.5Arms.  + 105 hours at 7.5Arms.  + 104 hours at 8.5Arms.</p>	CB17-8	<p>After 718 hours of test:  30 hours at 2.5Arms.  + 72 hours at 3.5Arms.  + 102 hours at 4.5Arms.  + 92 hours at 5.5Arms.  + 105 hours at 6.5Arms.  + 105 hours at 7.5Arms.  + 104 hours at 8.5Arms.  + 108 hours at 8.5Arms  + 97 hours at 8.5Arms  + 77 hours at 8.5 Arms</p>	CB17-11
<p>After 718 hours of test:  30 hours at 2.5Arms.  + 72 hours at 3.5Arms.  + 102 hours at 4.5Arms.  + 92 hours at 5.5Arms.  + 105 hours at 6.5Arms.  + 105 hours at 7.5Arms.  + 104 hours at 8.5Arms.  + 108 hours at 8.5Arms.</p>	CB17-9	<p>After 718 hours of test:  30 hours at 2.5Arms.  + 72 hours at 3.5Arms.  + 102 hours at 4.5Arms.  + 92 hours at 5.5Arms.  + 105 hours at 6.5Arms.  + 105 hours at 7.5Arms.  + 104 hours at 8.5Arms.  + 108 hours at 8.5Arms  + 97 hours at 8.5Arms  + 77 hours at 8.5Arms  + 78 hours at 10Arms  -&gt; Total 972 hours</p>	CB17-12

**Analysis of the results:**

The capacitance of the capacitor banks remains the same (low frequency part). It seems that the ESL of the capacitor banks changed slightly (high frequency part). This variation may be essentially due to differences in the position of the capacitor bank, when it is connected to the frequency analyzer.

**Analysis of the results:**

The impedance of this capacitor bank remains the same during all the tests.

## 14 CONCLUSION

In absence of detailed impedance data, the calculation of the maximum current expected on each capacitor in a bank is an issue and the relevant reliability too. In the part 6.2, two methods were presented to help tantalum capacitor users checking if their design respects the ratings/de-ratings rules.

No failure was observed during the parallel configuration tests. The impedances remained the same throughout the tests. The leakage current of one capacitor bank showed appreciable changes but still remaining lower than the maximum specified in the manufacturer datasheet.

The presented tests were performed on only a few capacitors, and for this reason any generalization of the results of this study should be taken with great care.

The effects of the soldering process on capacitors long-term reliability was not part of this study but it may have an impact on the performances of the tantalum capacitors and on the explanation of the failures occurred in ESA programs. The study of the influences of the soldering process on the performances of tantalum capacitors should be object of a next investigation.

## 15 ANNEXES

### 15.1 Annex 1: Determination of the maximum RMS current in a TAJ (K RHJ) 10uF 35V case D

Single configuration

Method of the manufacturer with the typical ESR

Assuming to apply a square current waveform with duty cycle=0.5, the RMS current at 25°C has to be lower than 1 A RMS to respect the rated power dissipation for that package (150mW) by using the typical ESR values in function of frequency at 25°C provided by AVX.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I <sup>2</sup>	Typical ESR [Ohms]	P [W]
1.00	130000	1	130000	1.270441417	0.898337741	0.807010697	0.1621	1.31E-01
		3	390000	0.423480472	0.299445914	0.089667855	0.1194	1.07E-02
		5	650000	0.254088283	0.179667548	0.032280428	0.1043	3.37E-03
		7	910000	0.181491631	0.128333963	0.016469606	0.09801	1.61E-03
		9	1170000	0.141160157	0.099815305	0.009963095	0.0945	9.42E-04
		11	1430000	0.115494674	0.081667067	0.00666951	0.09209	6.14E-04
		13	1690000	0.097726263	0.069102903	0.004775211	0.09025	4.31E-04
		15	1950000	0.084696094	0.059889183	0.003586714	0.08876	3.18E-04
		17	2210000	0.074731848	0.052843397	0.002792425	0.08753	2.44E-04
		19	2470000	0.066865338	0.047280934	0.002235487	0.0865	1.93E-04
		21	2730000	0.06049721	0.042777988	0.001829956	0.08564	1.57E-04
		23	2990000	0.055236583	0.039058163	0.00152554	0.08492	1.30E-04
		25	3250000	0.050817657	0.03593351	0.001291217	0.08431	1.09E-04
		27	3510000	0.047053386	0.033271768	0.001107011	0.0838	9.28E-05
		29	3770000	0.043808325	0.030977163	0.000959585	0.08337	8.00E-05
		31	4030000	0.040981981	0.028978637	0.000839761	0.083	6.97E-05
		33	4290000	0.038498225	0.027222356	0.000741057	0.0827	6.13E-05
		35	4550000	0.036298326	0.025666793	0.000658784	0.08244	5.43E-05
				sqrt of sumsq		0.992171325		

Fig. 51: manufacturer method to obtain the maximum rms current with the typical ESR

Maximum RMS current via the maximum ESR given by the manufacturer

The maximum of the real part of the impedance (ESR max is specified in the datasheet) can be used to determine the power dissipation. Rated Pd (150mW) is achieved for a the square wave current with 50% duty cycle equal to 0.39 A RMS with a considered series resistor of 1Ω.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I <sup>2</sup>	Typical ESR [Ohms]	P [W]	Total P [W]			
0.39	130000	1	130000	0.495921512	0.350669464	0.122969073	1	1.23E-01	1.50E-01			
		3	390000	0.165307171	0.116889821	0.01366323	1	1.37E-02				
		5	650000	0.099184302	0.070133893	0.004918763	1	4.92E-03				
		7	910000	0.07084593	0.050095638	0.002509573	1	2.51E-03				
		9	1170000	0.05510239	0.038963274	0.001518137	1	1.52E-03				
		11	1430000	0.045083774	0.031879042	0.001016273	1	1.02E-03				
		13	1690000	0.038147809	0.026974574	0.000727628	1	7.28E-04				
		15	1950000	0.033061434	0.023377964	0.000546529	1	5.47E-04				
		17	2210000	0.029171854	0.020627616	0.000425499	1	4.25E-04				
		19	2470000	0.026101132	0.018456288	0.000340635	1	3.41E-04				
		21	2730000	0.02361531	0.016698546	0.000278841	1	2.79E-04				
		23	2990000	0.021561805	0.015246498	0.000232456	1	2.32E-04				
		25	3250000	0.01983686	0.014026779	0.000196751	1	1.97E-04				
		27	3510000	0.018367463	0.012987758	0.000168682	1	1.69E-04				
		29	3770000	0.017100742	0.01209205	0.000146218	1	1.46E-04				
		31	4030000	0.015997468	0.011311918	0.000127959	1	1.28E-04				
		33	4290000	0.015027925	0.010626347	0.000112919	1	1.13E-04				
		35	4550000	0.014169186	0.010019128	0.000100383	1	1.00E-04				
		sqrt of sumsq						0.387297751				
		PI		3.14159265								

Fig. 52: method to obtain the maximum rms current with the maximum ESR

### Maximum RMS current after the measure of the single impedance

With the frequency analyser the impedance of the single capacitor is measured at 25°C. Assuming to apply a square current waveform with duty cycle=0.5, the current waveform applied to the capacitor is decomposed in Fourier series. It is then possible to calculate the RMS power dissipation at each harmonic with the measured impedance. Root-square sum of the individual harmonic contributions gives the RMS power dissipation for one capacitor after characterization. The RMS current at 25°C has to be lower than 0.74 A RMS to respect the rated power dissipation for that package (150mW) by using the measured impedance at 25°C.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I <sup>2</sup>	Typical ESR [Ohms]	P [W]	Total P [W]			
0.74	130000	1	130000	0.937840163	0.663153139	0.439772086	0.294	1.29E-01	1.50E-01			
		3	390000	0.312613388	0.221051046	0.048863565	0.229	1.12E-02				
		5	650000	0.187568033	0.132630628	0.017590883	0.21	3.69E-03				
		7	910000	0.133977166	0.094736163	0.008974941	0.2	1.79E-03				
		9	1170000	0.104204463	0.073683682	0.005429285	0.194	1.05E-03				
		11	1430000	0.085258197	0.060286649	0.00363448	0.191	6.94E-04				
		13	1690000	0.072141551	0.051011178	0.002602202	0.189	4.92E-04				
		15	1950000	0.062522678	0.044210209	0.001954543	0.187	3.65E-04				
		17	2210000	0.055167068	0.039090908	0.001521703	0.187	2.85E-04				
		19	2470000	0.049360009	0.034902797	0.001218205	0.186	2.27E-04				
		21	2730000	0.044659055	0.031578721	0.000997216	0.186	1.85E-04				
		23	2990000	0.040775659	0.028832745	0.000831327	0.186	1.55E-04				
		25	3250000	0.037513607	0.026526126	0.000703635	0.186	1.31E-04				
		27	3510000	0.034734821	0.024561227	0.000603254	0.187	1.13E-04				
		29	3770000	0.032339316	0.02286735	0.000522916	0.187	9.78E-05				
		31	4030000	0.030252908	0.021392037	0.000457619	0.188	8.60E-05				
		33	4290000	0.028419399	0.02009555	0.000403831	0.188	7.59E-05				
		35	4550000	0.026795433	0.018947233	0.000358998	0.189	6.79E-05				
		sqrt of sumsq						0.732421114				
		PI		3.14159265								

Fig. 53: method to obtain the maximum rms current with a measured ESR of one capacitor

## 15.2 Annex 2: Determination of the maximum RMS current in a TPS (M R0200) 22uF 35V case D

### Single configuration

#### Method of the manufacturer with the typical ESR

Assuming to apply a **square current waveform** with duty cycle=0.5, the RMS current at 25°C has to be lower than **1.19 A RMS** to respect the rated power dissipation for that package (150mW) by using the **typical ESR** values in function of frequency at 25°C provided by AVX.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I' [A]	Typical ESR [Ohms]	P [W]	Total P [W]			
1.20	130000	1	130000	1.528410709	1.080749577	1.168019648	0.1112	1.30E-01	1.50E-01			
		3	390000	0.509470236	0.360249859	0.129779961	0.08236	1.07E-02				
		5	650000	0.305682142	0.216149915	0.046720786	0.0775	3.62E-03				
		7	910000	0.218344387	0.154392797	0.023837136	0.07521	1.79E-03				
		9	1170000	0.169823412	0.120083286	0.014419996	0.0736	1.06E-03				
		11	1430000	0.138946428	0.098249962	0.009653055	0.07235	6.98E-04				
		13	1690000	0.117570055	0.083134583	0.006911359	0.07136	4.93E-04				
		15	1950000	0.101894047	0.072049972	0.005191198	0.07057	3.66E-04				
		17	2210000	0.089906512	0.063573505	0.00404159	0.06994	2.83E-04				
		19	2470000	0.080442669	0.056881557	0.003235511	0.06944	2.25E-04				
		21	2730000	0.072781462	0.051464266	0.002648571	0.06905	1.83E-04				
		23	2990000	0.06645264	0.046989112	0.002207977	0.06874	1.52E-04				
		25	3250000	0.061136428	0.043229983	0.001868831	0.06849	1.28E-04				
		27	3510000	0.056607804	0.040027762	0.001602222	0.06829	1.09E-04				
		29	3770000	0.052703818	0.037267227	0.001388846	0.06814	9.46E-05				
		31	4030000	0.049303571	0.03486289	0.001215421	0.06802	8.27E-05				
		33	4290000	0.046315476	0.032749987	0.001072562	0.06792	7.28E-05				
		35	4550000	0.043668877	0.030878559	0.000953485	0.06785	6.47E-05				
		sqrt of sumsq					1.193636525					
		PI		3.14159265								

Fig. 54: manufacturer method to obtain the maximum rms current with the typical ESR

