TECHNICAL INFORMATION

SURGE CURRENT TESTING OF RESIN DIPPED TANTALUM CAPACITORS

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Abstract:

Resin dipped solid tantalum capacitors subjected to fast switch-on surges from a low impedance source have a low but significant instantaneous failure rate similar to that for metal cased tantalum capacitors. This failure is affected by external circuit conditions, by capacitor construction and by various applied stresses. The mechanism progresses through several stages. For the initial stage the voltage seems of more importance than the current. The high current availability is necessary for the second stage to appear. The effect of over voltage and thermal stresses and of the presence of moisture have been studied together with the effects of capacitor leakage current and ESR.

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Introduction

Although solid tantalum capacitors have an excellent record of high reliability, a particular problem has been highlighted over the past few years as the capacitors are used increasingly in low impedance circuits where there is a high current source available. In some of these circuits there is a risk of catastrophic failure during switch-on. Provided that voltage derating is applied and that precautions are taken to prevent voltage overshoots and reversals this risk is very low. As there are circuits where derating is not practical an alternative safeguard has been used, namely screening the components going into these positions.

The work reported here is some of the laboratory investigations into the causes of this failure mechanism, generally known as "surge current"- or "high inrush current"-failure. The results quoted below are based on resin dipped styles of solid tantalum capacitor. The early stages of breakdown are essentially identical in the other encapsulated styles but there are differences in behavior in the subsequent stages. Also the sensitivity to temperature cycling is quite different in the various styles. Obviously the metal cased version is immune from changes related to external humidity.

From considerations both of theoretical calculations of the conditions for oscillatory charging and of practical experience the 47μF 25V code was chosen as the basis for the majority of the trials.

Test Circuit

The test circuit used for these investigations is similar in principle to that used by other authors[1-3]. Three pulses were given, each of 1 second duration with 1 second discharge through a 1K ohm resistor between pulses. Almost all failures occurred in the first pulse except when voltages approaching twice rated voltage were used. Voltage waveforms were monitored on an oscilloscope. Breakdown was detected from the waveform or audibly and the current supply was disconnected via a manual switch.

Experience from Promotion Screening

Analysis of the yield of production batches which were 100% screened showed a bigger variation batch to batch than that between different voltage ratings, capacitance level or capacitor size. Discounting the batches with above average level of rejects the rest of the results showed a slight increase in failure rate with increased capacitor size and voltage rating but the increase was much lower than anticipated from the range of surface area of the dielectric or from theories of dielectric breakdown.

There was no indication that one source of tantalum powder was any better than any other. Differences in powder type (sodium reduced or electron beam, differences in particle size or degree of agglomeration) or sinter temperature, which are needed to cover the whole spread of the product, did not show up as important factors in the number rejected in the screening procedure.

This insensitivity to powder type or quality coupled with the batch to batch variability suggests that perhaps the basic cause of the problem lies in the manufacturing methods rather than in the capacitor design. However against that must be set the fact that all manufacturers' products seem to have similar behavior in spite of the major differences in manufacturing equipment and methods. An alternative suggestion is that whatever the size of the capacitor or whatever the voltage, there is just one length of tantalum wire per anode. The tantalum wire-powder junction is one of the weak points of the capacitor. This will be considered further later on.

Current or Voltage Control?

It has been assumed by other authors that this failure mechanism relates to the high inrush current during switch-on.

To check whether this is the case an experiment was carried out with variations in the level of series resistance and inductance which allows wide variations in the severity of:

Peak positive current,
Peak negative current,
Peak voltage,
Voltage at peak current,
Rate of increase of current, and
Product of current and voltage.

Ninety-three 47μF 25V capacitors were measured for ESR at 10KHz and then separated into various groupings. The first 66 were split into two groups and one was surge tested with a total circuit inductance of 0.5μH and the other with 4.2μH. The surge test was carried out at 30V rather than at rated voltage in order to generate a higher proportion of failures. Table I shows the number of failures against ESR level and inductance. There is no obvious trend with ESR but a significant increase with added inductance. To obtain further information the remaining 27 capacitors were split into two groups. The higher ESR split was tested with an additional 0.25Ω in series. The lower split was surge tested at a voltage of 21V. Table II combines the failure level with the relevant ranges of peak current, voltage and rate of rise of current.

ESR	0.5µH			4.2µH		
Ω	GROUP	NO. TESTED	NO. FAILED	GROUP	NO. TESTED	NO. FAILED
0.15-0.16	A	1	0	B	1	0
0.16-0.17		2	0		2	1
0.17-0.18		7	1		8	0
0.18-0.19		6	0		6	2
Sub Total		16	1		17	3
0.19-0.20	C	8	0	D	8	2
0.20-0.22		5	0		5	0
0.22-0.24		3	0		2	1
0.24-0.26		1	0		1	0
Sub Total		17	0		16	3
Total	A + C	33	1	B + D	33	6

Table I. Effect of Resistance and Inductance on Failure Rate

GROUP	SURGE VOLTAGE (V)	ESR Ω	L (µH)	PEAK I+ (A)	PEAK I- (A)	PEAK V	V at PEAK I+	MAX dI/dt (A/µS)	NUMBER OF FAILURES
A	30	.15-.19	.5	113-130	0.7	30-31	9-11	60	1/16
B	30	.15-.19	4.2	66-71	22-30	40-43	18-19	7.1	3/17
C	30	.19-.25	.5	93-113	0	30	7.9	60	0/17
D	30	.19-.25	4.2	59-66	13-22	37-40	16-18	7.1	3/16
E	30	.19-.25 + added .25	4.2	41	0	30	10	7.1	0/20
F	21	.15-.19	4.2	46-50	15-22	28-30	13	5.0	0/17

An example of the type of waveform associated with these conditions is shown in Figure 1.

Table II. Comparison of Peak Voltage & Current with Failure Rate

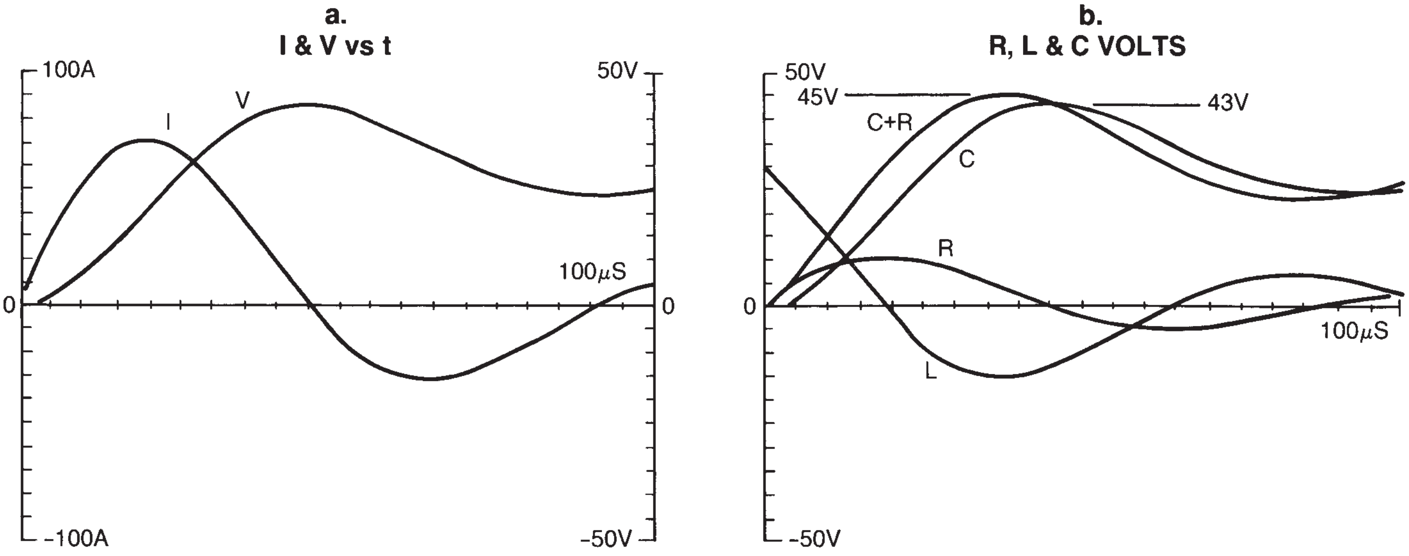
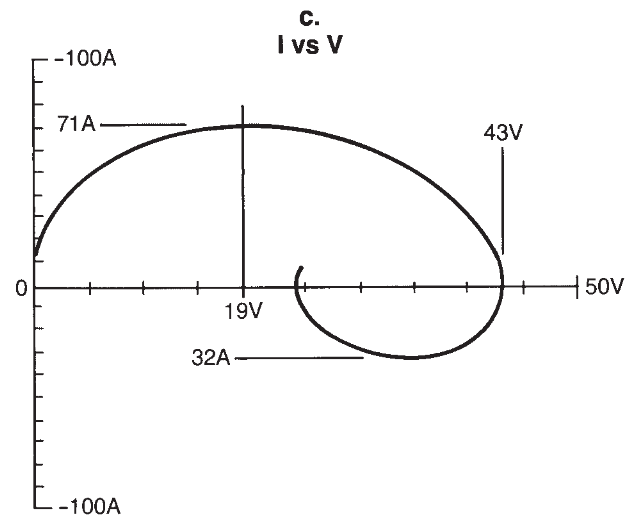
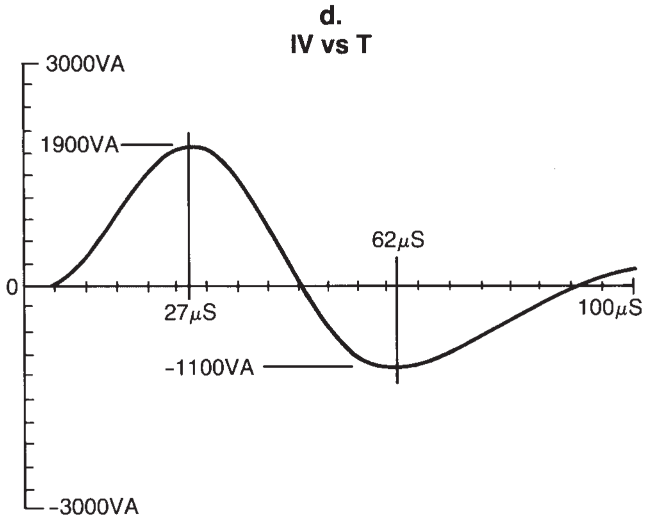