#### Maximum RMS current via the maximum ESR given by the manufacturer

The maximum of the real part of the impedance (ESR max is specified in the datasheet) can be used to determine the power dissipation. Rated Pd (150mW) is achieved for a the square wave current with 50% duty cycle equal to 0.87 A RMS with a considered series resistor of 0.2Ω.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I' [A]	Typical ESR [Ohms]	P [W]	Total P [W]			
0.87	130000	1	130000	1.108914266	0.784120797	0.614845425	0.2	1.23E-01	1.50E-01			
		3	390000	0.369638089	0.261373599	0.068316158	0.2	1.37E-02				
		5	650000	0.221782853	0.156824159	0.024593817	0.2	4.92E-03				
		7	910000	0.158416324	0.112017257	0.012547866	0.2	2.51E-03				
		9	1170000	0.123212696	0.087124533	0.007590684	0.2	1.52E-03				
		11	1430000	0.100810388	0.071283709	0.005081367	0.2	1.02E-03				
		13	1690000	0.085301097	0.060316984	0.003638139	0.2	7.28E-04				
		15	1950000	0.073927618	0.05227472	0.002732646	0.2	5.47E-04				
		17	2210000	0.065230251	0.046124753	0.002127493	0.2	4.25E-04				
		19	2470000	0.058363909	0.041269516	0.001703173	0.2	3.41E-04				
		21	2730000	0.052805441	0.037339086	0.001394207	0.2	2.79E-04				
		23	2990000	0.048213664	0.034092209	0.001162279	0.2	2.32E-04				
		25	3250000	0.044356571	0.031364832	0.000983753	0.2	1.97E-04				
		27	3510000	0.041070899	0.029041511	0.000843409	0.2	1.69E-04				
		29	3770000	0.038238423	0.027038648	0.000731088	0.2	1.46E-04				
		31	4030000	0.035771428	0.025294219	0.000639798	0.2	1.28E-04				
		33	4290000	0.033603463	0.023761236	0.000564596	0.2	1.13E-04				
		35	4550000	0.031683265	0.022403451	0.000501915	0.2	1.00E-04				
		sqrt of sumsq					0.866024141					
		PI		3.14159265								

Fig. 55: method to obtain the maximum rms current with the maximum ESR

### Maximum RMS current after the measure of the single impedance

With the frequency analyser the impedance of the single capacitor is measured at 25°C. Assuming to apply a square current waveform with duty cycle=0.5, the current waveform applied to the capacitor is decomposed in Fourier series. It is then possible to calculate the typical RMS power dissipation at each harmonic with the measured impedance. Root-square sum of the individual harmonic contributions gives the RMS power dissipation for one capacitor after characterization. The RMS current at 25°C has to be lower than 0.91 A RMS to respect the rated power dissipation for that package (150mW) by using the measured impedance at 25°C.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I <sup>2</sup>	Typical ESR [Ohms]	P [W]	Total P [W]
0.91	130000	1	130000	1.162028231	0.821678042	0.675154805	0.191	1.29E-01	1.50E-01
		3	390000	0.387342744	0.273892681	0.075017201	0.149	1.12E-02	
		5	650000	0.232405646	0.164335608	0.027006192	0.138	3.73E-03	
		7	910000	0.166004033	0.117382577	0.013778669	0.134	1.85E-03	
		9	1170000	0.129114248	0.09129756	0.008335245	0.132	1.10E-03	
		11	1430000	0.10563893	0.074698004	0.005579792	0.131	7.31E-04	
		13	1690000	0.089386787	0.063206003	0.003994999	0.13	5.19E-04	
		15	1950000	0.077468549	0.054778536	0.003006888	0.13	3.90E-04	
		17	2210000	0.068354602	0.048334002	0.002336176	0.13	3.04E-04	
		19	2470000	0.061159381	0.043246213	0.001870235	0.132	2.47E-04	
		21	2730000	0.055334678	0.039127526	0.001530963	0.132	2.02E-04	
		23	2990000	0.050522967	0.035725132	0.001276285	0.1325	1.69E-04	
		25	3250000	0.046481129	0.032867122	0.001080248	0.1335	1.44E-04	
		27	3510000	0.043038083	0.03043252	0.000926138	0.134	1.24E-04	
		29	3770000	0.040069939	0.028333726	0.0008028	0.1345	1.08E-04	
		31	4030000	0.037484782	0.026505743	0.000702554	0.1355	9.52E-05	
		33	4290000	0.035212977	0.024899335	0.000619977	0.137	8.49E-05	
		35	4550000	0.033200807	0.023476515	0.000551147	0.1375	7.58E-05	
				sqrt of sumsq		0.907504332			
PI	3.14159265								

Fig. 56: method to obtain the maximum rms current with a measured ESR of a capacitor

### 15.3 Annex 3: Determination of the maximum RMS current in a TPS (K R0300) 10uF 35V case D

#### Single configuration

#### Method of the manufacturer with the typical ESR

Assuming to apply a square current waveform with duty cycle=0.5, the RMS current at 25°C has to be lower than 0.9 A RMS to respect the rated power dissipation for that package (150mW).

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I'	Typical ESR [Ohms]	P [W]	Total P [W]			
0.91	130000	1	130000	1.155573694	0.817113995	0.667675282	0.1153	7.70E-02	1.50E-01			
		3	390000	0.385191231	0.272371332	0.074186142	0.9154	6.79E-02				
		5	650000	0.231114739	0.163422799	0.026707011	0.07784	2.08E-03				
		7	910000	0.165081956	0.116730571	0.013626026	0.07133	9.72E-04				
		9	1170000	0.128397077	0.090790444	0.008242905	0.06783	5.59E-04				
		11	1430000	0.105052154	0.07428309	0.005517978	0.06565	3.62E-04				
		13	1690000	0.088890284	0.062854923	0.003950741	0.06411	2.53E-04				
		15	1950000	0.077038246	0.054474266	0.002967446	0.06293	1.87E-04				
		17	2210000	0.067974923	0.048065529	0.002310295	0.06197	1.43E-04				
		19	2470000	0.060819668	0.043006	0.001849516	0.06117	1.13E-04				
		21	2730000	0.055027319	0.03891019	0.001514003	0.06047	9.16E-05				
		23	2990000	0.050242335	0.035526695	0.001262146	0.05987	7.56E-05				
		25	3250000	0.046222948	0.03268456	0.00106828	0.05935	6.34E-05				
		27	3510000	0.042799026	0.030263481	0.000915878	0.05889	5.39E-05				
		29	3770000	0.039847369	0.028176345	0.000793906	0.05849	4.64E-05				
		31	4030000	0.037276571	0.026358516	0.000694771	0.05814	4.04E-05				
		33	4290000	0.035017385	0.02476103	0.000613109	0.05783	3.55E-05				
		35	4550000	0.033016391	0.023346114	0.000545041	0.05756	3.14E-05				
		sqrt of sumsq					0.90246356					
		PI		3.14159265								

Fig. 57: manufacturer method to obtain the maximum rms current with the typical ESR

#### Maximum RMS current via the maximum ESR given by the manufacturer

Maximum ESR from the datasheet: ESRmax=0.3Ω (at 100Khz) Rated Pd (150mW) is achieved for a square wave current equal to 0.71 A RMS.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I'	Typical ESR [Ohms]	P [W]	Total P [W]			
0.71	130000	1	130000	0.905423601	0.640231168	0.409895949	0.3	1.23E-01	1.50E-01			
		3	390000	0.301807867	0.213410389	0.045543994	0.3	1.37E-02				
		5	650000	0.18108472	0.128046234	0.016395838	0.3	4.92E-03				
		7	910000	0.129346229	0.091461595	0.008365223	0.3	2.51E-03				
		9	1170000	0.100602622	0.071136796	0.005060444	0.3	1.52E-03				
		11	1430000	0.082311236	0.058202833	0.00338757	0.3	1.02E-03				
		13	1690000	0.069647969	0.049248551	0.00242542	0.3	7.28E-04				
		15	1950000	0.060361573	0.042682078	0.00182176	0.3	5.47E-04				
		17	2210000	0.053260212	0.037660657	0.001418325	0.3	4.25E-04				
		19	2470000	0.047653874	0.033696377	0.001135446	0.3	3.41E-04				
		21	2730000	0.04311541	0.030487198	0.000929469	0.3	2.79E-04				
		23	2990000	0.039366244	0.027836138	0.000774851	0.3	2.32E-04				
		25	3250000	0.036216944	0.025609247	0.000655834	0.3	1.97E-04				
		27	3510000	0.033534207	0.023712265	0.000562272	0.3	1.69E-04				
		29	3770000	0.031221503	0.022076937	0.000487391	0.3	1.46E-04				
		31	4030000	0.029207213	0.020652618	0.000426531	0.3	1.28E-04				
		33	4290000	0.027437079	0.019400944	0.000376397	0.3	1.13E-04				
		35	4550000	0.025869246	0.018292319	0.000334609	0.3	1.00E-04				
		sqrt of sumsq					0.707104887					
		PI		3.14159265								

Fig. 57: method to obtain the maximum rms current with the maximum ESR

### Maximum RMS current after the measure of the single impedance

With the frequency analyser the impedance of the single capacitor is measured at 25°C. Assuming to apply a square current waveform with duty cycle=0.5, the current waveform applied to the capacitor is decomposed in Fourier series. It is then possible to calculate the typical RMS power dissipation at each harmonic with the measured impedance. Root-square sum of the individual harmonic contributions gives the RMS power dissipation for one capacitor after characterization. The RMS current at 25°C has to be lower than 0.93 A RMS to respect the rated power dissipation for that package (150mW) by using the measured impedance at 25°C.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I <sup>2</sup>	Typical ESR [Ohms]	P [W]	Total P [W]
0.93	130000	1	130000	1.18781194	0.839909878	0.705448603	0.101	7.13E-02	8.24E-02
		3	390000	0.395937313	0.279969959	0.078383178	0.08	6.27E-03	
		5	650000	0.237562388	0.167981976	0.028217944	0.07	1.98E-03	
		7	910000	0.16968742	0.119987125	0.01439691	0.065	9.36E-04	
		9	1170000	0.131979104	0.09332332	0.008709242	0.0615	5.36E-04	
		11	1430000	0.107982904	0.076355443	0.005830154	0.0595	3.47E-04	
		13	1690000	0.091370149	0.064608452	0.004174252	0.0579	2.42E-04	
		15	1950000	0.079187463	0.055993992	0.003135327	0.057	1.79E-04	
		17	2210000	0.069871291	0.049406463	0.002440999	0.056	1.37E-04	
		19	2470000	0.062516418	0.044205783	0.001954151	0.0553	1.08E-04	
		21	2730000	0.056562473	0.039995708	0.001599657	0.055	8.80E-05	
		23	2990000	0.051643997	0.036517821	0.001333551	0.0546	7.28E-05	
		25	3250000	0.047512478	0.033596395	0.001128718	0.0545	6.15E-05	
		27	3510000	0.043993035	0.031107773	0.000967694	0.0542	5.24E-05	
		29	3770000	0.040959032	0.02896241	0.000838821	0.0541	4.54E-05	
		31	4030000	0.038316514	0.027093867	0.000734078	0.054	3.96E-05	
		33	4290000	0.035994301	0.025451814	0.000647795	0.054	3.50E-05	
		35	4550000	0.033937484	0.023997425	0.000575876	0.054	3.11E-05	
				sqrt of sumsq		0.927640528			
PI									
3.14159265									

Fig. 58: method to obtain the maximum rms current with a measured ESR of a capacitor