Figure 1. 47µF Capacitor Charged to 30V, ESR 0.15 ohms, L4.2µH





The peak voltage quoted is that across the dielectric only, not across the total capacitor. Where a range of peak values is given in Table II the actual value depends on the capacitor ESR, a lower ESR given higher peak value throughout.

Analyzing the results in Table II shows the following features:

Groups A thru D	The peak positive current (I+) is highest without added inductance and yet the failure rate is higher with inductance.
Groups A thru D + F	The peak negative current (I-) is highest with added inductance, however additional trials (Group F) with a further selected 17 capacitors in the range 0.15-0.19 ESR achieved the same level of peak negative current as Group D but without exceeding 30V and they did not show failures.
Groups A thru F	The majority of failures occurred when the voltage exceeded the 30V applied.
Groups A thru F	There could be some correlation between failures and the voltage for peak current. This is related to the plots of “IV vs Time” in Figure 1 and judgment is reserved on this factor.
Groups A thru F	There is no correlation between failures and maximum rate of rise of current.
Groups D & E	Addition of 0.25 ohm resistance into the circuit (Group E as compared with Group D) eliminated the voltage overshoot and also eliminated the failures.

This series of experiments suggests that voltage is more important than current in initiating the surge failures.

Obviously as the voltage is increased there will be greater incidence of failure due to dielectric breakdown. The ringing resulting from the inductance increases the possibility of breakdown due to the higher peak voltage. Note however that these only occur for some tens of microseconds in the conditions covered here and so such breakdown must be initiated within that time scale.

Overvoltage Testing

The level of failures at rated voltage is generally so low that it would be necessary to test many hundreds or even thousands of capacitors to obtain statistically significant comparisons for many of the investigations. Consequently there will be big advantage in using accelerated conditions for the test, such as overvoltage, provided that no new mechanism is introduced in so doing. An indication of the effect of overvoltage testing is shown in the following experiment where four manufacturers’ 1μF 35V resin dipped capacitors were compared.

All of the capacitors were of the premium grade available from the suppliers and the AVX capacitors were tested both as standard product and as screened by the 100% production surge screening at rated voltage. 200 capacitors from each source were surge tested at 35V. Those surviving were then tested at 50V and then at 60V. The tests were continued in some cases to 70V at which level the hexfets in the switch circuit had a tendency to fail when the capacitors became short circuit. Consequently only a restricted number were subjected to that level of surge. The percentage failures expressed as the accumulative totals are shown in Table III.