### 15.4 Annex 4: impedances, ESRs, and X of TAJD 22uF 35V

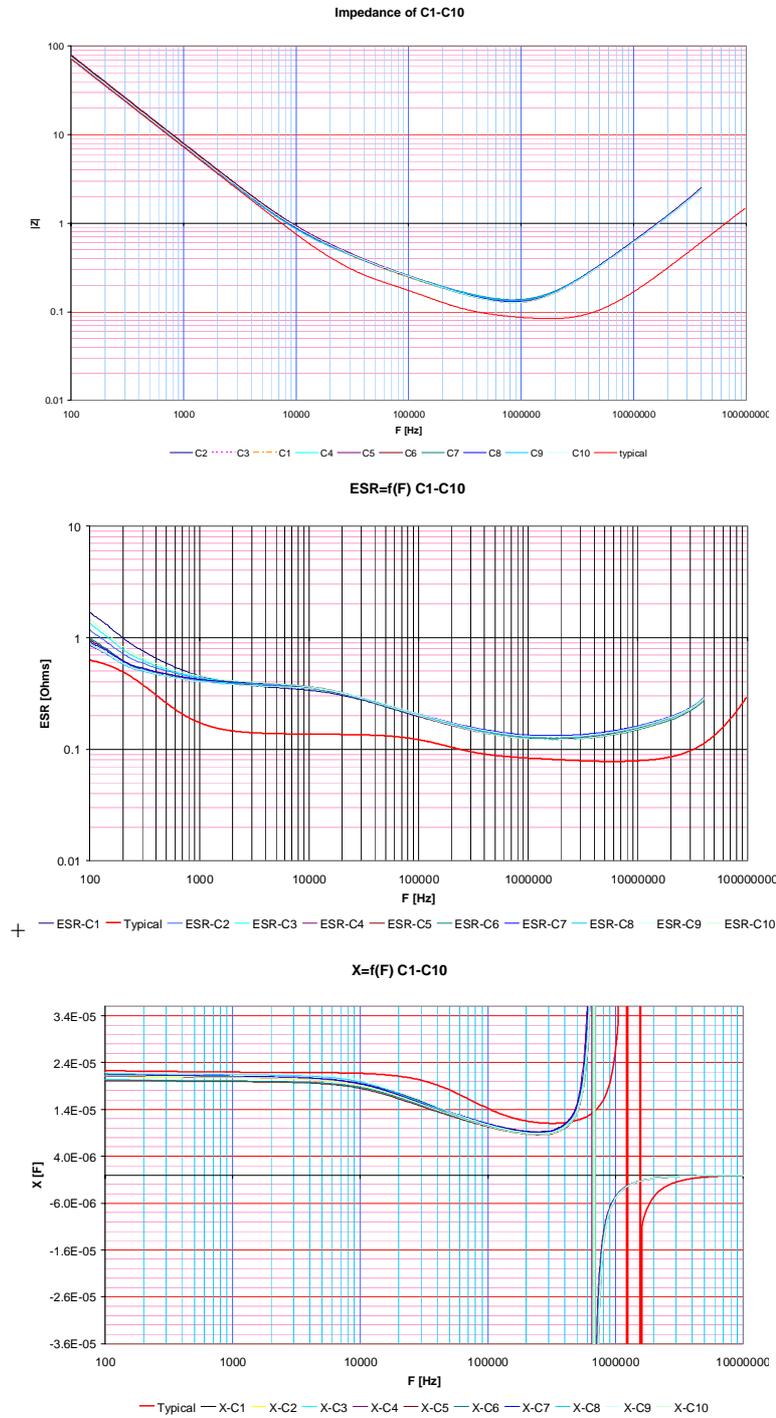


Fig 59a b and c: Impedances, ESRs and Capacitances of 10 capacitors (C1-C10) TAJD 22uF 35V

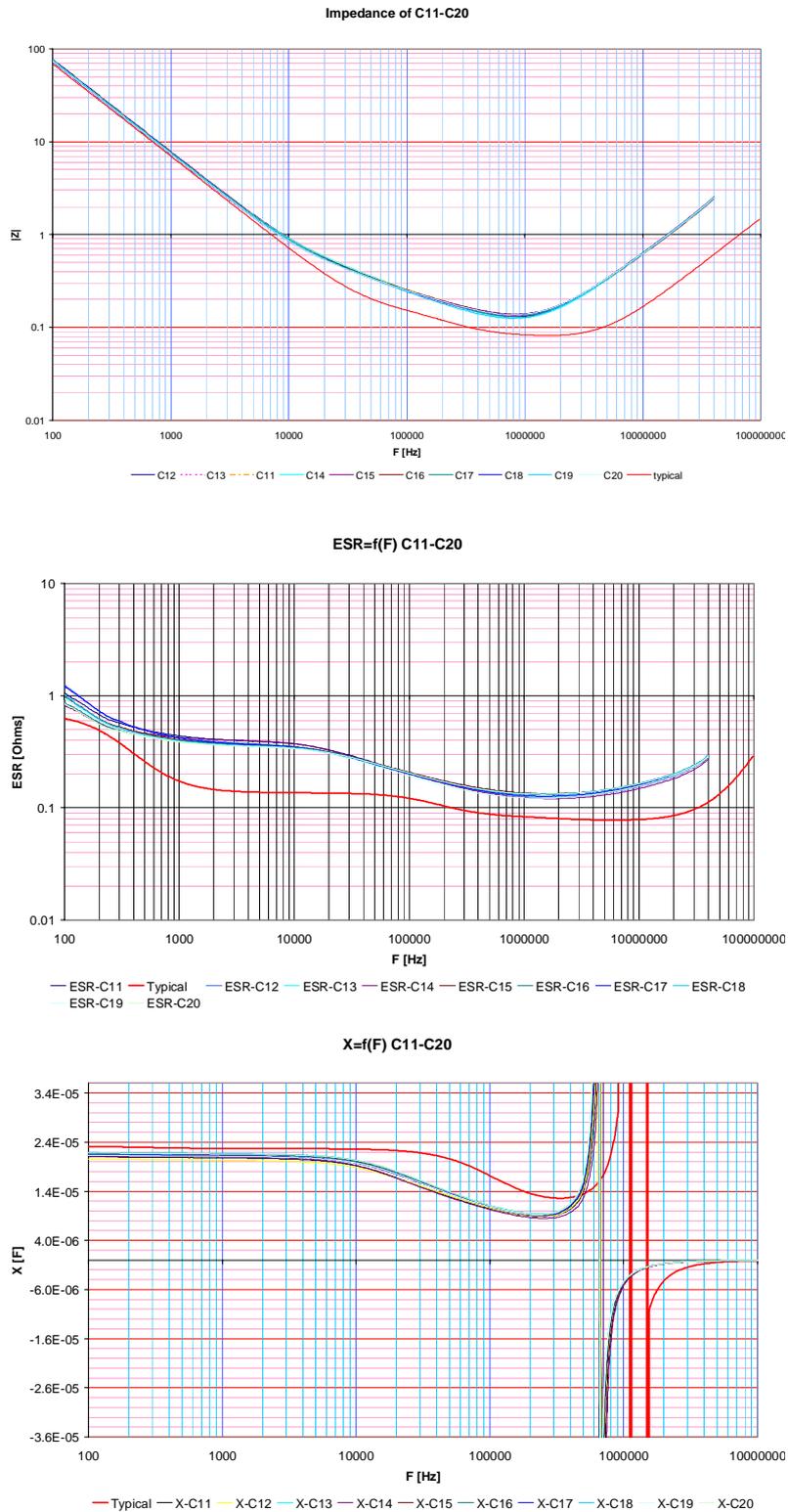


Fig 60a, b and c: Impedances, ESR and capacitances of 10 capacitors (C11-C20) TAJD 22uF 35V

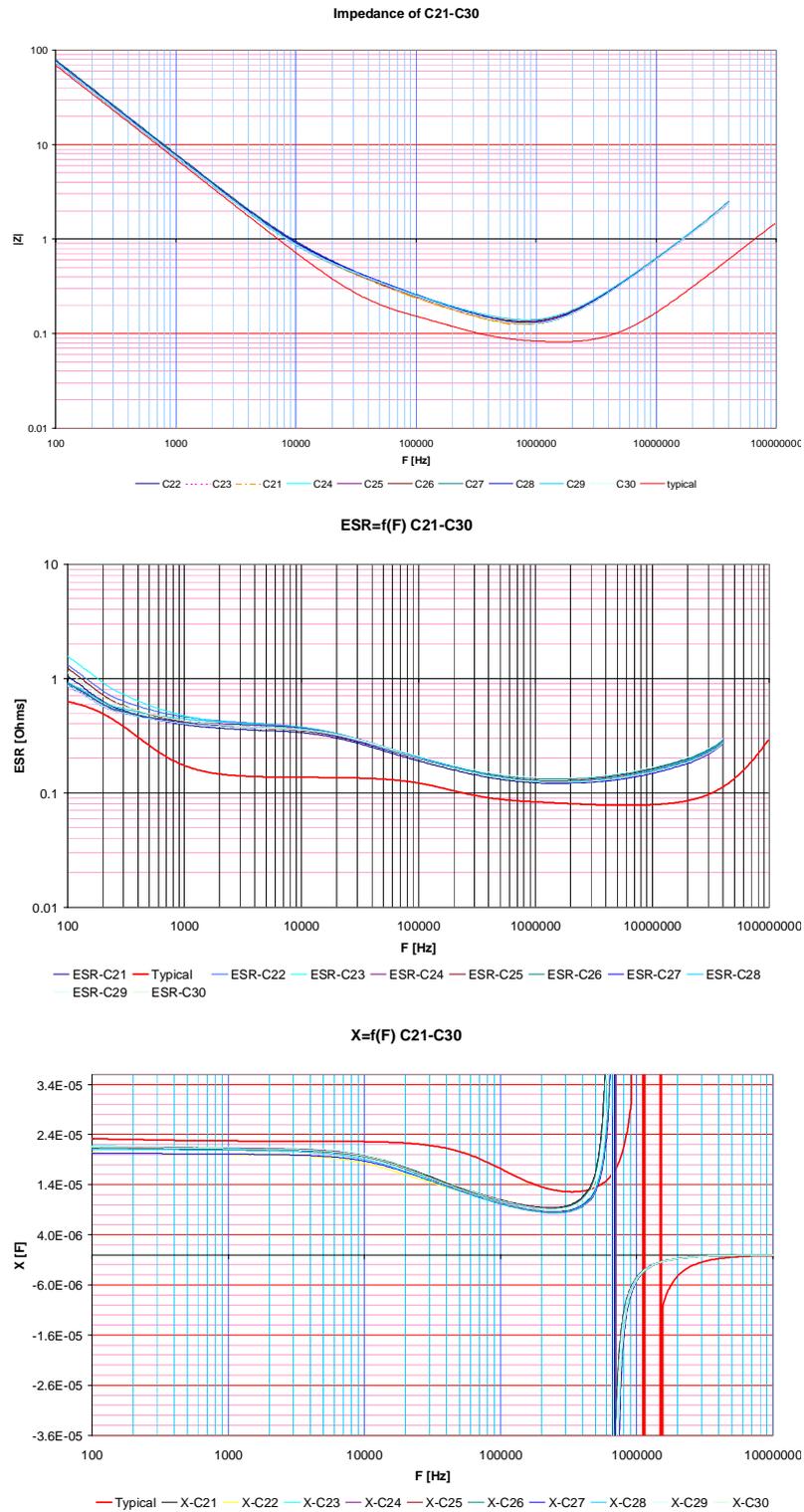


Fig 61 a, b and c: Impedances, ESR and capacitances of 10 capacitors (C21-C30) TAJD 22uF 35V

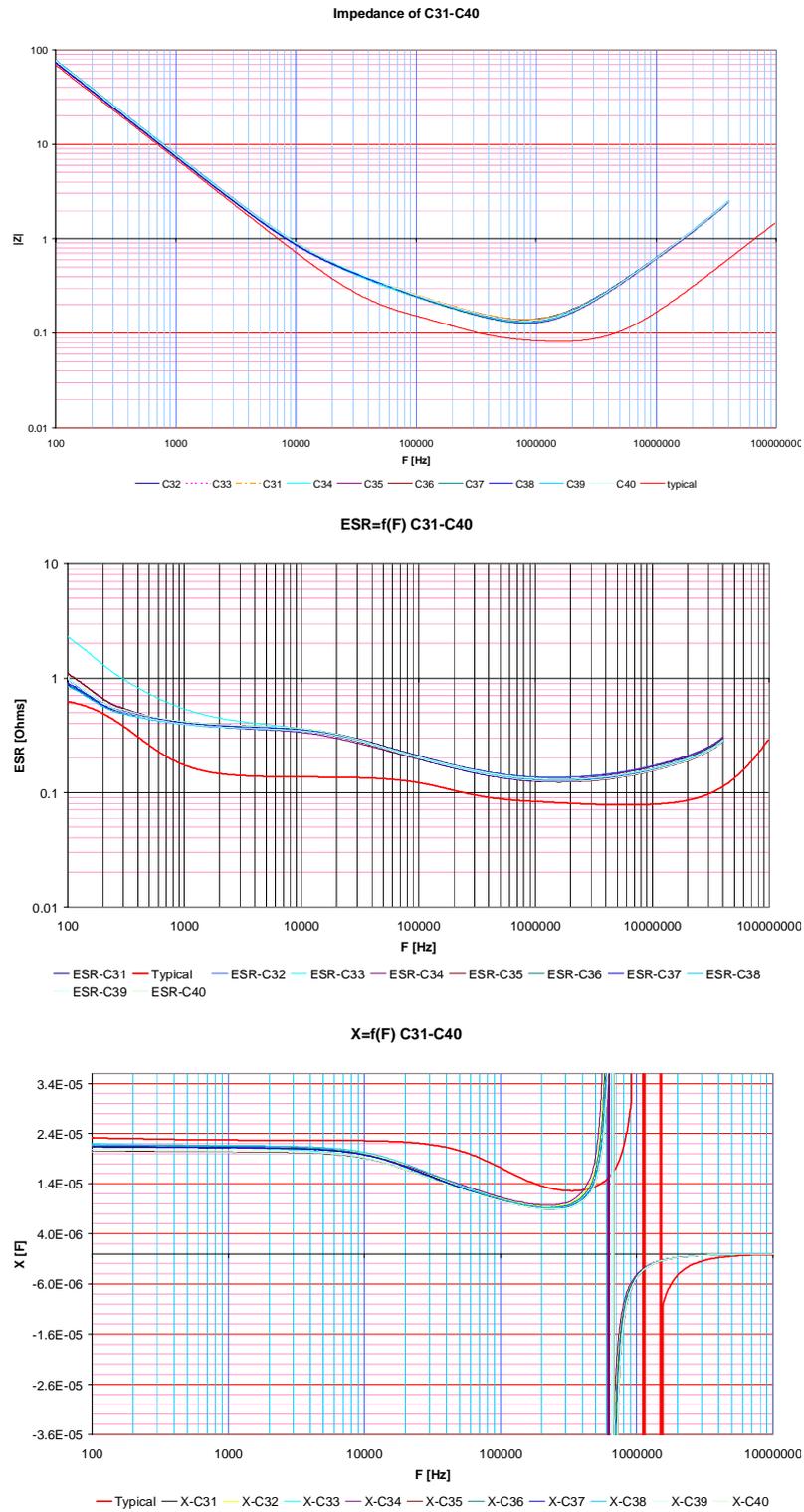


Fig 62 a, b and c: Impedances, ESR and capacitances of 10 capacitors (C31-C40) TAJD 22uF 35V

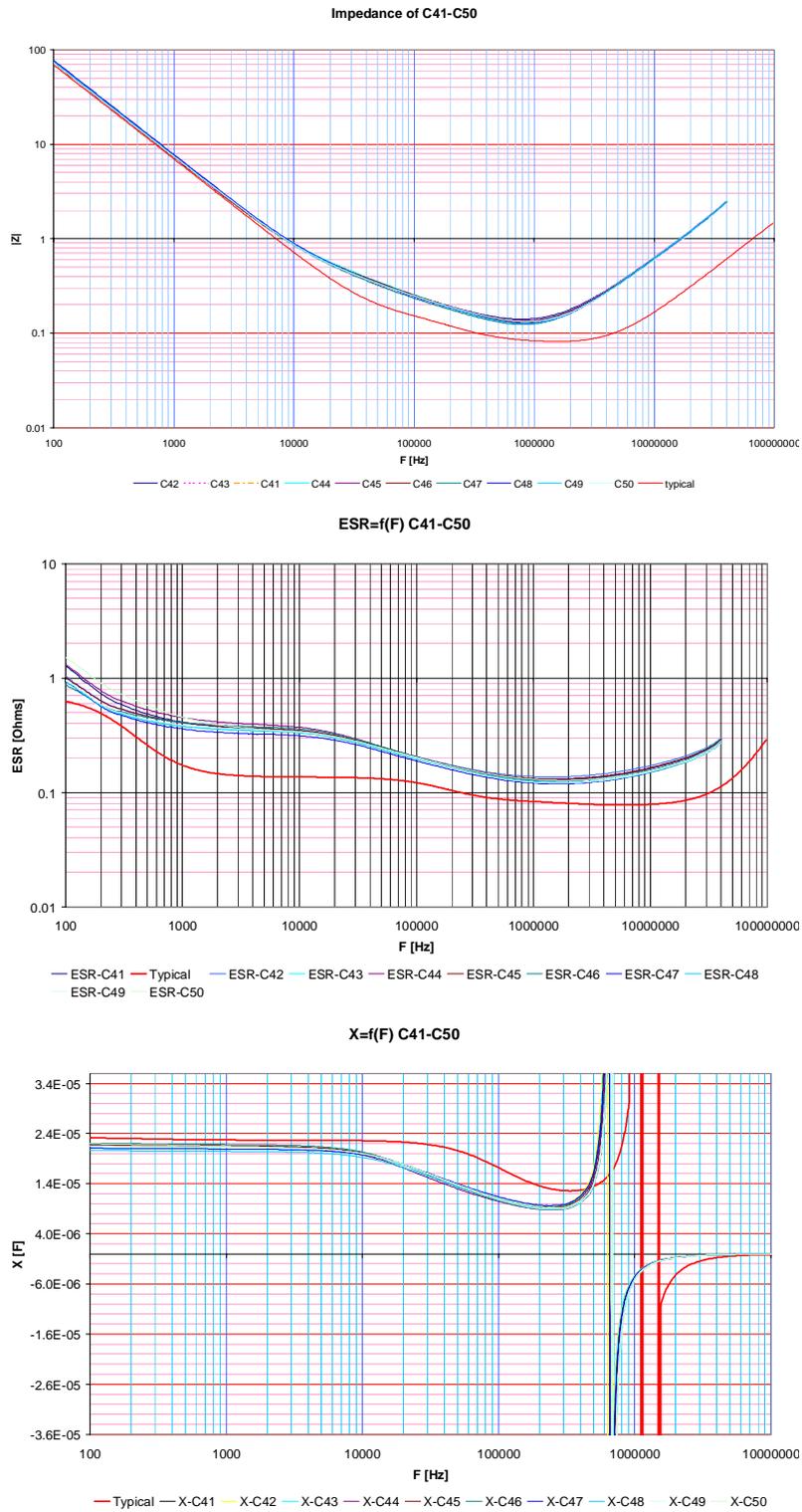


Fig 63 a, b and c: Impedances, ESR and capacitances of 10 capacitors (C41-C50) TAJD 22uF 35V

## 15.5 Annex 5: impedances, ESRs, and X of TAJD 10uF 35V

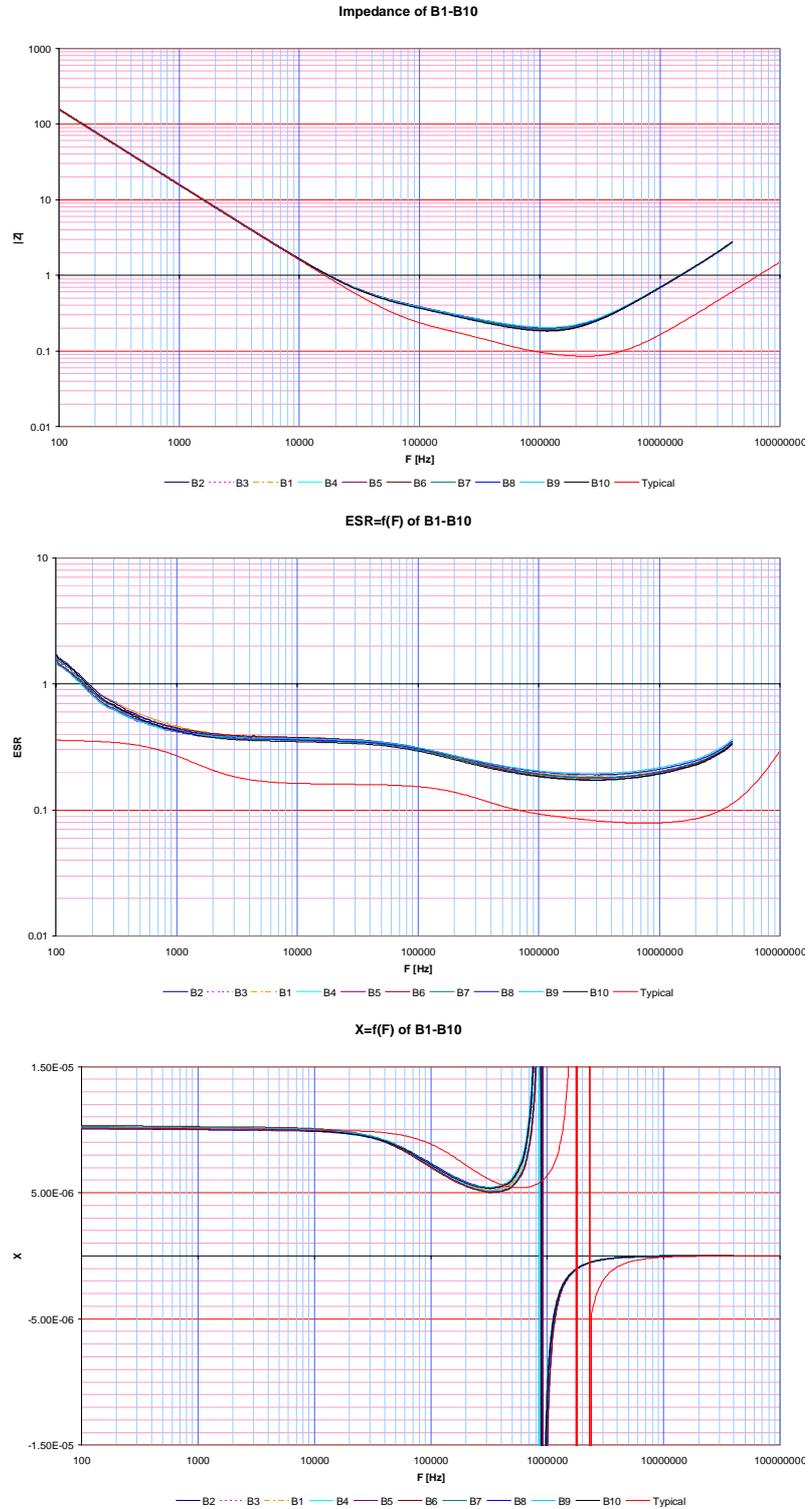


Fig 64 a, b and c: Impedances, ESRs and Capacitances of 10 capacitors (B1-B10) TAJD 10uF 35V