MANUFACTURER	ACCUMULATIVE % SURGE FAILURE				60V SURGE WITHOUT STEPS
	35V	50V	60V	70V	
AVX	0.5	2	10	55/201 = 27.5%	13
AVX Screened	0	0	3.5	23/100 = 23%	8
A	0	5.5	13.5	80/201 = 40%	22
B	0	7	38.5	Not Tested	56
C	1.5	12.5	31.5	34/60 = 57%	41

Table III. Failure Rate of 1μF 35V Resin Dipped Tantalum Capacitors

In addition 100 capacitors were tested at 60V without the lower voltage steps. This gave higher levels of failure for the 60V test (Table 111) in all groups suggesting that surging can clear some of the faults which might otherwise fail at the higher stress level.

The AVX screening process at rated voltage makes an improvement all the way through to at least 60V. It seems reasonable from these results to assume that there is no sudden appearance of a new mechanism as the severity is increased to approaching twice rated voltage. Similar conclusions were reached in the experiments with 47µF 25V capacitors stressed up to 40V.

SURGE VOLTAGE	ACCUMULATIVE FAILURE RATE % (Number Tested in Brackets)		
	ROOM TEMP.	85ºC	125ºC
20		10% (10)	
25		10% (10)	
30	3% (30)	10% (20)	10% (10)
35	3% (30)	20% (20)	30% (10)
40	7% (30)	60% (20)	80% (10)
45	33% (30)	70% (10)	90% (10)
50	50% (10)	90% (10)	

Table IV. Effect of Temperature on Failure Rates

Environmental Conditions

Effect of Temperature: For checks at high temperature 47µF 25V capacitors were mounted in aluminum blocks and heated to either 85ºC or 125ºC. They were then subjected to increasing surge voltages with a temperature recovery period in the oven between each voltage level. The results in Table IV show that increased temperature leads to more failures but that the difference between 85ºC and 125ºC is less than might be expected if 2/3 derating is considered appropriate for this failure mode.

Temperature Cycling: From a variety of tests it has been found that the surge performance of resin dipped capacitors was deteriorated by temperature cycling. Such an effect has previously been reported for the metal eased version[3] and there it was found that the lower temperature excursion was the detrimental part of the cycle. A similar check has been carried out with screened 47µF 25V capacitors using 10 rapid temperature cycles within the climactic category range of -55ºC to +85ºC. When retested for surge the failure rate was as follows:

-55ºC to 85ºC	30%
-55ºC to room temperature (-20ºC)	0%
Room temperature to +85ºC	23%

Therefore for this style the deterioration was mainly during the higher temperature excursion.

This deterioration could be eliminated by methods which relieved the tensile stresses resulting from thermal expansion of the resin, in particular in the region around the tantalum wire.

Effect of Moisture: Three different trials have been carried out to determine how sensitive the resin dipped capacitors were to moisture. Firstly, screened 47µF 25V capacitors have been held in a steam atmosphere at 100ºC for 1 hour and then surge tested at 30V with a 33% failure rate. After drying a similarly steam treated group for an hour at 85ºC the failure rate was 11%. In the second test 47µF 25V capacitors were stored at room temperature for 5 days over either silica gel or water with no effect on surge performance.

For the third test 198 screened capacitors from 10 different 25 or 35V codes were stored for 21 days at 40ºC and 95% RH and then surge tested at rated voltage (Table V). All of the 35V batches and the bigger anode 25V batches had failures which had been generated since they were 100% tested. The average failure rate was 7% so it was concluded that this storage under damp heat conditions was detrimental at least for the 25 and 35V codes.

In the first and last of these trials there was thermal stress as well as moisture present. From the work in the previous section it could well be that a large part of the deterioration is of thermal origin.

Breakdown Sites

Internal examination of capacitors which had started to pass high currents but had not gone to destruction showed various locations of breakdown site but the majority showed breakdown at or near the wire entry into the anode. This was the case whether the wire was pressed into the powder compact before sintering or welded on afterward. In a number of instances the wire had burned through creating an open circuit. In spite of this predominance of the wire location as a breakdown area it cannot be taken as evidence that this is the primary fault site. There were several instances of destruction around the wire coupled with a separate patch on the side of the anode. Sectioning and stripping techniques which removed the tantalum and the normal oxide dielectric but left the thermally deteriorated oxide suggested that there was no tracking connecting the two sites.