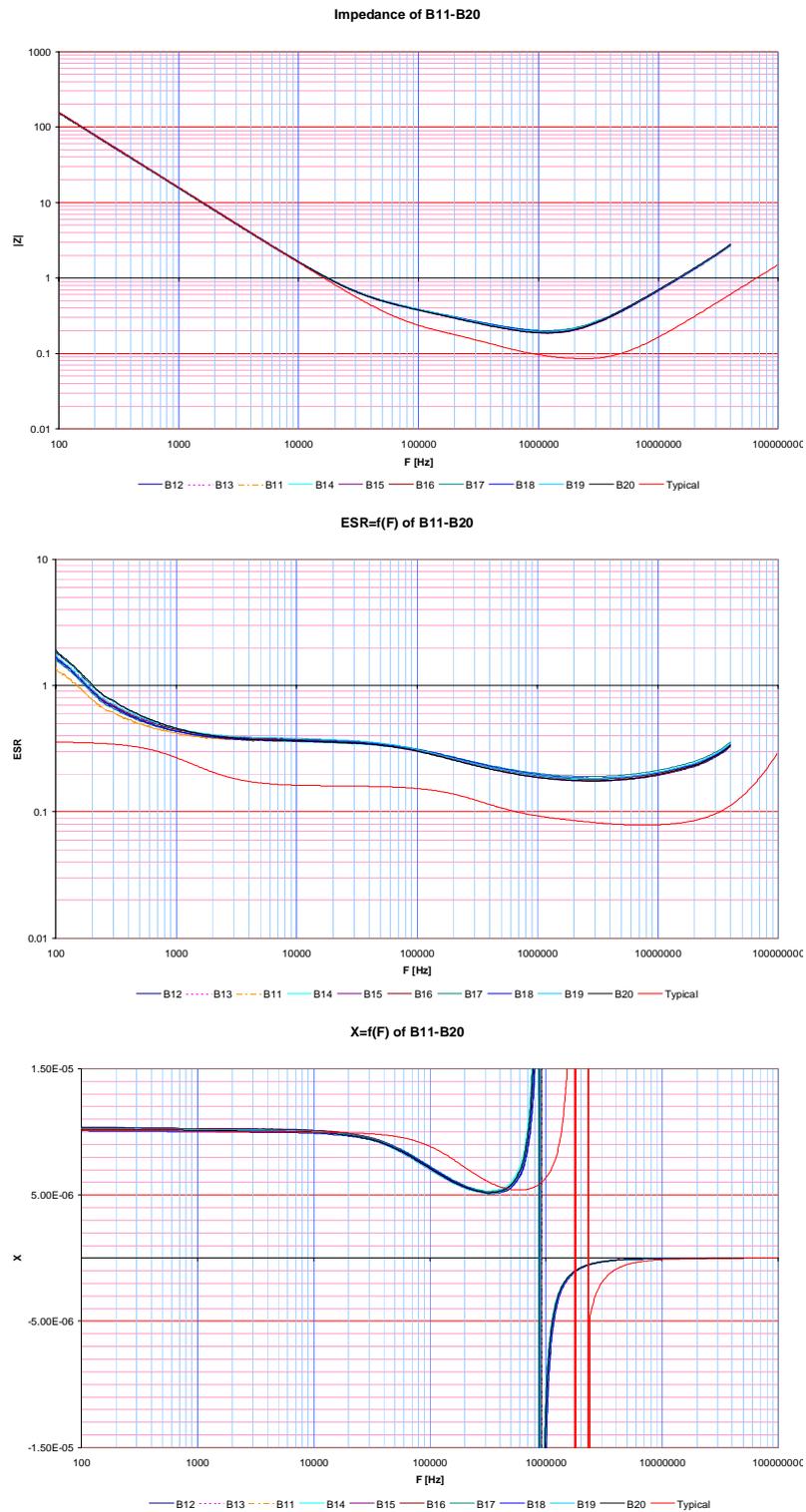


Fig 65 a, b and c: Impedances, ESRs and Capacitances of 10 capacitors (B21-B30) TAJD 10uF 35V

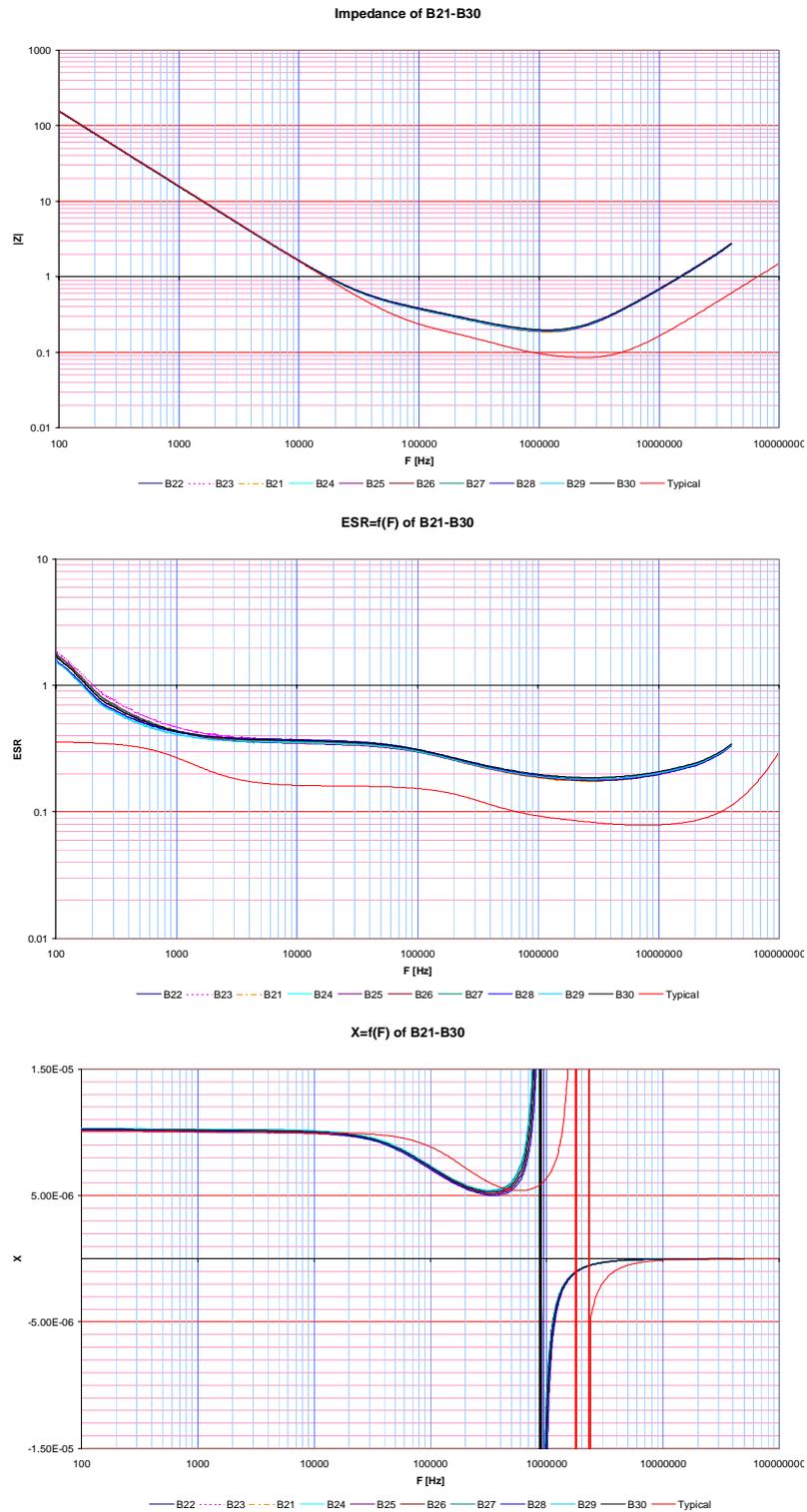


Fig 66a, b and c: Impedances, ESRs and Capacitances of 10 capacitors (B21-B30) TAJD 10uF 35V

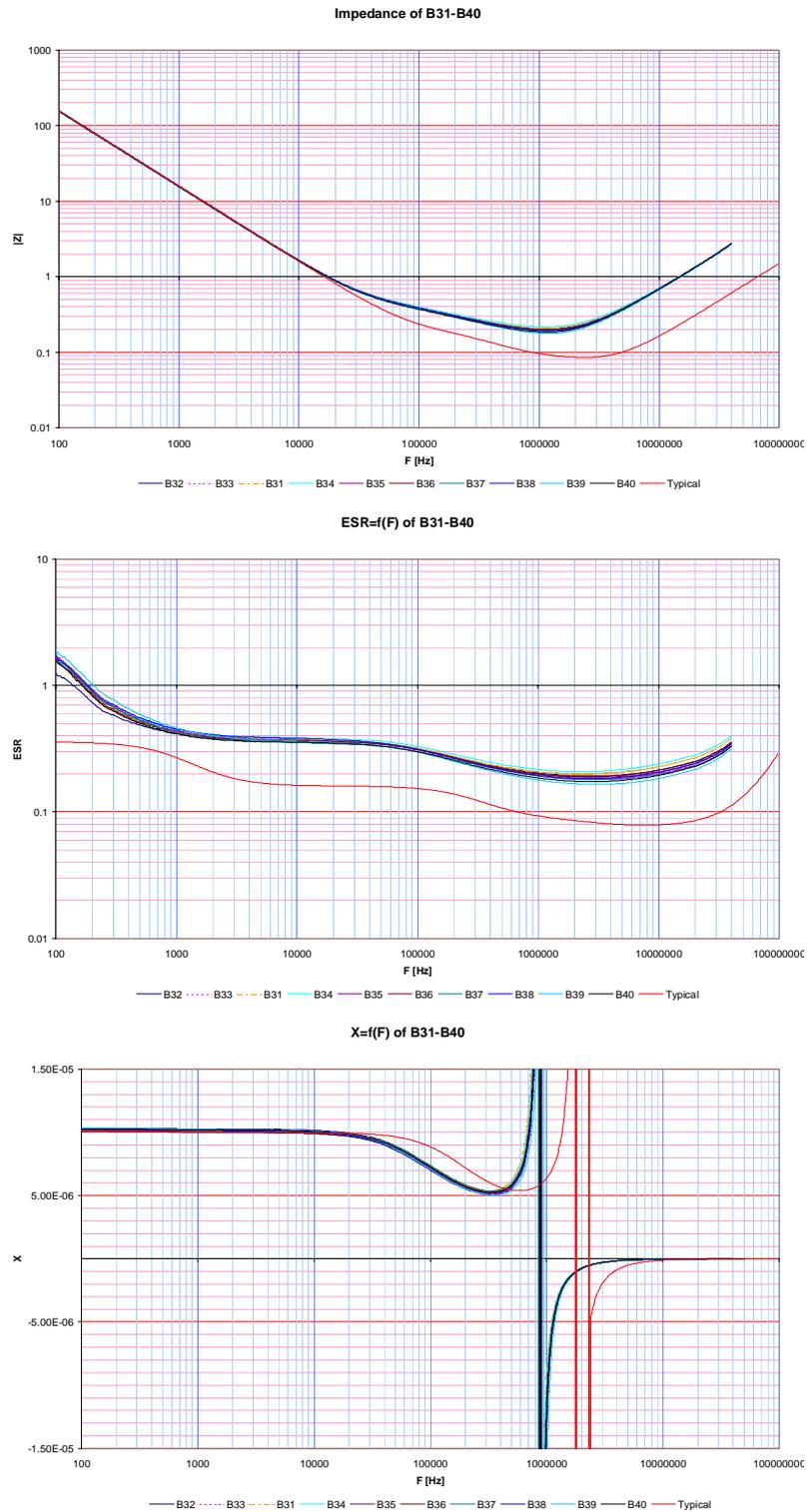


Fig 67 a, b and c: Impedances, ESRs and Capacitances of 10 capacitors (B31-B40) TAJD 10uF 35V

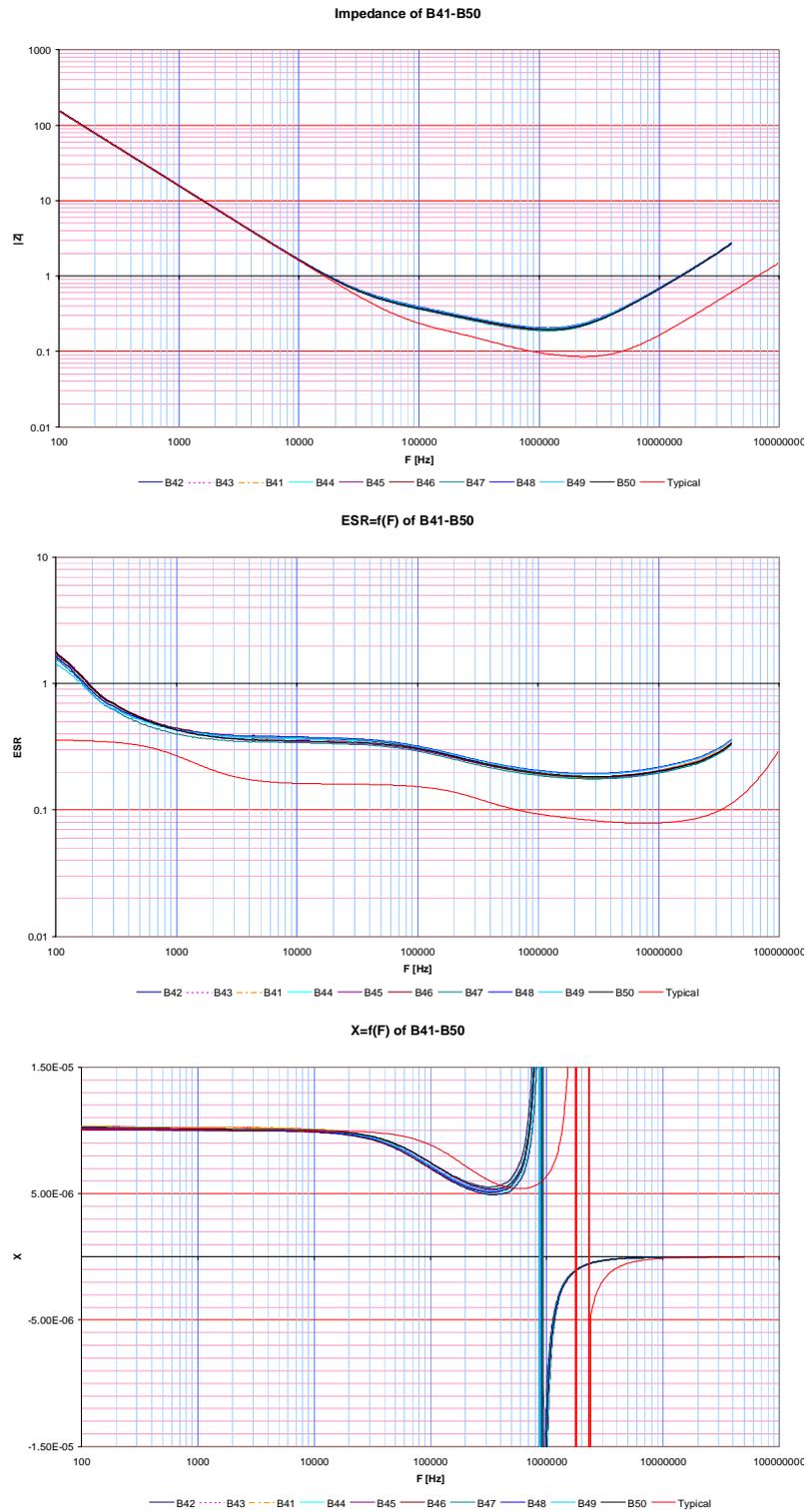


Fig 68 a, b and c: Impedances, ESRs and Capacitances of 10 capacitors (B41-B50) TAJD 10uF 35V

## 15.6 Annex 6: Comparisons of the impedance before and after the soldering process for Capacitor banks (CB13 to CB17) of TAJD 22uF 35V (C1 to C50)

Note that the graphs of the capacitor bank impedances obtained **before** the test results is **calculated** from the parallelization of the capacitors tested individually; the graphs of the capacitor bank impedances obtained **after** the test results is **measured** from the capacitor banks after the soldering.

The differences of the impedances are mainly due to the additional parasitic resistances and inductances of the PCB and the solder joints.

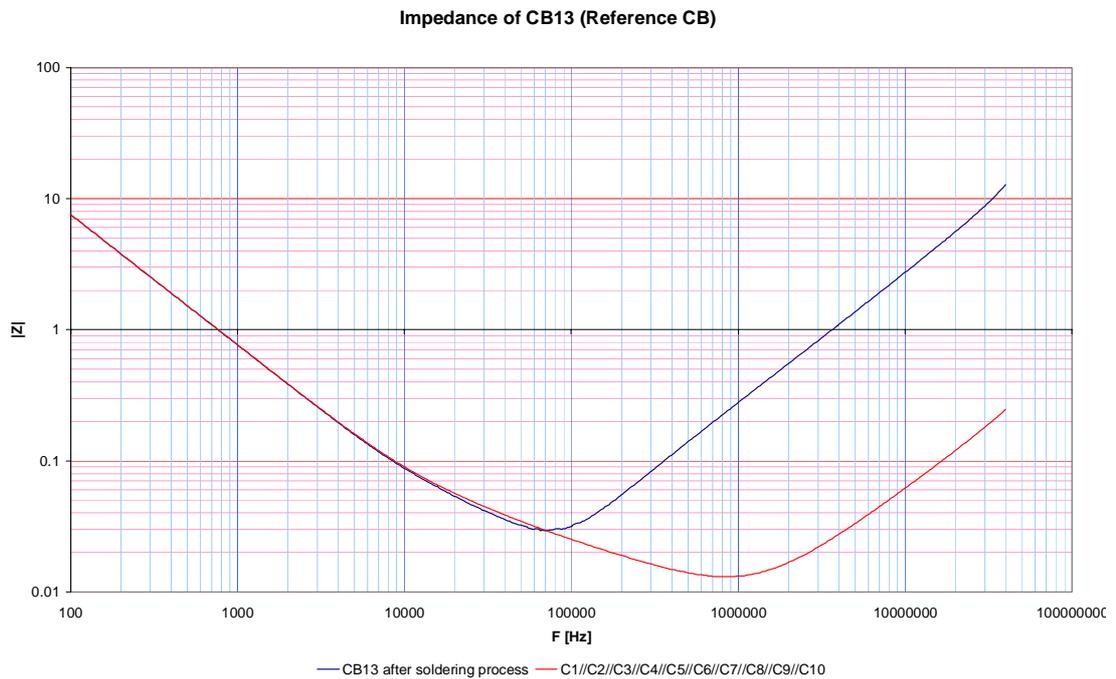


Fig. 69: Comparisons of the impedances of CB13 before and after the soldering process for the TAJD 22uF 35V

**Impedance of CB14**

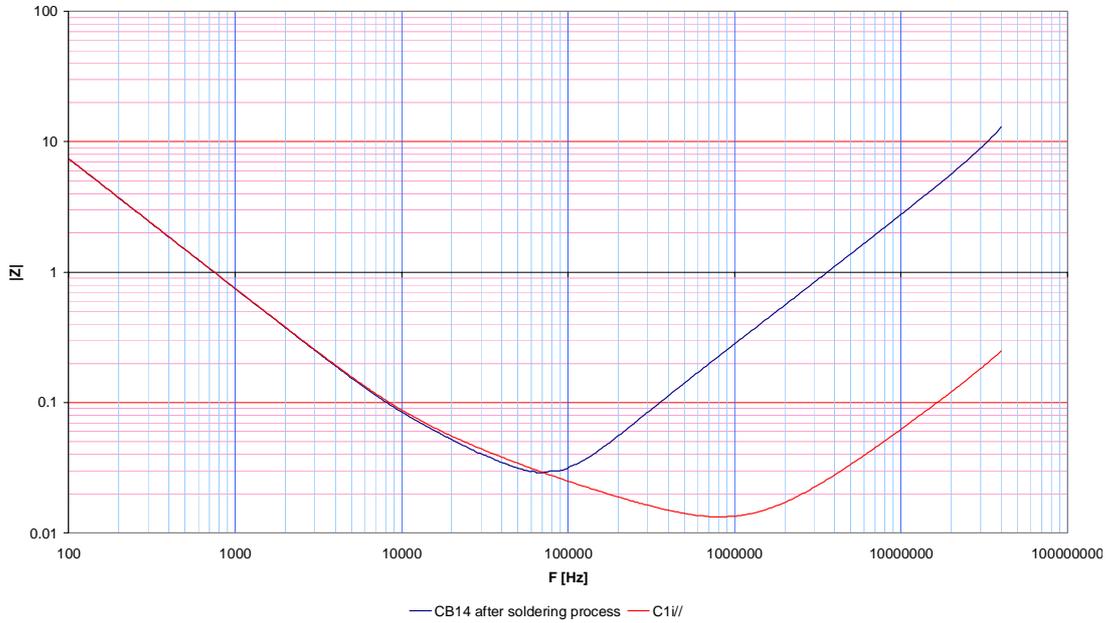


Fig. 70: Comparisons of the impedances of CB14 before and after the soldering process for the TAJD 22uF 35V

**Impedance of CB15**

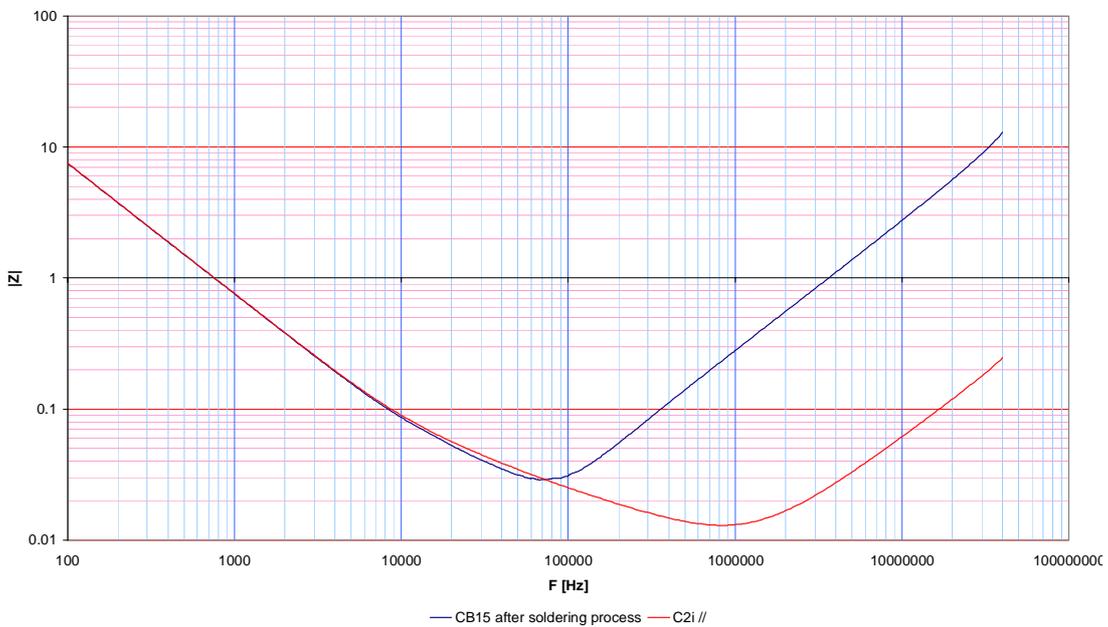


Fig. 71: Comparisons of the impedances of CB15 before and after the soldering process for the TAJD 22uF 35V