To explain the appearance of two separate regions of destruction within the time scale of a small fraction of a second, it is postulated that the primary fault was on the side of the anode and that the very high currents from that passing through restricted contact area between the wire and the powder, overheated that region as well.

Stages in the Failure Sequence

There can be three distinct stages in the breakdown sequence, although the capacitor may not necessarily go through all three. The first, which can occur in well under 1 millisecond from application of voltage is a momentary breakdown at a localized fault region. If the current supply is limited this can self-heal with no apparent permanent damage.

Clearing or self-healing can apparently also sometimes occur even when high currents are available: presumably whether this happens depends on the size of the primary fault. Without clearing, the primary fault is maintained in the conductive state by the high current and probably spreads due to thermal breakdown of surrounding dielectric. In this second stage this electrical heating results in temperatures of hundreds of degrees, generating gas from organic matter within the contact layers and the encapsulant. The gas pressure can then disrupt the encapsulant and may generate an open-circuit by moving the negative lead out of contact with the anode.

Under some conditions a third stage in the sequence may be initiated by the second. The temperature generated by the electrical discharge could be high enough locally to set off a chemical reaction between the tantalum and manganese dioxide with the liberation of a considerable amount of thermal energy. This could take the temperature up to several thousand degrees very rapidly, leading to a fire risk.

The sequence through to this final stage proceeds in a fraction of a second. These observations are based on a very severe method of test with extremely high current availability, minimum series resistance and often with overvoltage. With lower maximum currents the failure mode is less likely to progress to this third stage.

CODE	NO. TESTED	NO. FAILED SURGE
2.2 µF 25V	20	0
10 µF 25V	20	0
15 µF 25V	20	0
47 µF 25V	20	1
68 µF 25V	20	2
1 µF 35V	20	1
6.8 µF 35V	20	4
10 µF 35V	20	2
22 µF 35V	20	1
47 µF 35V	18	3
Total	198	14

Table V. Surge Failures after Humidity Testing

Influence of Leakage Current

Various attempts have been made to relate failure rate with leakage current, all without success. Besides the normal leakage current at low measurement voltage or at overvoltage, leakage selections with different temperature or voltage coefficients and leakage currents after very short charging times have all been checked. None showed any connection with this surge phenomenon even though the level of current could be several orders different in the selected groups. This was a very surprising finding as it had been anticipated that the leakage current would be a good indicator of faults in the dielectric. It is possible that some types of defects which could lead to failure undergo clearing or self-healing under the conditions of leakage current measurement.

Clearing

A number of lines of study lead to the conclusion that clearing the fault areas occurs under a wide range of electrical treatments. Even the surge current test itself can cause clearing of some faults. It has not been possible so far to identify any cleared areas using electron microscopy but that is not surprising as the area involved would be a minute proportion of the total dielectric film.

Furthermore there is a problem of identifying those capacitors which undergo clearing as it involves very low total energy and only need occur in a small proportion of the capacitors subjected to the treatment. Even if a likely candidate area were to be observed there would remain the task of proving that it had been generated by the clearing action. In spite of the absence of definite evidence it is felt that clearing is an important consideration in this investigation.

Comments

The fact that solid tantalum capacitors are used extensively in low impedance circuits shows that the risks of component failure in the field are very low. 100% screening reduces this risk even further. Therefore it is necessary to stress that there is no justification for replacing the tantalums by other capacitors (which would obviously have their own limitations). Rather, the aim must be for manufacturers to identify and remove the causes, and the work described here shows that this aspect is being actively pursued.

Within the length of this paper it has only been possible to touch on some of the aspects considered so far. Besides the experience of screening production quantities running into many millions of components, over 30,000 surge tests have been carried out by hand to obtain data for detailed analysis. Even so because of batch variability and the general low level of failures some of the conclusions reached can only be considered as tentative. To obtain statistically significant results in any one test large numbers of capacitors from a selection of different batches are required. An alternative approach is to use reasonably large numbers and to build up confidence in the significance of the results through the consistency of behavior. This has been the approach used in the present work. In the meantime safeguards are available to the users of tantalum solid capacitors through screening procedures which remove the small proportion which might otherwise be in doubt for these particular circuit conditions, that is in these low impedance, high current applications where adequate voltage derating cannot be ensured.

Acknowledgments

Several Engineers at the AVX Tantalum Unit in Paignton contributed to the investigations above. Special mention must be made to Hugh Davies who participated in many of the experiences.

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