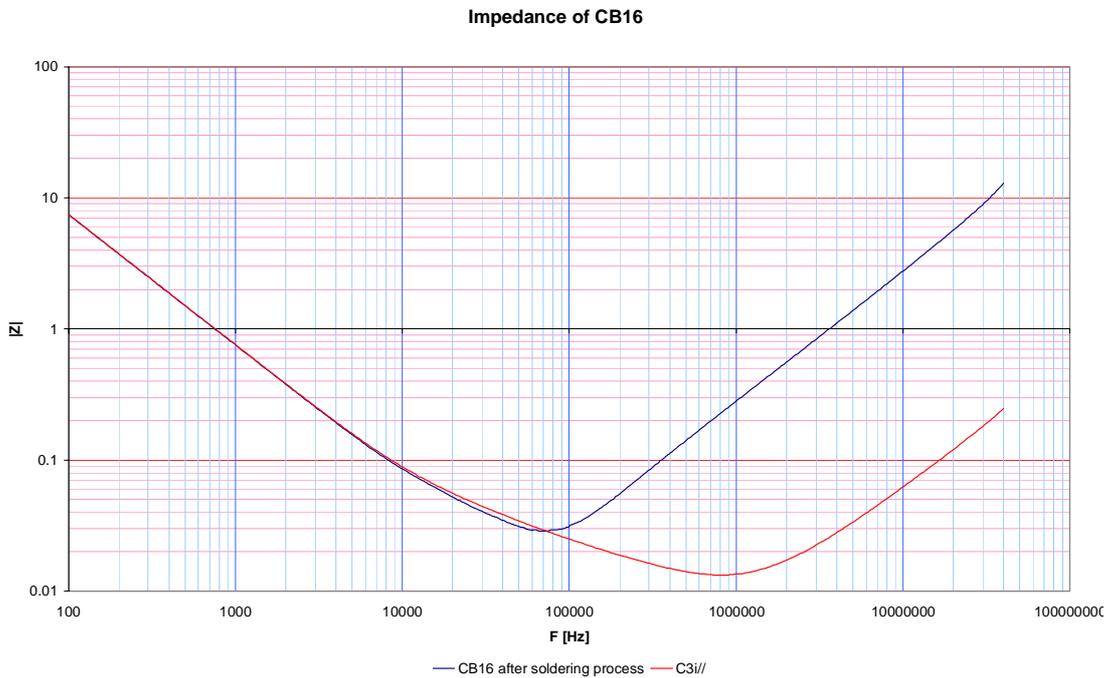


Fig.72: Comparisons of the impedances of CB16 before and after the soldering process for the TAJD 22uF 35V

+

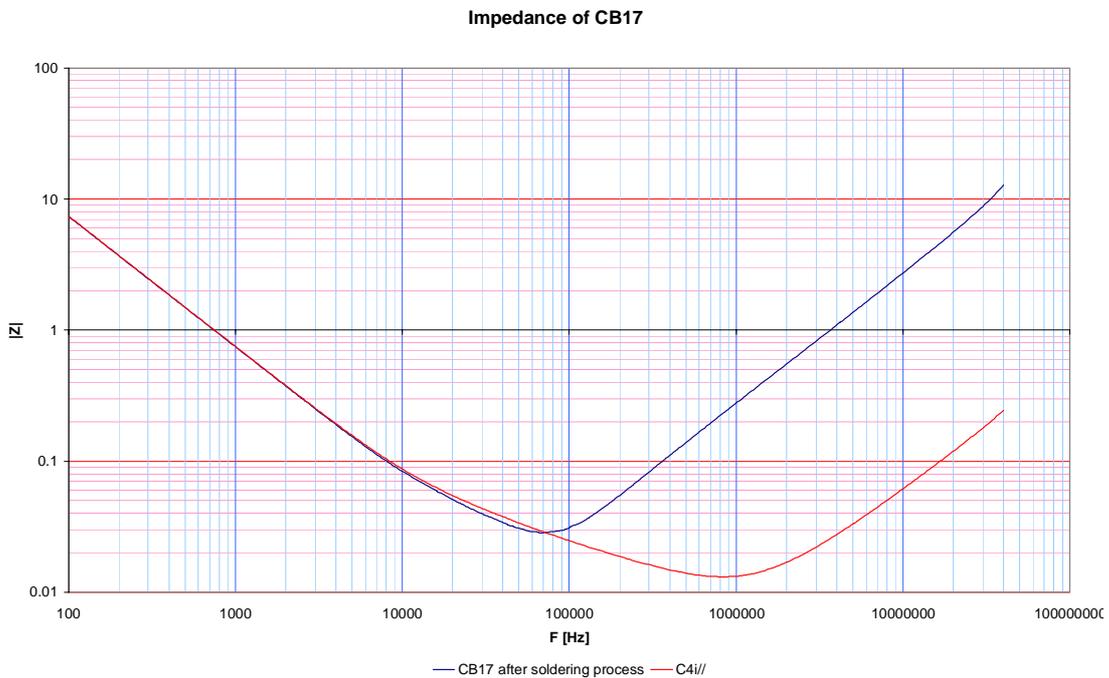


Fig. 73: Comparisons of the impedances of CB17 before and after the soldering process for the TAJD 22uF 35V

## 15.7 Annex 7: Comparisons of the impedance before and after the soldering process for Capacitor banks (CB7 to CB11) of TAJD 10uF 35V (B1 to B50)

Note that the graphs of the capacitor bank impedances obtained **before** the test results is **calculated** from the parallelization of the capacitors tested individually; the graphs of the capacitor bank impedances obtained **after** the test results is **measured** from the capacitor banks after the soldering.

The differences of the impedances are mainly due to the additional parasitic resistances and inductances of the PCB and the solder joints.

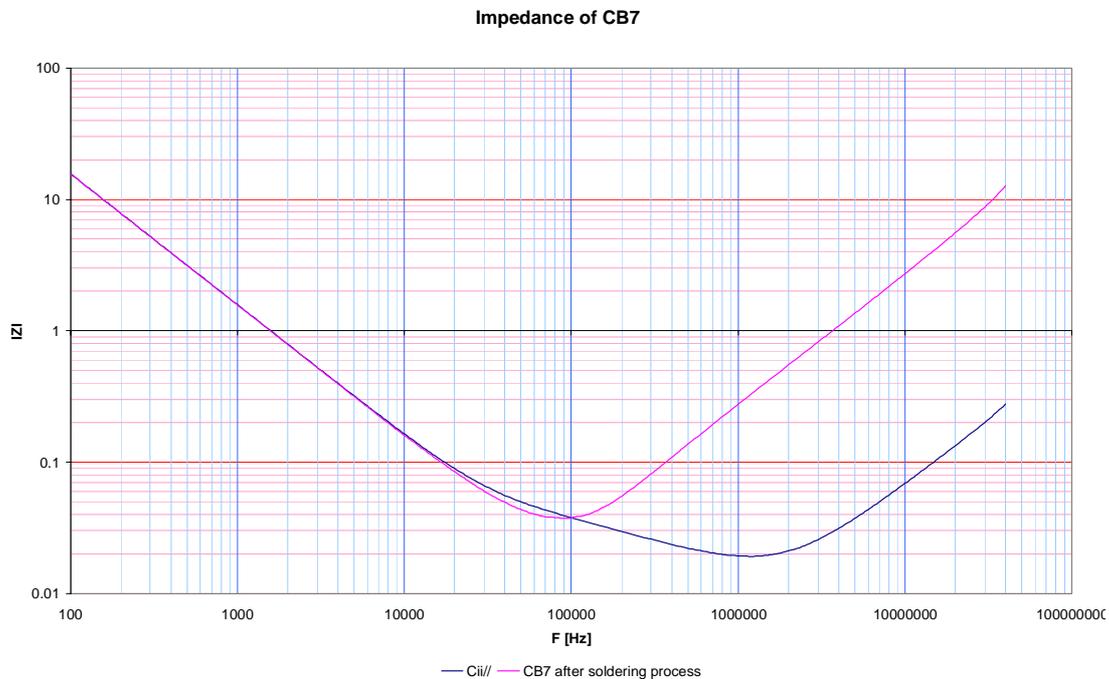


Fig. 74: Comparisons of the impedances of CB7 before and after the soldering process for the TAJD 10uF 35V (B1...B10)

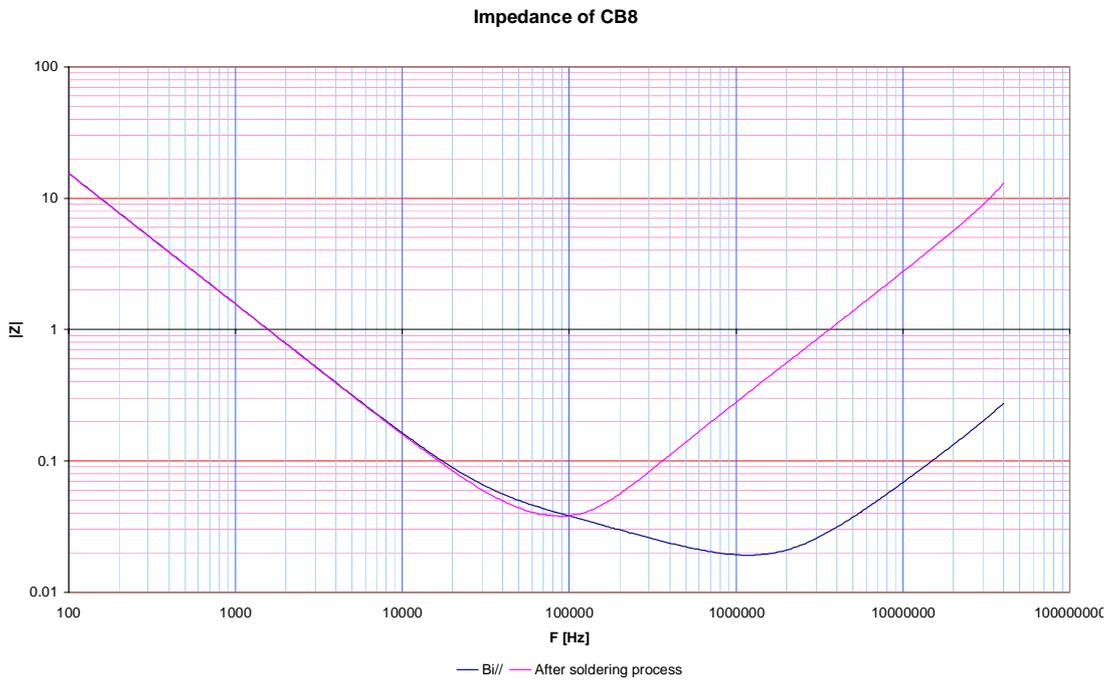


Fig. 75: Comparisons of the impedances of CB8 before and after the soldering process for the TAJD 10uF 35V (B11...B20)

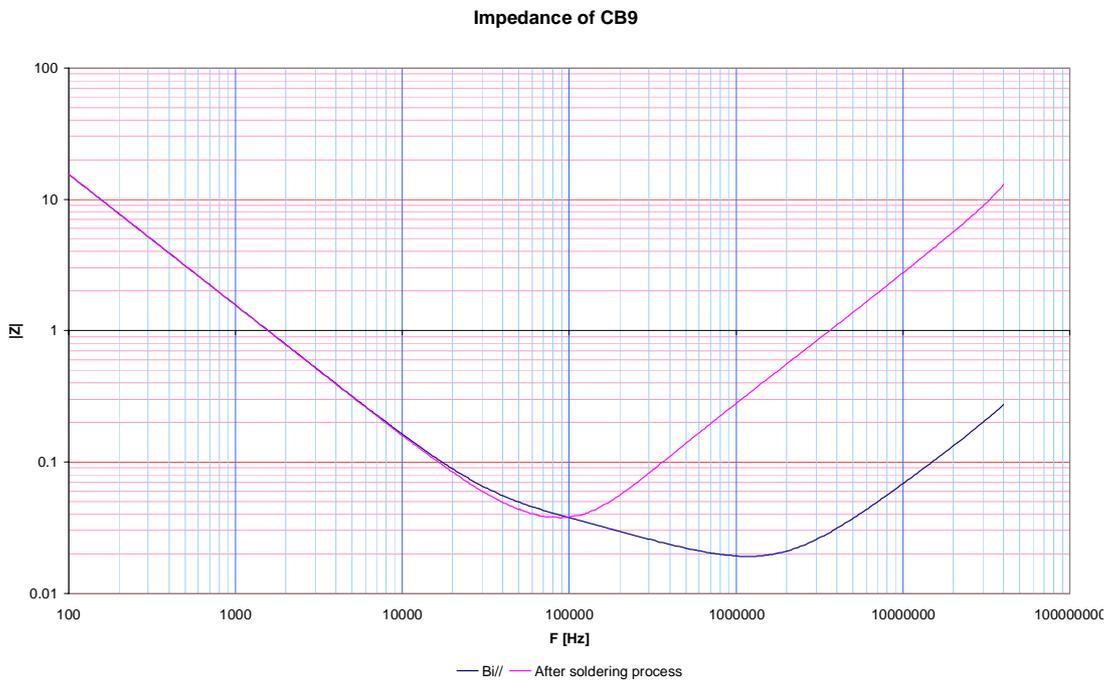


Fig. 76: Comparisons of the impedances of CB9 before and after the soldering process for the TAJD 10uF 35V (B21...B30)

**Impedance of CB10**

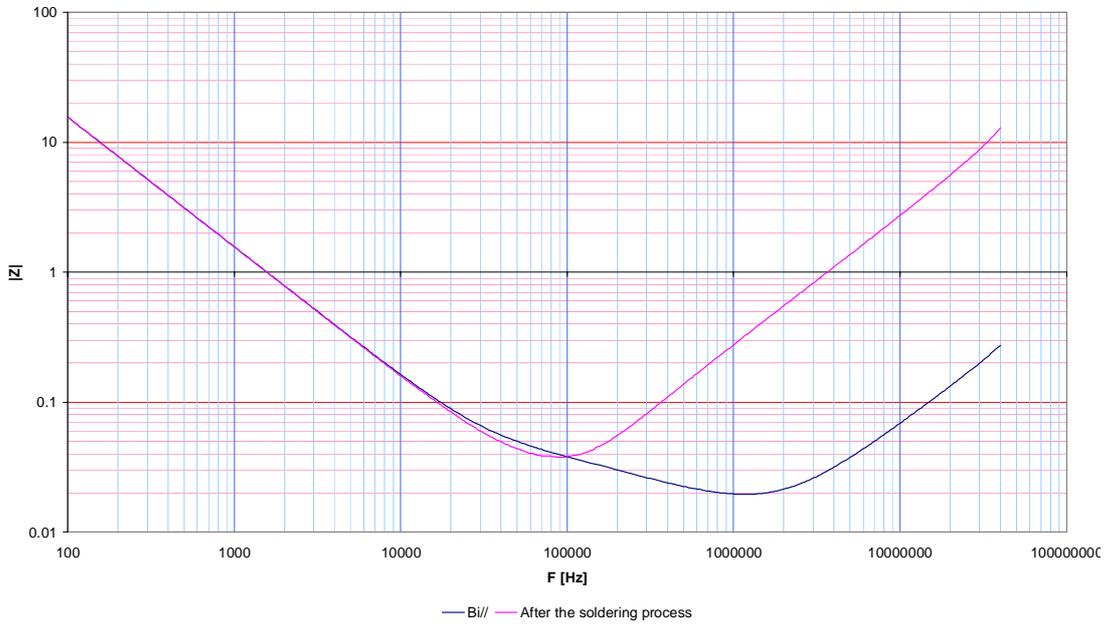


Fig. 77: Comparisons of the impedances of CB10 before and after the soldering process for the TAJD 10uF 35V (B31...B40)

**Impedance of CB11**

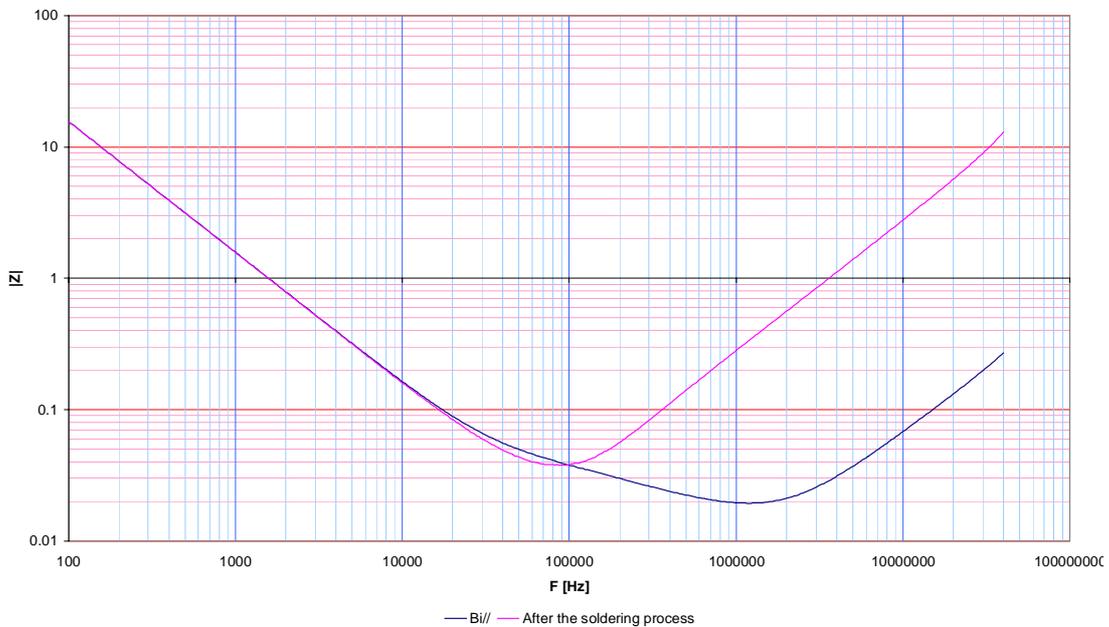


Fig. 78: Comparisons of the impedances of CB11 before and after the soldering process for the TAJD 10uF 35V (B41...B50)

## 15.8 Annex 8: Heating plates System

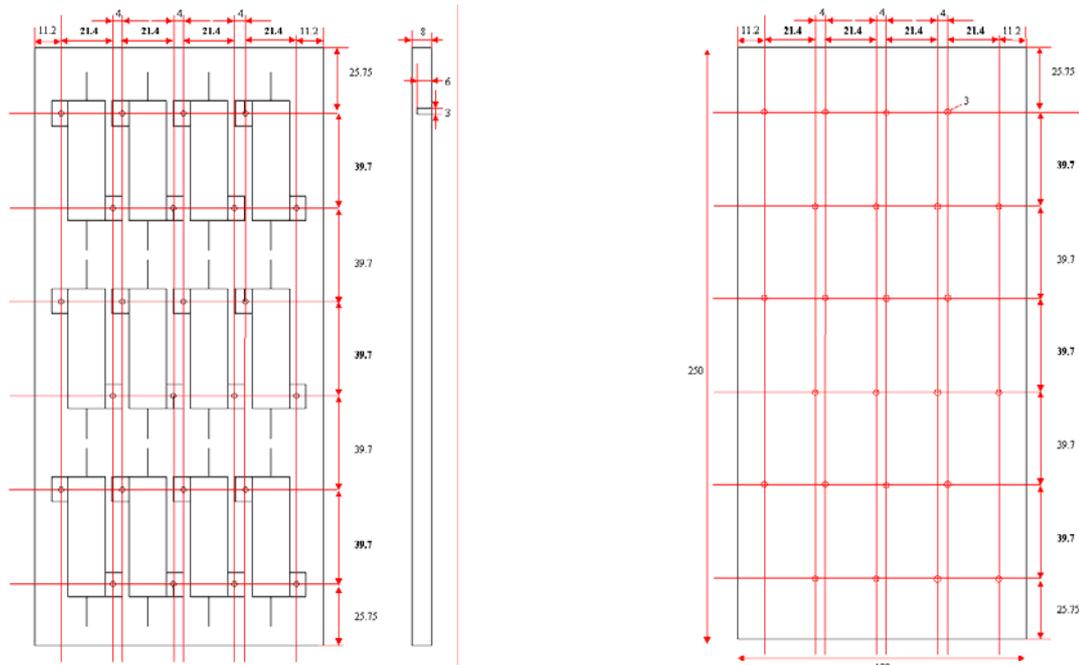


Fig. 79a and b: Aluminium plate to heat the capacitor bank to 85degC

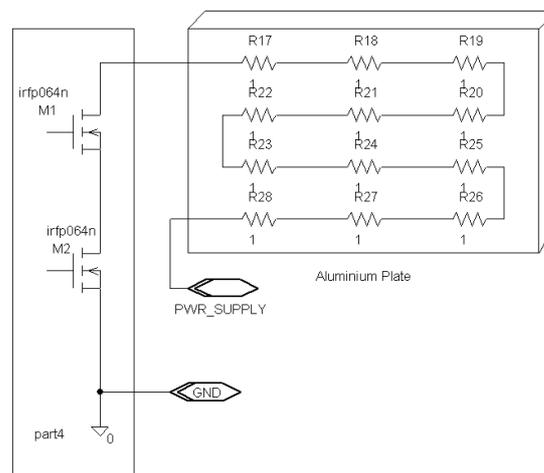


Fig. 80: Power part of the heating plate

The circuit shown in Fig 81 controls the MFETs. Please note that the figure 81 presents only the circuit used to control one MFET. The same circuit is duplicated to control the second MFET. This precaution allows having two autonomous control circuits.

The heart of the temperature control card is a LM335. This device is a temperature sensor, which is connecting on the resistors side of the heating plate. It is supplied by a constant current (#1 mA) with the intermediate current mirror build with Q1 and Q2 (part 1 of the fig. 81).

The signal from the temperature sensor is an image of the temperature. This signal is filtered via a differential amplifier, designed with an operational amplifier Lm124 (part 2 of fig. 81).

The filtered signal from the differential amplifier is then compared to a reference voltage with a Schmidt trigger (provided with a very small hysteresis to avoid the oscillating control of the MFET).

When the temperature is higher than the programmed threshold, then the signal from the differential amplifier exceeds the temperature voltage reference and the gate of the MFET is close to zero (the current in the heating resistors is switched-off until the temperature signal from the differential amplifier reached the temperature voltage reference of the Schmidt trigger).

Which this simple control principle it is possible to control the temperature of the capacitors at 85 degC +/-2degC.

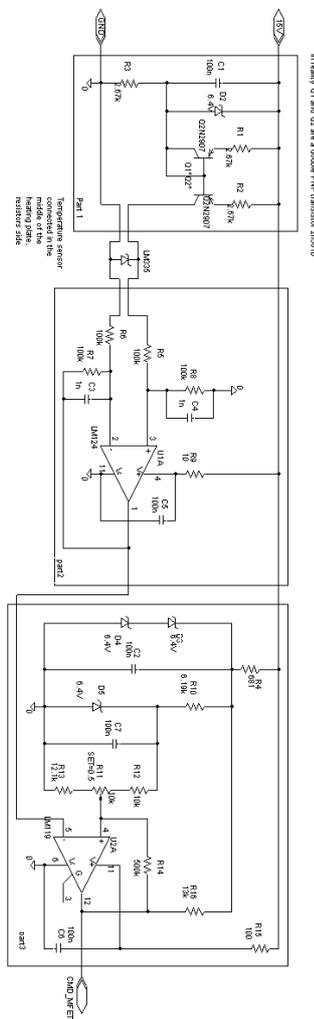


Fig. 81: Schematic of the temperature control card of the heating plate.